Ascending Prices and Package Bidding: An Experimental Analysis*

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We use theory and experiment to explore the effectiveness of price-guided mechanisms to assign resources in package allocation problems. Two mechanisms are tested: the combinatorial clock auction (CCA) of Porter, Rassenti, Roopnarine, and Smith (2003) and a matched version of the simultaneous ascending auction (SAA), similar to designs currently in use for spectrum and electricity sales. Unlike earlier experiments, we report not only comparative efficiency and revenue but also statistics about bidder behavior. In our experiments, the CCA fails to achieve core outcomes (efficient and entailing competitive revenues) except in special environments where a particular search algorithm happens to find efficient allocations.

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I. Introduction

Neoclassical economics studies resource allocation problems in which linear prices can support and guide an efficient allocation. While the scope of the theory encompasses much, it also excludes much. For example, in Dutch flower auctions, buyers are typically concerned about fixed shipping costs and may prefer to buy a large quantity of flowers or none at all. In such cases, finding an efficient allocation is generally a difficult combinatorial problem for which the solution has no supporting linear prices. A more complicated example is the allocation of landing rights at a congested airport. An airline with a hub-and-spoke system might wish to acquire rights for all its destinations in the same quarter hour, but might be flexible about when the quarter hour begins. Similar examples occur in real estate sales, in which a buyer might want to buy several adjacent lots or buildings to develop an office cluster or shopping center, in radio spectrum, in which a new entrant might want to acquire licenses with sufficient scale and scope to support its business plan, and in many other settings. In each case, the efficient solution can require a combinatorial optimization and linear market-clearing prices may fail to exist.

How can resource allocation mechanisms be designed to assign goods efficiently in these *package allocation problems*? According to the revelation principle, one can limit attention to direct mechanisms for some theoretical purposes, but direct mechanisms raise the issue of communication and computational complexity. For example, with just twenty items for sale, there are $2^{20} > 10^6$ possible packages a bidder might buy. In a direct mechanism, each bidder needs to report a value for every package.[1] The resulting burdens on communications and on computational systems for finding efficient resource allocations can be too high even for problems of this modest size.

Responding to this challenge, various researchers in economics and computer science have proposed dynamic auction mechanisms, cousins of the Walrasian

[1] Besides complexity, the package allocation problem sometimes also suffers from a difficult trade-off among individual bidder incentives, group incentives, and seller revenues. The Vickrey auction, which is strategy-proof for individual bidders, can lead to low (or even zero!) seller revenues despite ample competition and has unusual vulnerabilities to coalitional deviations. See Ausubel and Milgrom (2005) and Rothkopf (2007).

tatonnement, which use past bids and linear prices to set minimum bids on each package and to provide bidders with useful information to guide their bidding. What makes these auctions different from a *tatonnement* is that current and *past* bids are all used in a single optimization in at least some rounds to determine the provisionally winning bids. For example, if bids of 10 for A and 4 for B lose to a bid of 15 for the package AB and if a bid of 6 is subsequently made for B, then the old losing bid of 10 for A can become a winning bid, because it is part of the unique combination of bids that achieves the maximum total of 16.

There are two quite different approaches to using individual *item prices* to help solve package allocation problems of this sort. One approach attempts to find item prices that are approximate market clearing prices. If goods are substitutes for all bidders, then market-clearing item prices exist (Milgrom (2000), Gul and Stacchetti (1999)) and these support an efficient goods assignment. As in neoclassical economics, these market-clearing item prices are anonymous – the same for all bidders. If goods are not substitutes, then market clearing item prices do not generally exist, but there are non-anonymous ("bidder-specific") *package prices* to support the efficient assignment and one can look for the item prices that best approximate those.[2] This is the approach taken by the RAD design of Kwasnica, Ledyard, Porter, and DeMartini (2005).

The RAD mechanism is a multi-round package auction. At each round, RAD uses the collected bids to find the feasible allocation that maximizes the seller's total revenue. Then, it solves a second, dual optimization to find the item prices that minimize the distance in a particular metric to non-anonymous package prices that support the allocation. In the next RAD round, the minimum bid for any package is the sum of the corresponding item prices, plus a minimum bid increment. In the accompanying experiments, the RAD design performs significantly better than the simultaneous multiple round auction design used by the US Federal Communications Commission for radio spectrum sales.

[2] More precisely, a vector of item prices p defines a price for any package that is the sum of the item prices of the elements of the package, so p can be chosen to minimize the distance between these package prices and the non-anonymous package prices that support the efficient assignment.

A problematic aspect of the RAD design is that the prices can fluctuate widely and unpredictably from round to round. This poses difficult strategic bidding issues. For example, a bidder who sees a suddenly high minimum bid for some package may choose to delay making its bids in hopes that the prices will fluctuate down again.

The second approach to item pricing is more heuristic and is not based on finding prices to support the final allocation, even approximately. To establish a precise foundation for the second approach, we formulate and prove two theorems concerning how the pattern of bidding during a dynamic auction – not just the bids or prices at the final round – can lead to allocations that are efficient or in the core.

Our theorems apply to a wide class of dynamic package auctions in which the payments by bidders are the highest bids they make during the auction for the packages they win. The theorems do not require that item prices be used nor do they restrict in any way the dynamics of how bids are solicited. For example, the theorem applies to RAD, to heuristic linear pricing mechanisms, and even to the ascending proxy auction of Ausubel and Milgrom (2002), which makes no use of item prices.

Let N denote the set of bidders, x an assignment of goods, x_j the package of goods assigned to bidder j, and v_j bidder j's value function. Then, the total value of the goods assignment x is $\sum_{j\in N} v_j(x_j)$. Let $\beta_j(x_j)$ denote the highest price that j bids for package x_j during the course of the auction.

Associated with the package allocation problem is a cooperative game in which the players are the bidders N and the seller. If the seller and a set of bidders S form a coalition, then they maximize their value by choosing an allocation $x(S)\in \arg\max_x \sum_{j\in S} v_j(x_j)$. In particular, $x(N)$ is an efficient assignment. The value of the coalition consisting of the seller and bidder set S is $w(S)=\sum_{j\in S} v_j(x_j(S))$; any coalition that excludes the seller has value zero. An allocation $(x,\beta(x))$ is in the *core* if the corresponding payoff imputation π satisfies $\pi_0+\sum_{j\in S}\pi_j \geq w(S)$ for every set of bidders S.

In our experiment, it is often the case that there are only a few significant groupings of bidders, such as the global bidder acting alone or two regional bidders acting together, and only a few significant packages for each bidder. With these patterns in mind, let us say that a set of bidders *S* (and the corresponding coalition comprising those bidders and the seller) is *relevant* if there is some core imputation π such that $\pi_0 + \sum_{i \in S} \pi_i = w(S)$. By a standard property of systems of linear inequalities, the core allocations are precisely those for which the corresponding payoff imputations satisfy $\pi_0 + \sum_{i \in S} \pi_i \geq w(S)$ for every relevant set of bidders *S*; that is, we can omit the inequalities for other sets of bidders. By the *relevant packages*, we will mean the packages $x_i(S)$ for some relevant set of bidders *S* and some bidder $i \in S$.

We consider auctions in a class *A* that selects an assignment $\bar{x}$ to maximize the seller's revenue: $\bar{x} \in \arg\max_x \sum_{j \in N} \beta_j(x_j)$ and has bidder *j* pay $\beta_j(\bar{x}_j)$. Let $\bar{\pi}_j = v_j(\bar{x}_j) - \beta_j(\bar{x}_j)$ denote bidder *j*'s profit from the auction assignment and let $\bar{\pi}_0 = \sum_{j \in N} \beta_j(\bar{x}_j)$ denote the corresponding seller revenue.

<u>Theorem 1</u>. Consider any auction in class *A*. If, for all relevant packages $x_i(S)$, $v_i(x_i(S)) - \beta_i(x_i(S)) \leq \bar{\pi}_i$, then the final allocation $(\bar{x}, \beta(\bar{x}))$ is a core allocation.

<u>Proof</u>. At the final allocation, the total payoff to the coalition consisting of the seller and the set of bidder *S* is given by:

$$\begin{aligned} \sum_{i \in N} \beta_i(\bar{x}_i) + \sum_{i \in S} \bar{\pi}_i &\geq \sum_{i \in S} \beta_i(x_i(S)) + \sum_{i \in S} \bar{\pi}_i \\ &\geq \sum_{i \in S} v_i(x_i(S)) = w(S) \end{aligned} \tag{1}$$

The first inequality is justified because the auction selects the assignment $\bar{x}$ over any other assignment including *x*(*S*); the second follows from the hypothesis of the theorem. The final equality is the definition of *w*(*S*). The allocation $(\bar{x}, \beta(\bar{x}))$ is thus feasible and unblocked by any relevant coalition; that is, any coalition consisting of the seller and a relevant set of bidders. **QED**

Theorem 2. Consider any auction in class A. If, for all bidders i, $v_i(x_i(N)) - \beta_i(x_i(N)) \le \bar{\pi}_i$, then the goods assignment $\bar{x}$ is efficient.

