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Efficient (re-)scheduling: An auction approach☆

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Abstract

We consider one-sided scheduling problems like the un/loading at sea-ports. These are typically handled on a first-come-first-serve basis, which is grossly inefficient. We propose a scheduling auction in the spirit of the Clark–Groves–Vickrey mechanism, and shows that it is free of the deficiencies that tend to plague it in other applications.

Keywords: Auctions; Rationing; Queuing; Priority pricing

JEL classification: D44; D45

1. Introduction

In a variety of settings, a given capacity has to be rationed among different parties, and a schedule has to be arranged that determines who shall be served when. First-come-first-served is the most frequently used scheduling rule. Sea-ports employ it to allocate time slots at berth. It is, however, blatantly inefficient. This suggests the search for better mechanisms which improve welfare and give those

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institutions that employ them a competitive edge. In this paper, we propose an efficient scheduling mechanism for one-sided scheduling problems, where schedules for service at one location can be viewed as independent of other schedules. That mechanism is an application of the Clark–Groves–Vickrey (C–G–V) rule to a two-sided exchange problem. It achieves the first-best schedule in dominant strategies, is deficit-free, and entails nonnegative prices that are shadow prices. It also allows for forward sales of time slots and assures that slots sold in advance are voluntarily brought back to the auction.

Sea-ports seem to fit reasonably well the pattern of one-sided scheduling problems. Therefore, we refer to that application.

Sea-ports typically allow shipping lines to book slots in advance. This so-called "rendezvous system" allocates part of the port capacity. The remaining capacity is assigned shortly before vessels are handled or as late as when they lined up in port on a first-come-first-serve basis (see Ghosh (2002) and Psaraftis (1998)).

There is a literature on queuing in ports. Dasgupta and Ghosh (2000) demonstrate that using prices to regulate queue performance can make a significant difference, using data from the port of Calcutta. And Ghosh (2002) proposes a standard sequential English auction to allocate time slots at berth.

The port scheduling problem is also related to the well-known "queuing problem" (see Marchand (1974) and Naor (1969)). However, "queuing" assumes random arrival and impatience (everyone wants to be served as soon as possible). This makes it unsuitable for port scheduling, since vessel operators plan their arrival in advance, and thus neither arrive randomly nor do they always wish to be served at the first slot available.

Section 2 states the assumptions, Section 3 the proposed auction, and Section 4 characterizes its properties. Section 5 explains why standard auction mechanisms should not be used. Section 6 concludes.

2. Assumptions and notation

Suppose there are $n \geq 2$ vessels that need to be queued for unloading during a given time window. Each ship is denoted by an index $i \in N := \{1, 2, \ldots, n\}$. Vessels may require a different amount of time for unloading. Some vessels may have already secured a slot in a previous forward transaction.

Based on the time required for unloading, the port authority computes all feasible time allocations. A feasible allocation, $\alpha^r := \{\alpha_1^r, \ldots, \alpha_n^r\}$, is a complete schedule; component α_i^r states at which time ship i shall be unloaded, and the sum total of allocated slots does not exceed the available time. The set of all feasible allocations is denoted by $A := \{\alpha^1, \ldots, \alpha^m\}$. Similarly, the restricted set of feasible allocations that apply if a particular slot s is not available is denoted by A_{-s}.

3. The proposed auction

We propose the following auction, described as a direct revelation mechanism. There, bidders are asked to report their profits from being served according to each feasible allocation (relative to being served at some given alternative slot), and the auctioneer selects an allocation and associated prices, as a function of the messages by all n bidders.

A "bid" by bidder i is a vector $\tilde{\pi}_i$ that states his reported profits for each and every feasible allocation $\alpha \in A$:

$$\tilde{\pi}_i := \left(\tilde{\pi}_i\left(\alpha_i^1\right), \tilde{\pi}_i\left(\alpha_i^2\right), \ldots, \tilde{\pi}_i\left(\alpha_i^m\right)\right). \quad (1)$$

Bidders may not tell the truth; therefore a bid $\tilde{\pi}_i$ may deviate from true profits, which are denoted by π_i.