Proof. The total value of the final goods assignment is

$$\begin{aligned}\sum_{i\in N} v_i(\bar{x}_i) &= \sum_{i\in N} \beta_i(\bar{x}_i) + \sum_{i\in N} \bar{\pi}_i \\ &\ge \sum_{i\in N} \beta_i(x_i(N)) + \sum_{i\in N} \bar{\pi}_i \\ &\ge \sum_{i\in N} v_i(x_i(N))\end{aligned} \tag{2}$$

The first equation follows from the definition of $\bar{\pi}_i$; the first inequality follows because $\bar{x}$ maximizes revenues; and the last from the hypothesis of the theorem. **QED**

Theorems 1 and 2 explain how a dynamic auction can encourage efficient or core outcomes to emerge. To promote those results, the auction mechanism must (1) assist each bidder j in identifying the relevant packages (x_j) on which to bid, (2) allow bidders to easily make bids at the relevant levels ($\beta_j(x_j) \ge v_j(x_j) - \bar{\pi}_j$) for those packages, and (3) encourage losing bidders to bid all the way up to their full values ($\beta_j(x_j) = v_j(x_j)$) for relevant packages.

Like RAD, the *combinatorial clock auction* (CCA) introduced by Porter, Rassenti, Roopnarine, and Smith (2003) is a multi-round mechanism that determines individual item prices in each round and sets the price of a package in any round to be the sum of the prices of the items in the package. At each round, given the current prices, bidders identify a package, or several packages, which they offer to buy at those prices. Provisionally winning bids and bidders are calculated. A bidder is said to demand an item if it is a provisional winner of a package containing the item or if it has placed a bid on a package containing the item in the current round. If two or more bidders demand an item, then the price of that item is increased for the next round. The auction ends when no prices are increased.

Depending on how bidders behave, the CCA has properties that *could* lead to efficient or core outcomes for the easy case of substitute goods or for the harder general case. For the substitutes case, if bidders were to bid only for the package that is most preferred at the current prices, and if all price increments are sufficiently small, then the auction has properties similar to the simultaneous ascending auction: the final allocation is the efficient one and the final prices are approximate market-clearing prices. In the harder general case, treating price increments as negligible, if the final cost for some package *x* is *p*, then each bidder has a chance to bid for *x* at every price up to and including *p*, so the CCA guarantees at least the possibility that legal bids can satisfy the conditions of Theorems 1 and 2. In contrast, because the prices that emerge during RAD can be subject to large jumps from round to round, the item prices necessary for making the relevant bids may never be offered at any round during the course of the auction.

In the initial experiment testing the CCA design, Porter, Rassenti, Roopnarine, and Smith (2003) report remarkable results. In 25 auction trials, efficiencies of 99% are reported in two trials and 100% in the remaining 23 trials. Our results, reported below, show more modest success. Comparisons between those earlier results and ours are limited because certain details of the auction rules, the bidder interfaces, and valuations and bid data from the earlier experiment were not available to us.

These initial experimental results are surprising and suggest that further experiments testing similar designs could be fruitful. But experiments alone cannot resolve the comparative performance of alternative package auctions designs over a usefully wide range of settings. To illustrate the limits of experimental testing for comparing package auction designs, consider the experiment used to test proposed designs to sell radio spectrum licenses for FCC auction 73 (Brunner, Goeree, Holt, and Ledyard (2007), Goeree, Holt Jr., and Ledyard (2007)). This experiment entailed selling 18 licenses – 12 “national” licenses and 6 “regional” licenses.[3] The number of possible packages (all non-empty subsets of the set of 18 items) is 262,143, and the space of possible values for a bidder has that same number of dimensions. To simplify, the experiment was designed so that no bidder could purchase more than 6 licenses and synergies satisfied a linear formula by which with each new license won, all the licenses a bidder won increased by 20% over their stand alone values. The authors of this

[3] The experiment was designed to model the impact of package bidding for the C-band in FCC auction 73 which had 12 licenses in total. The experiment was commissioned by the FCC to determine the potential impact of different package auction designs on the C-band, so that a number of the design elements were dictated by the FCC. The computer interface had a calculator that would aid bidders in creating and evaluating any package they wanted to.

experiment do not claim to do anything more than test some interesting value patterns, and we agree that is a necessary perspective. To explore systematically even a one hundred dimensional subspace of the full set of values – an impractically hard task – would require imposing hundreds of thousands of restrictions on the set of possible bidder values. With such an enormous domain of values to explore, the only hope for learning general lessons from an experiment lies in identifying a theory to extrapolate from the observations of a tiny fraction of the possibilities: theory and experiment must work together.

We take a step in that direction with our two theorems, which identify bids whose presence necessarily lead to core or efficient outcomes in a large set of dynamic package auctions. We can use the theorems to examine whether those bids are more or less likely to be made in alternative auction mechanisms and in particular environments. For example, it seems likely that losing bidders will more often (approximately) exhaust their full values in an ascending price auction than in a sealed-bid auction, because such bids are (approximately) dominated in a sealed-bid auction. Bidder interfaces that make it cheaper to specify many bids in a round make it more likely that the conditions of the theorems will be satisfied. The range of prices that emerge for a package during the auction, information that bidders receive about whether their bids are provisionally winning, and the opportunities that are lost if bidders with provisional winning bids fail to make new bids, can all affect the likelihood that the conditions of the theorems are satisfied.

How might bidders know which packages are relevant? In our experiment, bidders have more cues than just the prices and their own values to guide them in selecting the packages on which to bid. “Regional bidders” are assigned zero values for items outside their regions and have a particular geographic structure of synergy values. The name “regional bidder”, the zero values, and the pattern of synergies all provide important cues about which packages are likely to be relevant. If bidders bid only on a small number of packages – as they do in our experiment – then such knowledge would make it more likely that the chosen packages are relevant ones, leading more frequently to efficient outcomes and core payoffs.

The likelihood that a bidder succeeds in bidding on all relevant packages is influenced by fine details of the auction rules and their implementation. Defaults in the bidder interface that, for example, result in continued bidding on the same packages from round to round unless the subject makes a change, are likely to increase the number of packages bid on, making coverage of relevant packages more likely. Changes in the bidder interface from our initial SAA auctions to later ones provide some direct evidence about this effect. Small variations in the bid increment rules that reduce the likelihood of early termination would also seem to make it more likely that the final auction outcome is a core allocation. Experiments like ours that identify the provisionally winning packages for bidders might discourage subjects from continuing to bid on those packages; that could diminish the frequency of bidding on relevant packages compared to an auction in which provisionally winning bids remain unreported. However, bidders might be reluctant to enter an auction in which they are "kept in the dark" regarding their status, so that there might be a tradeoff between providing this information to induce participation and the positive properties of the CCA mechanism.[4]

For a bidder who wants to bid on relevant packages, the complexity of package auction environments can pose a serious challenge. Consider, first, the cognitive demands placed on a bidder by a package auction experiment with eighteen items for sale. Given any set of prices, a bidder has to survey more than 262,000 packages to identify the most profitable one at current prices. Plainly, without a special structure for the valuations, that is far beyond the capability of an unaided human subject. In practice, bidders in high value spectrum auctions often use elaborate bidder support software to help guide their decisions. This poses an experimental design problem, for it would hardly be interesting to learn that if bids are sorted and presented to bidders according to some criterion X, then the bidders most often choose bids at each round that are highly ranked by X. Thus, it is important to report in detail the sorts of decision support provided to bidders.

Besides the issues complicating individual decisions, there are a number of strategic problems that are particular to package allocation problem, including the *exposure problem*, two *protocol problems* – the *threshold problem* and the *package*

[4] This is, of course, an empirical issue which can only be settled by appealing to data, more than likely data obtained from field settings.

coordination problem, and the *collusion problem*. The exposure problem arises when a non-package auction mechanism is used in the package allocation setting. To illustrate it, consider a bidder who regards items A and B to be complementary and wants to buy the package AB at the current prices in a simultaneous ascending auction. Bidding on both items individually risks acquiring just A or just B and leaves the bidder *exposed* to the possibly of a loss. Evidence of the exposure problem might be found in the reluctance of bidders in the simultaneous ascending auction to bid for A or B even when winning the package would be profitable. It might also include evidence that a bidder who is provisionally a winner on A is only willing to bid up to the marginal value for item B, even when its standalone value is lower than its price. The threshold problem is one that can potentially arise in package auctions. To illustrate the problem (first identified in Ledyard, Porter, and Rangel (1997)), suppose that bidders for A and B separately are competing with a bidder who has bid a sum β for the package AB. To win, the sum of the prices for the two single-item bids must exceed β and any two bids which achieve that can be winning. Thus, every package auction mechanism can be regarded as embedding a bargaining protocol by which the smaller bidders attempt to *coordinate* their packages so that they fit together without overlapping, and to adjust their bid prices so that the total reaches the *threshold*. A bargaining protocol which enables smaller bidders to coordinate both packages and bid amounts might enable bidders simply to *collude*, dividing up the seller's lots and refraining from bidding against one another, so there may be a design trade-off between solving the collusion problem and the coordination and threshold problems.[5]

Yet another special issue in package auction experiments concerns what to measure. Previous experiments invariably report some measure of the efficiency of the experimental outcome. Sometimes, comparative revenues are also reported, but there is typically no standard by which to determine whether revenues attain a reasonable level.