The combined "bid vector" of all bidders, $\tilde{\pi} := (\tilde{\pi}_1, \tilde{\pi}_2, \ldots, \tilde{\pi}_n)$ determines which allocation is chosen and how the associated schedules are priced, according to the following rules.

"*Allocation rule*": For each bid vector, $\tilde{\pi}$, the mechanism selects the allocation, $\alpha^*(\tilde{\pi})$, that maximizes bidders' welfare, which is the sum of their bids:

$$\alpha^*(\tilde{\pi}) := \arg\max_{\alpha \in A} W(\alpha, \tilde{\pi}), \quad W(\alpha, \tilde{\pi}) := \sum_{j \in N} \tilde{\pi}_j\left(\alpha_j\right). \quad (2)$$

This rule selects the efficient allocation, defined as the maximizer of the sum total of true profits, if bidders bid truthfully $\tilde{\pi}_i = \pi_i$, for all $i \in N$.

A similar allocation rule is applied to two hypothetical circumstances: when bidder i is excluded from participation in the mechanism, and when bidder i is excluded *and* at the same time, a particular slot s is not available:

$$\alpha^*_{-i}(\tilde{\pi}_{-i}) := \arg\max_{\alpha \in A} W_{-i}(\alpha, \tilde{\pi}_{-i}), \quad (3)$$

$$\alpha^*_{-i,-s}(\tilde{\pi}_{-i}) := \arg\max_{\alpha \in A_{-s}} W_{-i}(\alpha, \tilde{\pi}_{-i}), \quad (4)$$

$$W_{-i}(\alpha, \tilde{\pi}_{-i}) := \sum_{j \neq i} \tilde{\pi}_j\left(\alpha_j\right). \quad (5)$$

"*Pricing rules*": Bidders are required to pay a "service price" for the slot allocated to them, and receive a "selling price" if they already own a slot and supply it to the auction.

The *service price* to be paid by bidder i if he is awarded slot $\alpha_i^*(\tilde{\pi})$ is equal to the negative externality that his participation inflicts upon all other bidders:

$$P\alpha_i^*(\tilde{\pi}) := W_{-i}\left(\alpha^*_{-i}(\tilde{\pi}_{-i}), \tilde{\pi}_{-i}\right) - W_{-i}\left(\alpha^*(\tilde{\pi}), \tilde{\pi}_{-i}\right). \quad (6)$$

The *selling price* to be paid to bidder i for a slot s, if he owns it but supplies it to the auction, is equal to the positive externality to others that occurs if he supplies slot s yet does not participate in the auction as a buyer:

$$P_{si} = W_{-i}\left(\alpha^*_{-i}(\tilde{\pi}_{-i}), \tilde{\pi}_{-i}\right) - W_{-i}\left(\alpha^*_{-i,-s}(\tilde{\pi}_{-i}), \tilde{\pi}_{-i}\right). \quad (7)$$

These rules induce a noncooperative game, characterized by the following payoff functions, defined on bidders' messages, which are their strategies. The payoff function of a bidder i who does not already own some slot (we may call him a "*buyer*": b) is

$$\Pi_i^b(\tilde{\pi}) = \pi_i\left(\alpha_i^*(\tilde{\pi})\right) - p_{\alpha_i^*(\tilde{\pi})} = \pi_i\left(\alpha_i^*(\tilde{\pi})\right) + W_{-i}(\alpha^*(\tilde{\pi}), \tilde{\pi}_{-i}) - W_{-i}\left(\alpha^*_{-i}(\tilde{\pi}_{-i}), \tilde{\pi}_{-i}\right). \quad (8)$$