[5] A full strategic analysis of the CCA for the incomplete information case is difficult or impossible. Nevertheless, it is possible to characterize some full information equilibria, provided bid increments are treated as negligibly small. The equilibrium analysis is then essentially the same as for the ascending proxy auction of Ausubel and Milgrom (2002): for every core imputation π, there is a Nash equilibrium in which every bidder *j* makes every bid for which the potential profit is at least π_j. See also the similar equilibria for alternative package auctions described by Bernheim and Whinston (1986) and by Day and Milgrom (2007). These equilibrium characterizations combine to highlight the core as an interesting theoretical standard.

Milgrom (2007) has identified the *core* of the package assignment game as setting a reasonable competitive revenue standard for package auctions, and we have argued above that there are behaviors that lead toward core allocations for the CCA. We investigate revenues in relation to the core in our experiments. We also attempt to measure various aspects of bidder behavior, particularly as they relate to Theorems 1 and 2.

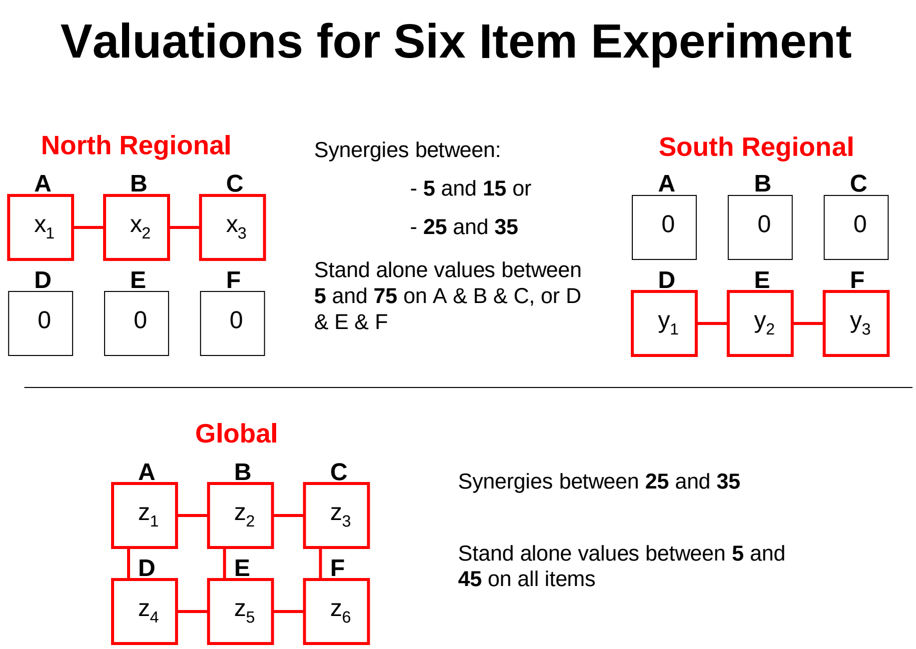
Given the difficulty of the package auction problem, a useful way to evaluate the performance of mechanisms like the CCA is to compare them to a closely matched version of the simultaneous ascending auction (SAA), which is a non-package auction that is widely used in a variety of applications. Milgrom (2000) has shown that when goods are substitutes, if all bidders bid straightforwardly, and if bid increments are small, then the SAA outcome is a competitive equilibrium (and hence a core allocation), and that any substantial weakening of the substitutes requirement can reverse that conclusion.

Our experiment compares a "clock auction" implementation of the simultaneous ascending auction – similar to ones that are sometimes used for selling electrical power contracts – and a CCA design. The use of a clock auction implementation allows us to ensure that the bidder interfaces for the two are very similar, so that significantly different results cannot be attributed to large differences in presentation formats. Given the vast complexity of large environments, we limit attention to small auction settings with just four or six items. This reduces the cognitive challenges facing bidders and may lighten the role of the decision support software provided to the bidders. Even within a relatively low dimensional space of package values, our simulations explored only special cases, as described in detail below. Within that set, we tested various parameter configurations to identify the expected performance of the two selected mechanisms with simulations using a kind of "straightforward" bidding, in which subjects bid just for the single most profitable package at each round. A similar rule has had some success in explaining bidder behavior in another complex auction experiment—that of Brewer and Plott (1996). Based on the simulations, we identified cases that we believed might be "interesting" cases to explore experimentally, including ones in which simulations showed the simpler simultaneous ascending auction performed better than the combinatorial clock auction.

II. Experimental Design and Procedures[6]

We conducted auctions with either four or six items for sale with similar demand structures in both cases. In what follows we focus on the six item case, illustrated in Figure 1. There were three bidders in each market: A North regional bidder interested in items A, B and C, placing positive value on these items with zero value for the others, and with positive synergies between items AB and BC. Similarly, there was a South regional bidder with positive value for items D, E, and F, with zero for the others, and with positive synergies between items DE and EF. Finally, there was a Global bidder with positive value for all six items and positive synergies between pairs AB, BC, DE, EF, AD, BE, and CF.

Figure 1



The standalone values for the regional bidders were integer iid values from the support [5, 75] and with either low synergy values (integers consisting of *a single* random draw from [5, 15]) or high synergy values (integers consisting of *a single* random draw from

[6] The full set of instructions, along with more sample screen shots, is available at www.econ.ohio-state.edu/kagel/KLM _instructions.pdf.

[25, 35]). Thus, synergy values were the same between all pairs of items, with standalone values varying between items. The high or low synergy regime was in place for both regional bidders at the same time and was announced prior to each auction. The standalone values for the global bidder were integer iid values from the support [5, 45] and with synergy values consisting of *a single* random draw from [25, 35] in all cases. Thus, in the case of low synergy values for the regional bidders, the global bidder faced relatively weaker competition than when the regional bidders had higher synergy values. Further, the lower standalone values for the global bidder meant that they had to rely more on the synergies for profits as opposed to the regional bidders who relied more on their higher average standalone values. Roles as a regional or global bidder changed randomly from auction to auction, with bidders' valuations changing as well.

The four item auctions were the same as the six item auctions but with standalone items C and F dropped.

CCA Auctions: In the CCA auctions bids are for a package of items so that, for example, subjects could bid on a package containing A, B **and** C, as well as a package containing A and B or a package containing A or B alone. Bids for each bidder were XOR bids, meaning that only one of the bids could be a winning bid in any given round of the auction. In the CCA, when a bid wins, the bidder is assigned *all* the items in its winning package, and only those items. Package bids are particularly valuable when there are synergies between individual items as they eliminate the exposure risk associated with bidding for individual items at prices above their standalone values.

The auction proceeded in 25 second rounds during which subjects could submit as many package bids as they wished. Bidders submitted demands for packages, with the bid for each package consisting of the sum of the item prices in the package. Following each round, *tentative* winning bids were determined by a computational algorithm maximizing seller revenue.[7] The algorithm accounts for all current bids as well as all past bids to find the combination of bids that maximizes seller revenue. Prices associated with past bids are based on prices in the round in which the bid was originally placed.

[7] Ties for tentative winning bids, which are to be expected early on in the auction, were broken randomly with priority given to tentative winners in the previous round if prices do not change. Ties become less of a concern in later stages of the auction.

Prices for all items started at 5 ECUs, with price increases between rounds determined as follows: From the set of provisionally winning bids in the previous round and the set of new bids in the current round, if two or more bidders had positive demand for an item, then its price increased by a fixed amount (5 experimental currency units; 5 ECUs). (If some of the packages a subject bid on in the current round overlapped with her provisionally winning bid in the previous round, the prices of the overlapping items also increased.) Otherwise the price for an item remained the same.[8] Thus, by looking at which items had price increases for the current round, bidders could easily identify items bidders were actively competing for.

Following each round bidders were privately informed which, if any, of their bids was a provisionally winning bid.[9] In each round provisionally winning bids were automatically reentered, but not counted as new bids, so that any bidder content with their provisional allocation did not need to bid again. Subjects were encouraged to place bids on multiple potentially profitable packages particularly early on as "… the opportunity to make profitable bids on individual items or packages with low synergies, which may become provisional winners later in the auction, will only be present early in the auction."[10] There were no eligibility rules restricting what items subjects could bid on.

An auction ended after two consecutive rounds of no new bids, or what amounts to the same thing, no price increases. Two rounds were used to give everyone a chance to determine if they were satisfied, given current prices, on their provisional allocations.

SAA Auctions: Our version of the SAA is designed to have the same look for bidders as the CCA to which its performance is compared. These auctions also proceeded by rounds, with each round lasting for 25 seconds. Like the CCA auctions, a subject only had to click "set" next to any set of items to place a bid on those items (see Figure 2). However unlike the CCA, they could only make one such bid and that bid was interpreted and processed as a collection of independent item bids rather than as a package bid.

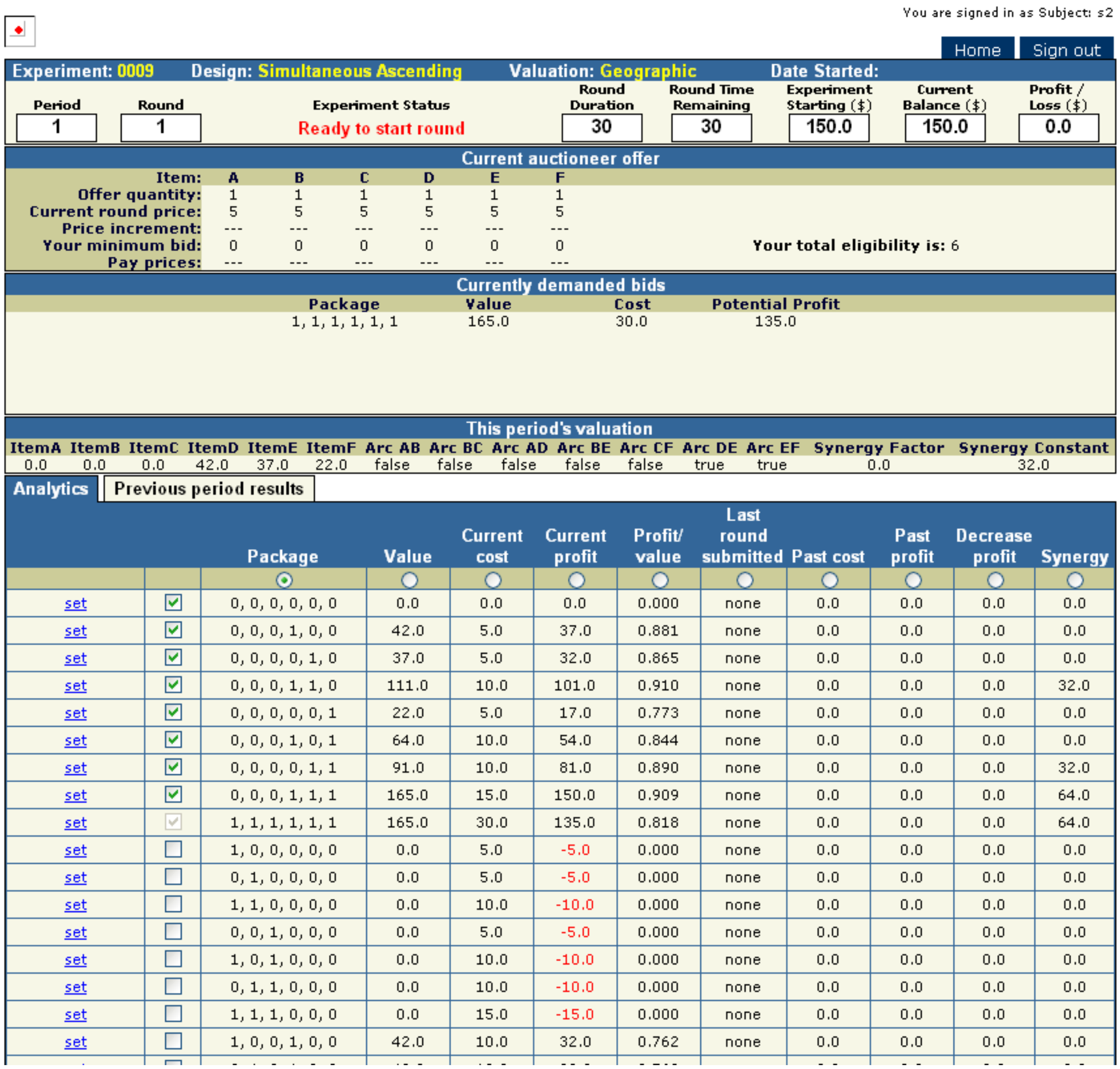
[8] Thus, prices were weakly increasing from round to round, unlike RAD (Kwasnica et al., 2005) or the FCC's Modified Package Bidding.

[9] Tentative winning bids were *not* announced in either the original Porter et al. (2003) experiment or in Brunner et al. (2007). As will be shown, this seemingly small design change has implications for auction outcomes.

[10] In a mechanism design experiment the instructions are part of the mechanism as bidders are informed of the favorable properties and operation of what will typically be a novel institution.

Prices of each item were computed separately, with prices increasing by 5 ECUs in each auction round with excess demand. The auction ends once there is no longer any excess demand for any item, with each item sold to the high bidder for that item at the current price. Thus, in bidding above their standalone value for an individual item in order to capture the synergy payoff associated with getting complimentary items, a bidder is exposed to possible losses; for example, she could win just one time and pay more than its standalone value. With strong complementarities between items, this "exposure problem" is considered one of the major drawbacks of the SAA auction. Our SAA auctions have a number of similarities to the procedures used by the FCC for selling radio spectrum licenses with the key exception that bids automatically increased by a fixed amount in each period with excess demand, so there was no scope for "jump bids."[11]

[11] In auction 73 the FCC adopted a similar rule not permitting "jump bids."



You are signed in as Subject: s2

Home | Sign out

Experiment: 0009 Design: Simultaneous Ascending Valuation: Geographic Date Started:

Period	Round	Experiment Status	Round Duration	Round Time Remaining	Experiment Starting ($)	Current Balance ($)	Profit / Loss ($)
1	1	Ready to start round	30	30	150.0	150.0	0.0

Current auctioneer offer

Item:	A	B	C	D	E	F
Offer quantity:	1	1	1	1	1	1
Current round price:	5	5	5	5	5	5
Price increment:	---	---	---	---	---	---
Your minimum bid:	0	0	0	0	0	0
Pay prices:	---	---	---	---	---	---

Your total eligibility is: 6

Currently demanded bids

Package	Value	Cost	Potential Profit
1, 1, 1, 1, 1, 1	165.0	30.0	135.0

This period's valuation

ItemA	ItemB	ItemC	ItemD	ItemE	ItemF	Arc AB	Arc BC	Arc AD	Arc BE	Arc CF	Arc DE	Arc EF	Synergy Factor	Synergy Constant
0.0	0.0	0.0	42.0	37.0	22.0	false	false	false	false	false	true	true	0.0	32.0

Analytics | Previous period results

		Package	Value	Current cost	Current profit	Profit/ value	Last round submitted	Past cost	Past profit	Decrease profit	Synergy
set	☑	0, 0, 0, 0, 0, 0	0.0	0.0	0.0	0.000	none	0.0	0.0	0.0	0.0
set	☑	0, 0, 0, 1, 0, 0	42.0	5.0	37.0	0.881	none	0.0	0.0	0.0	0.0
set	☑	0, 0, 0, 0, 1, 0	37.0	5.0	32.0	0.865	none	0.0	0.0	0.0	0.0
set	☑	0, 0, 0, 1, 1, 0	111.0	10.0	101.0	0.910	none	0.0	0.0	0.0	32.0
set	☑	0, 0, 0, 0, 0, 1	22.0	5.0	17.0	0.773	none	0.0	0.0	0.0	0.0
set	☑	0, 0, 0, 1, 0, 1	64.0	10.0	54.0	0.844	none	0.0	0.0	0.0	0.0
set	☑	0, 0, 0, 0, 1, 1	91.0	10.0	81.0	0.890	none	0.0	0.0	0.0	32.0
set	☑	0, 0, 0, 1, 1, 1	165.0	15.0	150.0	0.909	none	0.0	0.0	0.0	64.0
set	☑	1, 1, 1, 1, 1, 1	165.0	30.0	135.0	0.818	none	0.0	0.0	0.0	64.0
set	☐	1, 0, 0, 0, 0, 0	0.0	5.0	-5.0	0.000	none	0.0	0.0	0.0	0.0
set	☐	0, 1, 0, 0, 0, 0	0.0	5.0	-5.0	0.000	none	0.0	0.0	0.0	0.0
set	☐	1, 1, 0, 0, 0, 0	0.0	10.0	-10.0	0.000	none	0.0	0.0	0.0	0.0
set	☐	0, 0, 1, 0, 0, 0	0.0	5.0	-5.0	0.000	none	0.0	0.0	0.0	0.0
set	☐	1, 0, 1, 0, 0, 0	0.0	10.0	-10.0	0.000	none	0.0	0.0	0.0	0.0
set	☐	0, 1, 1, 0, 0, 0	0.0	10.0	-10.0	0.000	none	0.0	0.0	0.0	0.0
set	☐	1, 1, 1, 0, 0, 0	0.0	15.0	-15.0	0.000	none	0.0	0.0	0.0	0.0
set	☐	1, 0, 0, 1, 0, 0	42.0	10.0	32.0	0.762	none	0.0	0.0	0.0	0.0

Figure 2

Our version of the SAA auctions have a number of special properties not present in the CCA auctions.

1. *Activity requirement:* Each auction started with bidders eligible to bid on all items up for sale – six in this case. However, if in any given round a bidder failed to bid on some items, the total number of items it could bid on in subsequent rounds was reduced to the number of items bid on in that round. This "activity rule" was explained as necessary to have the auction close in a timely manner.

2. *Default bids:* Each round of the auction started with a default bid labeled "Currently demanded bid" which was the previous round's bid (or a bid on all items in the first

round of bidding). Any time a new bid was entered that reduced eligibility, the bidder was notified and required to reconfirm the bid.[12]

3. *Minimum bid requirements:* Once there was no longer any excess demand for an item, the current high bidder for that item was required to maintain their bid for the item, with this minimum bid requirement in effect unless someone else topped that bid. This minimum bid requirement held regardless of whether there was a positive profit on the item (or set of items) in question.