Similarly, the payoff function of a bidder i who already owns slot s and makes it available to the auction (we may call him "*seller/buyer*": *sb*) is

$$\Pi_i^{sb}(\tilde{\pi}) = \pi_i\left(\alpha_i^*(\tilde{\pi})\right) - p_{\alpha_i^*(\tilde{\pi})} + P_{si} = \pi_i\left(\alpha_i^*(\tilde{\pi})\right) + W_{-i}(\alpha^*(\tilde{\pi}),\tilde{\pi}_{-i}) - W_{-i}\left(\alpha_{-i,-s}^*(\tilde{\pi}_{-i}),\tilde{\pi}_{-i}\right). \quad (9)$$

If bidder i already owns slot s but does not supply it to the auction (we may call him a "*non-seller*": *ns*), his payoff function is

$$\Pi_i^{ns}(\tilde{\pi}) = \pi_i(s). \quad (10)$$

Whereas if he sells at the auction but does not buy there (we may call him a "*pure seller*": *s*), his payoff function is

$$\Pi_i^{s}(\tilde{\pi}) = P_{si} = W_{-i}\left(\alpha_{-i}^*(\tilde{\pi}_{-i}),\tilde{\pi}_{-i}\right) - W_{-i}\left(\alpha_{-i,-s}^*(\tilde{\pi}_{-i}),\tilde{\pi}_{-i}\right). \quad (11)$$

Note, Π_i^{ns} is only dependent on π_i, and Π_i^s is only dependent on $\tilde{\pi}_{-i}$.

4. Properties of the proposed auction

Theorem 1. *(1) Truthful bidding is an equilibrium in dominant strategies. It implies (2a) efficient (re-)scheduling; (2b) all slots that were sold forward are supplied to the auction; (2c) nonnegative prices; (2d) prices are shadow prices.*

Proof. (1) Consider a pure buyer. If he tells the truth, his payoff is equal to $\Pi_i^b(\pi_i, \tilde{\pi}_{-i})$. Whereas if he lies and reports $\tilde{\pi}_i \neq \pi_i$, and thus changes the allocation to $\alpha^k \neq \alpha^*(\pi_i, \tilde{\pi}_{-i})$, his payoff is reduced,

$$\begin{aligned}\Pi_i^b(\pi_i,\tilde{\pi}_{-i}) &= \pi_i\left(\alpha_i^*(\pi_i,\tilde{\pi}_{-i})\right) + W_{-i}(\alpha^*(\pi_i,\tilde{\pi}_{-i}),\tilde{\pi}_{-i}) - W_{-i}\left(\alpha_{-i}^*(\tilde{\pi}_{-i}),\tilde{\pi}_{-i}\right) \geq \pi_i\left(\alpha^k\right) \\ &\quad + W_{-i}\left(\alpha^k,\tilde{\pi}_{-i}\right) - W_{-i}\left(\alpha_{-i}^*(\tilde{\pi}_{-i}),\tilde{\pi}_{-i}\right),\end{aligned}$$

because $\alpha^*(\pi_i,\tilde{\pi}_{-i})$ is the maximizer of the sum

$$\pi_i\left(\alpha_i^*(\pi_i,\tilde{\pi}_{-i})\right) + W_{-i}(\alpha^*(\pi_i,\tilde{\pi}_{-i}),\tilde{\pi}_{-i})$$

and because adding the constant $W_{-i}(\alpha_{-i}^*(\tilde{\pi}_{-i}), \tilde{\pi}_{-i})$ to that sum does not change its maximizer.

The same argument applies to the seller/buyer because his payoff function differs only in the constant.

Finally, the payoff of the pure seller is independent of his message; therefore, he cannot gain from cheating either.

We now use this result in the proof of properties (2a–2d): (2a) By (1), the mechanism implements the allocation $\alpha^*(\tilde{\pi})=\alpha^*(\pi)$, which is efficient.