4. *Price rollback rules:* Given the indivisibilities inherent in the fixed price increase rule, near the end of an auction it would not be unusual for two bidders to drop their demand for the same item at the same time, moving from excess demand to zero demand. This would result in unsold items with a potentially large negative impact on efficiency. A price rollback rule, described in detail in the experimental instructions, was designed to deal with this situation.[13] This rule essentially randomly allocated the item in question to one of the bidders demanding the item in the previous round at the previous round's price, without precluding the opportunity for the losing bidder to buy the item at the higher price if they chose to do so.

Computer Interface and Aids for Subjects: Auctions with multiple items and synergies among them are quite complicated so that it seems essential to have as friendly a computer interface as possible, as well as to provide subjects with computational aids that they might expect to have from support staff in a field setting. The same set of bidding aids were provided in both SAA and CCA auctions. These are shown in the screen layout beginning with "Analytics/Previous periods results" in Figure 2 above and in Figure 3 below which provide sample starting screen shots for a South regional bidder in an SAA and CCA auction respectively.

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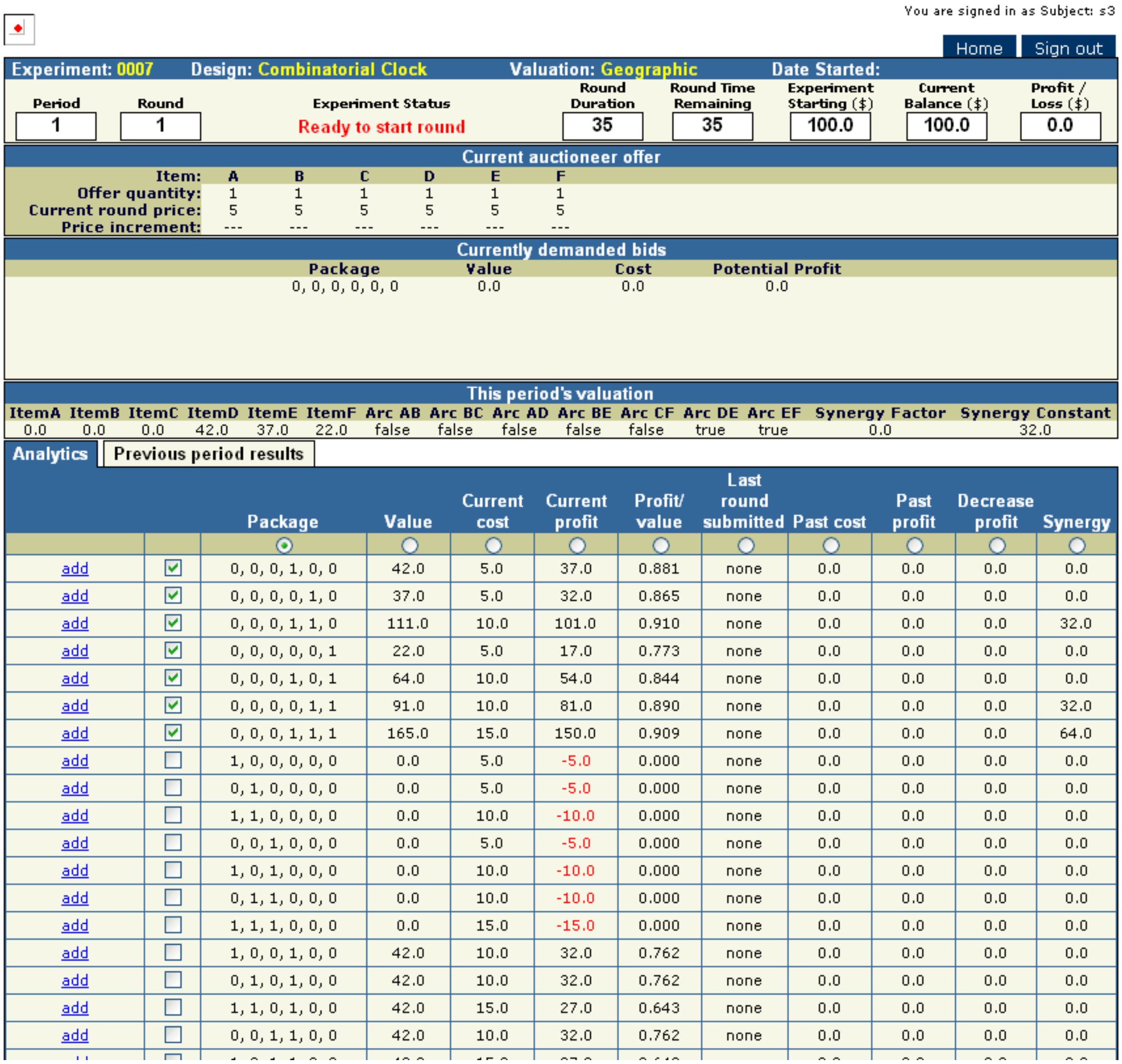
[12] An earlier set of SAA auctions showed that without these proactive procedures a number of subjects let their eligibility lapse well before it was profitable to do so. See the online Appendix http:xxxx for a comparison of outcomes in these earlier SAA4 auctions with the ones reported on here.

[13] The minimum bid requirement rule would not apply in this case as there would be no current high bidder for the item in question.



You are signed in as Subject: s3

Home | Sign out

Experiment: 0007 Design: Combinatorial Clock Valuation: Geographic Date Started:

Period	Round	Experiment Status	Round Duration	Round Time Remaining	Experiment Starting ($)	Current Balance ($)	Profit / Loss ($)
1	1	Ready to start round	35	35	100.0	100.0	0.0

Current auctioneer offer

Item:	A	B	C	D	E	F
Offer quantity:	1	1	1	1	1	1
Current round price:	5	5	5	5	5	5
Price increment:	---	---	---	---	---	---

Currently demanded bids

Package	Value	Cost	Potential Profit
0, 0, 0, 0, 0, 0	0.0	0.0	0.0

This period's valuation

ItemA	ItemB	ItemC	ItemD	ItemE	ItemF	Arc AB	Arc BC	Arc AD	Arc BE	Arc CF	Arc DE	Arc EF	Synergy Factor	Synergy Constant
0.0	0.0	0.0	42.0	37.0	22.0	false	false	false	false	false	true	true	0.0	32.0

Analytics | Previous period results

		Package	Value	Current cost	Current profit	Profit/ value	Last round submitted	Past cost	Past profit	Decrease profit	Synergy
add	☑	0, 0, 0, 1, 0, 0	42.0	5.0	37.0	0.881	none	0.0	0.0	0.0	0.0
add	☑	0, 0, 0, 0, 1, 0	37.0	5.0	32.0	0.865	none	0.0	0.0	0.0	0.0
add	☑	0, 0, 0, 1, 1, 0	111.0	10.0	101.0	0.910	none	0.0	0.0	0.0	32.0
add	☑	0, 0, 0, 0, 0, 1	22.0	5.0	17.0	0.773	none	0.0	0.0	0.0	0.0
add	☑	0, 0, 0, 1, 0, 1	64.0	10.0	54.0	0.844	none	0.0	0.0	0.0	0.0
add	☑	0, 0, 0, 0, 1, 1	91.0	10.0	81.0	0.890	none	0.0	0.0	0.0	32.0
add	☑	0, 0, 0, 1, 1, 1	165.0	15.0	150.0	0.909	none	0.0	0.0	0.0	64.0
add	☐	1, 0, 0, 0, 0, 0	0.0	5.0	-5.0	0.000	none	0.0	0.0	0.0	0.0
add	☐	0, 1, 0, 0, 0, 0	0.0	5.0	-5.0	0.000	none	0.0	0.0	0.0	0.0
add	☐	1, 1, 0, 0, 0, 0	0.0	10.0	-10.0	0.000	none	0.0	0.0	0.0	0.0
add	☐	0, 0, 1, 0, 0, 0	0.0	5.0	-5.0	0.000	none	0.0	0.0	0.0	0.0
add	☐	1, 0, 1, 0, 0, 0	0.0	10.0	-10.0	0.000	none	0.0	0.0	0.0	0.0
add	☐	0, 1, 1, 0, 0, 0	0.0	10.0	-10.0	0.000	none	0.0	0.0	0.0	0.0
add	☐	1, 1, 1, 0, 0, 0	0.0	15.0	-15.0	0.000	none	0.0	0.0	0.0	0.0
add	☐	1, 0, 0, 1, 0, 0	42.0	10.0	32.0	0.762	none	0.0	0.0	0.0	0.0
add	☐	0, 1, 0, 1, 0, 0	42.0	10.0	32.0	0.762	none	0.0	0.0	0.0	0.0
add	☐	1, 1, 0, 1, 0, 0	42.0	15.0	27.0	0.643	none	0.0	0.0	0.0	0.0
add	☐	0, 0, 1, 1, 0, 0	42.0	10.0	32.0	0.762	none	0.0	0.0	0.0	0.0

Figure 3

The important thing to note here are the aids provided to bidders consisted of a list of *all* possible bids, with corresponding analytic information, so that subjects could bid on items by simply clicking on the “add” or “set” space next to packages they were interested in. The analytic information was automatically updated at the end of each round. To make it easy for bidders to identify which items they were interested in there were a number of sorting options using the criteria listed in the columns - value, current cost, current profit, etc. A double sort routine was employed so that those packages with a check mark appeared at the top of the screen sorted by whatever criteria the subject chose, followed by the remaining packages sorted by the same criteria. Check marks were applied to all bids in previous rounds and, for regional bidders, packages containing only those items in their region of interest.[14]

Experimental Procedures: Subjects were recruited to participate in a series of three auctions taking place within a two week period each of which would last for approximately two hours. The first series was a training session where subjects were introduced to the experimental procedures and computer interface, followed by three dry runs, which was all that could be completed in the initial two hour period. Subjects were offered a $30 participation fee to be paid only after the completion of all three sessions, with half of session two's earnings withheld until completion of session three. Subjects were paid a flat $10 for participating in the initial training session. Given the complicated nature of the auctions, subjects were permitted to take the instructions home with them if they wanted to. Earnings in sessions 2 and 3 were advertised to range between $10 and $60 or more per person with average earnings of $30-$40 per person. Payoffs were denominated in experimental currency units (ECUs) with a minimum conversion rate of xx ECU = $1.00. Subjects were provided with starting capital balances of 150 ECUs with any profits earned in an auction added to these starting capital balances, and losses subtracted from it, with total earnings for a session consisting of a subject's end of session balance, less 130 ECUs.

Subjects' roles as a regional or global bidder were randomly determined prior to each auction, as were the bidders in their auction group. Each experimental session was designed to have five or more auctions (all with the same valuations) running at the same time. In case of an uneven number of subjects, the extras were on standby for that auction, and guaranteed to be active in the next auction. Subjects' computer screens only reported a bidder's own outcome until the end of the auction, when the allocation of units to all bidders in their auction was reported, along with a final analytics screen that they could play with. The latter was designed to give bidders a chance to see what they might have been able to accomplish had they bid differently.

[14] Automatic check marks for regional bidders were only employed in the six item auctions. These were initiated on account of the increased number of packages available to bid on. In the four item auctions bidders could effectively see all the packages on a single screen so the issue of possibly mistakenly choosing dominated packages was not as severe. Bidders able to add or delete a check mark by clicking on the box with the check mark.

Each auction began with bidders notified of their valuations and given a couple of minutes to play with the sort possibilities and to check any items/packages they might be particularly interested in. The six item auctions started out with each auction round lasting 25 seconds. After round 6 or 7 the round time was reduced to 20 seconds, and reduced further to 15 seconds after round 12 or so in order to speed things up. Once these shorter round times went into effect the auctioneer announced "round ending" a second or two prior to the round actually ending.[15]

Given the enormity of the valuation space we needed some device for determining which set of valuations to employ. For each set of auctions we conducted simulations in which simulated participants bid on the package with the highest next round profits. For the CCA auctions this involved bidding on only one package in each round. For the SAA auctions, bidding was myopic with no account taken of the possible exposure problem. For both four and six item auctions we conducted 100 simulations with randomly chosen valuations with low synergies for the regional bidders, and another 100 simulations with high synergies for the regional bidders. From these we picked a set of "interesting" valuations – several cases where straightforward bidding predicted that the CCA/SAA auctions would easily achieve 100% efficiency, several cases where the SAA auctions required bidders to suffer losses in order to achieve 100% efficiency, and cases where straightforward bidding did *not* achieve 100% efficiency in either the CCA or SAA auctions. In fact our selections were weighted towards the latter, with a special eye to cases with low predicted efficiency, particularly for the CCA auctions. In addition we included a mix of cases where 100% efficiency required the global bidder to get all the items, or the regional bidders to split the items, as well as cases in which 100% efficiency required all bidders to get at least one item.[16]

It became immediately apparent in the pilot sessions that subjects did not consistently follow straightforward bidding. Still, the simulations with random valuations and straight forward bidding guided our choice of which auctions to employ

[15] Four item auctions, which were conducted first, had fixed round times of 25 seconds. The change in procedures was done in anticipation of larger numbers of rounds in the six item auctions.
[16] Although the simulations were based on random draws, the instructions were clear not to suggest that bidders' valuations were randomly drawn.

given the limited number of auctions we could actually conduct, enabling us to choose some auctions satisfying each of the criteria described above.

[Insert Table 1 here]

Table 1 lists the auction sessions conducted with the number of subjects in each session, along with the number of auctions in each session.[17] Subjects were recruited through e-mail lists of students taking economics classes at the Ohio State University in academic year 2006-07.[18] Average earnings per subject for the six item auctions were $174, with minimum earnings of $90 and maximum earnings of $331, for subjects completing all three sessions, including the $30 show up fee and the $10 payment for session one. Average earnings per subject for the four item auctions were $125, with minimum earnings of $51 and maximum earnings of $243, for subjects completing all three sessions, including the $30 show up fee and the $10 payment for session one. Different sets of subjects participated in each series of auctions.

III. Experimental Results:

Approach: We focus on five aspects of the experimental outcomes: efficiency, revenue, profits, correlations among the first three, and bidder behavior. We hypothesize that near-efficient and near-core outcomes sometimes arise out of a mechanism like the one described by our two theorems, in which bidders bid aggressively on the relevant packages, with losing bidders bidding until their potential profits on relevant packages are nearly zero. For example, bidders might bid on all of the relevant packages at every round for which the potential earnings on that package are positive. If bidders behave in such a way, CCA outcomes will necessarily be efficient and the payoff vector formed from seller revenues and bidder profits will lie in the core. If failures to achieve core outcomes in an experimental trial result from bidders' failure either to identify the relevant packages, or to bid sufficiently aggressively on these packages, then the CCA

[17] There were two sets of pilot experiments which are not reported conducted in August and November of 2006 for both CCA and SAA auctions. They were used to refine the auction mechanisms so they would run smoothly and quickly, as well as our experimental procedures (e.g., would it really take most of two hours to go over the software and run a handful of auctions?). Indeed we would count designing the details of these two relatively complicated auction mechanisms, and implementing them in the software, as one of the major outputs of this project.

[18] What data we have suggests that experimental subjects recruited in this way have substantially higher than average SAT/ACT scores compared to the university population as a whole (Casari et al., 2007).

should exhibit low efficiency and low revenue in the same trial, so positive correlations between efficiency and revenue, both suitably normalized, are to be expected.

In contrast, for the SAA, the exposure problem could drive a negative correlation between revenue and efficiency, depending on bidder behavior. For example, a bidder who seeks to buy a package and finds the prices too high may continue to bid for an individual item until its price exceeds the bidders' marginal value of the item, which can result in high revenues and low efficiency. A bidder who fears exposure may alternatively choose not to bid above standalone values for individual items in the SAA, leading to lower revenues that are associated with possibly inefficient outcomes. Thus, according to theory, the correlation between efficiency and revenue in the SAA is not *a priori* clear.

The kinds of situations, or behavior, in which CCA bidders might fail to bid aggressively on relevant packages are several. One arises when there are very many packages and the bidder tires of entering bids. Another may arise when a provisionally winning bidder fails to make new bids on profitable packages. Prices may continue to rise while the bidder remains a provisional winner yet, by the time the bidder is no longer a provisional winner and again wishes to place bids, it may have already missed its last opportunity to place some relevant bids. We look for such situations in the analysis below.

Efficiency: Figures 4 and 5 compare average efficiency between auction mechanisms by auction for the four and six item cases respectively. Efficiency is calculated by taking the difference between actual surplus (S_{actual}) and the surplus resulting from a random allocation (S_{random}) and dividing through by the difference between the maximum possible surplus (S_{max}) and the (same) random allocation.[19] In taking the differences from a random allocation we account for the fact that efficiency measures are sensitive to bidders' absolute valuations. There is no need to do this for period by period comparisons since we employed the same sequence of valuations for both the SAA and CCA auctions. However, normalizing does adjust changes in absolute valuations when aggregating across auctions in different periods.

[19] The value of the random allocation is computed by taking the average of the surplus over all possible allocations – 3^4 and 3^6 respectively – assuming all items are sold in each auction.

[Insert Figures 4 and 5 here]

Using average efficiency in each auction period as the unit of observation, efficiency is higher in 11 out of 17 (64.7%) of the CCA4 auctions and in 13 out of 19 (68.9%) of the CCA6 auctions. Pooling across four and six items auctions, these differences are statistically significant at the .05 level using a (two-tailed) nonparametric sign test. Using efficiency in each individual auction as the unit of observation, average efficiency is 93.5% (0.012) for the CCA6 auctions versus 88.2% (0.015) for the SAA6 auctions (standard errors of the mean are in parentheses), and 94.8% (0.013) for the CCA4 auctions versus 87.2% (0.020) for the SAA4 auctions. Nonparametric (two-tailed) Mann-Whitney tests show these differences to be statistically significant at better than the1% level in both cases.[20] These differences in efficiency are not surprising given the strong complementarities between items in the valuations employed, and the fact that the CCA auction is explicitly designed to mitigate the resulting exposure problem.