(2b) Consider a ship-owner who had purchased a slot forward. Since

$$\Pi_i^{sb}(\pi) - \Pi_i^s(\pi) = \pi_i\left(\alpha_i^*(\pi)\right) - p_{\alpha_i^*(\pi)} = \Pi_i^b(\pi) \geq 0,$$

selling and buying (*sb*) payoff dominates pure selling (*s*).

Next, define $(s, \alpha^*_{-i,-s}(\pi_{-i}))$ as that allocation that awards slot s to bidder i and slots $\alpha^*_{-i,-s}(\pi_{-i})$ to the others bidders. Since $\alpha^*(\pi)$ is maximizer of W and subtracting a constant does not affect that maximizer, it follows that

$$\begin{aligned}\Pi_i^{sb}(\pi) - \Pi_i^{ns}(\pi) = & -\pi_i(s) + \pi_i\left(\alpha_i^*(\pi)\right) + W_{-i}(\alpha^*(\pi),\pi_{-i}) \\ & - W_{-i}\left(\alpha^*_{-i,-s}(\pi_{-i}),\pi_{-i}\right) \\ \geq & -\pi_i(s) + \pi_i(s) + W_{-i}\left(\alpha^*_{-i,-s}(\pi_{-i}),\pi_{-i}\right) \\ & - W_{-i}\left(\alpha^*_{-i,-s}(\pi_{-i}),\pi_{-i}\right) = 0.\end{aligned}$$

(2c) Service prices p are nonnegative because slots are private goods, and one bidder's participation can only reduce the capacity available to others (see Eq. (6)). Similarly, selling prices, P, are nonnegative because supplying at the auction while not participating as a buyer, benefits others (see Eq. (7)).

(2d) In equilibrium, bidder i is awarded slot $\alpha_i^*(\pi)$. Suppose a replica of that slot is made available to the auction. Then welfare increases by the amount $W_{-i}(\alpha^*_{-i}(\pi_{-i}), \pi_{-i}) - W_{-i}(\alpha^*(\pi), \pi_{-i})$; by Eq. (6), this is equal to the service price $p_{\alpha_i^*(\pi)}$. Therefore, services prices are shadow prices. A similar argument applies to selling prices. □

The last property entails that ports are also given the right incentives to invest in port capacity.

5. Why not use a standard auction?

It has been suggested that one should auction slots sequentially, in a standard, ascending-bid auction (see Ghosh (2002)). Each slot would then be allocated to the one who values it most; however, that allocation is generally inefficient.

A simple example explains the problem: suppose three vessels, called A, B, and C, demand to be handled at a port on a given day. Vessel A is considerably larger than B and C, and the port can handle either A alone or both B and C. Also let A's willingness to pay for immediate port handling, v_A, be considerably higher than that of B and C, v_B, v_C, yet smaller than the sum of the willingness to pay for serving B and C in sequence, v_{BC}. In that case, the standard auction allocates the port capacity to vessel A and neither serves vessel B nor C. This is inefficient since the value generated by this allocation, v_A, is lower than the value that it crowds out, v_{BC}.

6. Discussion

The present paper proposes an auction that solves the problem of scheduling in ports and similar applications. This mechanism is an adaptation of the generalized C–G–V rule to a two-sided exchange problem which is deficit free and yields nonnegative prices that are shadow prices. Therefore, it has ideal properties, unlike in many other applications of C–G–V mechanisms.

One may object that our mechanism is too complex for practical applications because it requires bidders to make package-bids on all feasible allocations. However, if bidders do not care about the time slots made available to others, they only need to distinguish allocations that award different slots to them. This considerably reduces the complexity of bidding.

However, the proposed mechanism is not suitable if there are significant interdependencies between schedules arranged at different locations, as in the case of airports, where take-off and landing must be coordinated. Moreover, it assumes independence of bidders' privately known willingness to pay for slots; therefore, it should not be applied if there are complementarities between slots, as in the scheduling of feeder service at hub ports.

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