Comparing these results to others reported in the literature, Porter et al. (2003) report average efficiency of close to 100% in their CCA auctions, with Brunner et al. (2007) reporting average efficiency of 90% for CCA auctions with high complementarities. There are some subtle differences among the implementations of the CCA auctions across experiments that could account for some of these differences. For example, Brunner et al. employ an activity rule where the number of items a subject can bid on is determined by their largest package bid in the immediately preceding round or the number of items in that bidder's conditionally winning bid (whichever is larger). In addition, provisionally winning bidders were not announced. In contrast, our design had no eligibility restrictions and informed provisionally winning bidders after each round.

Efficiency depends not only on the differences between the two auction mechanisms, but also on differences in the underlying valuations in conjunction with the mechanism in question. In auctions where the efficient allocation required all bidders to get at least one item, our simulations showed that efficiency would be relatively low in the CCA auctions with straightforward bidding. Although it is clear that bidders did not practice straightforward bidding, the experiments verified that the CCA auctions had a particularly difficult time achieving high efficiency in these cases, with the corresponding

[20] Unless stated otherwise, all statistical tests reported use nonparametric (two-tailed) Mann-Whitney tests.

SAA actions having significantly higher efficiency[21]: Using efficiency in each individual auction as the unit of observation, average efficiency was 89.2% (2.1%) in the CCA6 auctions in which the efficient allocation required all bidders to get at least one item compared to 94.4% (2.4%) in the SAA6 auctions ($p < .01$) (with standard errors of the mean in parentheses). And average efficiency was 90.9% (2.8%) in the CCA4 auctions in which the efficient allocation required all bidders to get at least one item compared to 92.7% (2.7%) in the SAA4 auctions ($p < .10$).[22] Note that these reduced efficiencies *cannot* be attributed to unsold units in the CCA auctions as there were very few cases where this happened: 2.9% (3/104) of the six item auctions and 4.9% (5/102) of the four item auctions, with only one unallocated item in each of these auctions.[23]

A second pattern of auction valuations of particular interest are those in which the efficient outcome calls for the global bidder to get zero items. One concern here is the threshold problem in which one, or both, of the regional bidders holds back on bidding hoping that the other one will cause prices to increase sufficiently to deter the global bidder.[24] The introduction of item prices that increase with excess demand is designed to deal with this issue (Kwasnica et al., 2005). So the question becomes: how well did it work in practice? We had nine six item auctions and eight four item auctions of this sort. The threshold problem does not appear to be a major factor for the CCA auctions in these cases as the regional bidders won all the items in 80% (39/49) of the CCA6 auctions and in 94% (45/48) CCA4 auctions. The SAA auctions have a much harder time with these auctions as only 17% (10/58) of the SAA6 auctions achieved the efficient outcome, along with 48% (23/48) of the SAA4 auctions. This translated into substantially higher efficiencies in these CCA auctions than in the corresponding SAA auctions.[25]

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[21] There were four six item auctions in which the efficient allocation required all bidders to get at least one item, and five four item auctions.

[22] Alternatively, only 8% of the six item CCA auctions in which the efficient allocation called for everyone to get at least one item achieved 100% efficiency versus 68% of the other six item CCA auctions. And 20% of the four item CCA auctions in which the efficient allocation required all bidders to get at least one item achieved 100% efficiency compared to 82% of all the other CCA auctions.

[23] The rollback rules essentially eliminated any unsold items in the SAA auctions.

[24] In multi-unit sealed bid auctions this is an issue as well, but for somewhat different reasons (see Cantillon and Pesendorfer (2007); also Chernomaz and Levin (2007) for experiments dealing with this issue).

[25] Average efficiency in these CCA6 (CCA4) auctions was 97.8% (99.0%) versus 91.4% (91.0%) in the SAA6 (SAA4) auctions ($p < 0.01$in both cases).

The exposure problem appears to be the primary factor underlying the poor performance of the SAA auctions here, as in 62.5% (30/48) of the SAA6 auctions and 100% (25/25) of the SAA4 auctions where the global bidder won one or more items, they earned negative profits. This highlights one side of the exposure problem: namely, global bidders having greater synergies than the regional bidders, and aggressively bidding to realize these synergies, can get stuck with only a subset of the items they are after, with negative consequences for efficiency.[26] Further, the fact that the CCA auctions achieve 100% efficiency in so many cases here suggests that the price guidance offered for items with excess demand in the CCA auctions largely mitigated any threshold problem, and that, absent any overlapping demands, there were no fitting problems for the regional bidders in these auctions. We will have more to say about the threshold problem below.

Conclusion 1: Overall efficiency is higher in the CCA compared to the SAA auctions, which is not surprising given the strong synergies between items built into the experimental design which package auctions are designed to deal with. However, efficiency is notably lower in CCA compared to SAA auctions in which the efficient outcome calls for all bidders to get one or more items, as the CCA too strongly promotes the formation of larger packages. The threshold problem is not severe for those CCA auctions where the efficient outcome calls for the regional bidders to get all the items. In contrast, the SAA auctions have consistently lower efficiency in these cases, largely as a result of the exposure problem.

Revenue: Figures 6 and 7 compare revenues between the two auction mechanisms by period for the four and six item cases respectively. We report revenue in terms of an index – as a percentage of the minimum revenue in the core. The core in a package auction can be understood as the set of competitive outcomes (Ausubel and Milgrom, 2002). Bargainers in a perfect auction have no reason to offer more than the minimum prices necessary to block non-core allocations, so that a reasonable full information standard for revenue is the minimum revenue in the core (see Day and Milgrom, 2007). Given that our bidders do not have full information, and that we are investigating challenging environments with simplified mechanisms for handling the combinatorial problem, we anticipate that core allocations will be hard to achieve.

[26] The FCC's simultaneous multiple round auctions allows a limited kind of "bid withdrawal" – a rule that was introduced amid controversy to mitigate the exposure problem. Following a withdrawal, if no other bid is made for the license, then the bidder is still obligated to pay the difference between the withdrawn bid and the eventual sale price for the license, so the exposure problem, while possibly mitigated, is not entirely eliminated by this device.

[Insert Figures 6 and 7 here]

Using average revenue per auction period as the unit of observation, revenue is higher in 14 out of 17 of the SAA4 auctions (but barely higher in 3 of these auctions) and in 8 out of 19 of the SAA6 auctions. Pooling across four and six item auctions, these differences just miss statistical significance at the 5% level under a two-tailed sign test. However, there appears to be a fundamental difference in revenue raised between the two auction formats as a function of the number of items bid on, so that pooling may not be appropriate here. In 10 out of 17 of the SAA4 auctions, average revenue per period was greater than the minimum revenue in the core, compared to 2 out of 19 of the SAA6 auctions.[27] Part of the reason for this is that bidders, particularly the global bidder, frequently suffered losses in the SAA auctions (46% and 36% of the SAA4 and SAA6 auctions respectively). We discuss these profit differences in more detail below, but the point here is that the potential for an exposure problem is substantially more severe in the SAA6 auctions compared to the SAA4 auctions, particularly for the global bidder. This might well have led subjects to bid more cautiously in the SAA6 auctions in order to avoid, or minimize, potential losses (which it looks like it did). As such, we do not feel comfortable pooling average period revenues between the four and six item auctions.

Comparing revenue using each individual auction as the unit of observation, average revenue is 91.8% (1.2%) minimum revenue in the core for the CCA6 auctions versus 89.4% (2.4%) in the SAA6 auctions ($p > 0.10$). But average revenue is significantly higher in the SAA4 auctions than in the CCA4 auctions: 100.3% (2.1%) versus 93.9% (1.5%) ($p < 0.01$).[28]

There are no directly equivalent revenue results from other multi-unit auction experiments against which to compare these results. Porter et al. (2003) do not report revenue comparisons between auction mechanisms. Brenner et al's. (2007) normalization is close to ours, using revenue as percentage of the efficient allocation.[29]

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[27] This rarely happens in the CCA auctions – occurring once in the four and six item auctions respectively.

[28] Renormalizing to express revenue as a percentage of the efficient allocation does not change these conclusions: Average revenue is higher in the CCA6 auctions compared to the SAA6 auctions (82.1% versus 79.9%) but again, the results are not significant at conventional levels. In contrast, average revenue is significantly higher in the SAA4 compared to the CCA4 auctions (82.5% versus 76.9%; $p < 0.01$).

[29] Brunner et al. employ actual revenue less the revenue from a random allocation in which bidders pay full value in the numerator and revenue from the efficient allocation less the revenue from a random allocation

They find that revenue is significantly higher in their version of the CCA auction than the simultaneous multi-round (SMR) auction employed by the FCC (the closest relative to our SAA auction), similar to our results for the six item auctions, but not the four item auctions. Their auctions involve bidding over more items than ours, with two global bidders competing over the same set of licenses. Their revenue results hold for both high and low synergy cases. But this comparison is strained by the fact that they had a relatively large number of items left unsold in their SMR auctions.

Conclusion 2: Average revenue is higher in the CCA6 compared to the SAA6 auctions, averaging a little over 90% of the minimum revenue in the core for the CCA auctions. But these differences are not large enough to be statistically significant at conventional levels. In contrast, average revenue is significantly higher in the SAA4 compared to the CCA4 auctions, averaging a just over 100% of the minimum revenue in the core in the SAA auctions. The greater potential exposure problem for bidders in the SAA6 compared to the SAA4 auctions more than likely accounts for the more cautious bidding in the SAA6 auctions.

Profits: Total profits as a percentage of the value of the efficient allocation were approximately the same between CCA6 and SAA6 auctions: 14.3% (0.014) versus 13.6% (0.025) ($p > 0.10$). However, total profits were substantially higher in the CCA4 compared to the SAA4 auctions: 20.2% (0.014) versus 10.5% (0.028) ($p < 0.01$). In both cases global bidder profits were lower than regional bidder profits for the SAA auctions: 9.46 versus 20.86 ECUs per capita for the SAA6 auctions and -6.6 versus 15.63 for the SAA4 auctions. For the CCA6 auctions, regional and global bidder profits were approximately the same: 15.64 for the global bidder versus 19.13 per capita for the regional bidders. But global bidder profits were a little less than half that of regional bidders in the CCA4 auctions: 9.18 versus 18.75 per capita for the regional bidders.

The fact that global bidder bidders' profits are lower than regional bidders in the SAA auctions is directly related to the greater exposure problem that they faced, along with their relatively aggressive pursuit of the profit opportunities inherent in the synergies between items. This is reinforced by that fact that in 46.1% of the SAA4 auctions global bidders earned negative profits compared to 6.4% of the regional bidders, with 35.8% of

in the denominator, so that the difference lies in taking differences from average revenue resulting from a random allocation in both the numerator and denominator.

the global bidders losing money in the SAA6 auctions compared to 5.3% of the regional bidders.

Our profit results stand in marked contrast to those reported in Brunner et al. (2007), where total bidder profits are lower, sometimes substantially lower, in CCA compared to SMR auctions. No doubt part of the reason for these differences has to do with our announcing provisional winners following each round of bidding, whereas in Brunner et al. provisional winners were not announced. The failure to announce provisional winners more than likely results in bidders competing against themselves at times. In our design bidders would only compete against themselves if they placed overlapping bids relative to a provisionally winning bid, with the latter relatively unlikely to occur in later auction periods, when final prices are set.

There are, however, several disadvantages to reporting provisionally winning bids in the CCA auctions. The first of these is relatively benign, as in a number of auction rounds, especially early on, there will be ties between provisionally winning bids, which are settled randomly, so that this information is relatively uninformative.[30]

A second disadvantage is potentially more damaging: reporting provisionally winning bids may help bidders to tacitly collude, stopping bidding early on if all bidders are satisfied with their current profits. There was at least one clear case in which this happened: Bidding in one of the CCA4 auctions ended in round 3, with prices at their starting values and profits of 45, 26, and 43 for the two regional bidders and the global bidder.[31] This occurred mid-way through the second full session of bidding, so that subjects would have correctly anticipated that they could not do much better by continuing to compete with each other.

A third disadvantage of reporting provisionally winning bids is that a provisionally winning bidder may use the information as part of a wait-and-see policy, hoping that the bid will eventually become a winner. If item prices rise substantially before the bid is no longer a provisional winner, the bidder can miss opportunities to

[30] Our instructions pointed this out to subjects.
[31] In this case no new bids were placed after round 1. There was a second, related, incident where an auction ended early (in round 6) in which one of the regional bidders stopped bidding, earning zero profits, well before it made sense to do so as their standalone value for item D was 61 with a price of 10, and their value for the package BD was 85 with a price of 20. The other two bidders earned profits of 72 and 28. Both of these auctions have been omitted from all of the calculations reported on the grounds that they are outliers.

place higher bids on that same package or other relevant packages, leading to either an inefficient assignment or a non-core (low revenue) outcome. As will be shown below, provisionally winning bidders typically did not bid again, even in cases where there were potentially higher profits to be earned by obtaining an alternative package.

Conclusion 3: Average profits were essentially the same or higher in CCA compared to SAA auctions. Global bidders earn lower profits on average than regional bidders in the SAA auctions as a consequence of their greater exposure problem in conjunction with aggressive pursuit of the profits inherent in these synergies.

Correlations: Positive correlations between efficiency and revenue in the CCA auctions are suggested by the logic of Theorems 1 and 2 for the CCA auctions. Outcomes are efficient when bidders find it easy to identify packages relevant for efficiency and when losing bidders bid aggressively on those packages. Those are normally the cases in which the global bidder's core-relevant package is the whole global package and the regional bidders' core-relevant packages are the full regional packages, so the same conditions that promote efficiency also promote core revenue levels, as losing bidders compete effectively and drives prices up. The contrary cases are exemplified by the "everyone wins some" cases, in which bidders who bid only on the global or large regional packages are fail to bid on relevant packages and fail to create the competition that drives revenues to the levels required by the core. This reasoning leads us to expect to find positive correlations between efficiency shortfalls and revenue shortfalls for the CCA auctions. These correlations are reported in Table 2 along with the corresponding correlations for the SAA auctions and between efficiency losses and bidder profits and bidder profits and revenue losses.

[Insert Table 2 here]

Looking at the CCA auctions first, we find the expected positive correlation between efficiency loss and revenue loss (0.385 and 0.244 for CCA6 and CCA4, respectively). That is, lower auction efficiency is positively correlated with larger losses in revenue relative to minimum revenue in the core.[32] Bidder profits, normalized by the value of the efficient allocation, are essentially unrelated to efficiency losses in the CCA6 auctions, but are negatively correlated with efficiency losses in the CCA4 auctions; i.e.,

[32] Alternatively, we could normalize revenue losses relative to the value of the efficient allocation. These correlations are essentially the same as those reported in Table 2.

the larger bidder profits are in any given auction, the less the efficiency loss for the CCA4 auctions. Bidder profits normalized by the value of the efficient allocation are positively correlated with revenue losses, with this positive correlation more pronounced in the CCA6 auctions, suggesting the loss of value from failures to identify core allocations is shared between the seller and the bidders.

Our two theorems apply to package auctions but not to SAAs, so they create no expectation of a positive correlation between efficiency and revenue for that case. Indeed, we find no significant correlations between revenue loss and efficiency loss in either set of SAA auctions. The near-zero correlation may reflect opposing effects that are realized in different SAA auctions. When the exposure problem is severe for the global bidder, that bidder may bid too high for individual licenses and suffer a loss, leading to low efficiency and high revenues. When the relevant packages are difficult to identify, bidders may fail to bid on those, reducing both efficiency and revenues. Like the CCA auctions, bidder profits are positively correlated with revenue losses in the SAA auctions, and are negatively correlated with efficiency losses.

Conclusion 4: Failures to reach core allocations are reflected in the CCA by losses of both efficiency and revenues, as might be expected from bidders' failure to meet the conditions of the theorems. This is reflected in positive correlations between efficiency losses and revenue losses. In contrast, in the SAA, there is no such correlation.

Rounds to Auction Completion: The average number of rounds to completion was quite similar across auction mechanisms. CCA6 auctions required an average of 16.8 (0.44) rounds per auction versus 18.3 (0.62) rounds for the SAA6 auctions. The CCA4 auctions required an average of 17.5 (0.62) rounds per auction versus an average of 15.3 (0.40) rounds for the SAA4 auctions.[33]

The one thing that does stand out in the data is that, not surprisingly, total bidder profits decrease systematically as the number of rounds in a given auction increase, regardless of which auction mechanism is used. For example, average profits of provisionally winning bidders decreased monotonically over rounds 1-5, 6-10, 11-15, 15-20 and 20 or greater in the CCA6 auctions, going from a high of 208.4 in rounds 1-5 to a

[33] We have dropped the two outlier CCA4 auctions with tacit collusion that ended quite early.

low of 17.6 in rounds greater than 20 for global bidders, and from a high of 113.6 to a low of 22.9 for regional bidders.

Conclusion 5: There were no major differences in rounds to completion between the SAA and CCA auctions.

Exposure Problems in SAA Auctions: The SAA auction presents bidders, especially global bidders, with an exposure problem: in attempting to capture the synergies between items, they may be wind up not getting the package desired while bidding above the standalone value of the items that they actually get. Bidders can respond to this either by a cautious policy, avoiding losses by bidding low (perhaps not exceeding standalone values), or by an aggressive strategy, attempting to capture synergies but risking losses. Either way, global bidder profits are reduced compared to what they can hope to achieve using a package bid, which avoids any exposure risk.

Auction rules that protect bidders from exposure might be expected to lead to improved participation, but that prediction is not tested in our experiments.[34] The bidder responses to exposure risk that could be partially observed with sufficiently many observations would include a large array of complex contingent plans, in which bidders' aggressiveness in any round depends on the provisionally winning packages and prices. This complexity makes it difficult to measure behavioral responses in ways that are both simple and adequately descriptive and to derive general characterizations from relatively small numbers of auctions.

As already noted, the exposure problem appears to have contributed to larger revenue losses in going from the SAA4 to the SAA6 auctions, as with more items both regional and global bidders were faced with a more extreme exposure problem in the six item auctions. But this does not give us any idea of the magnitude of the problem itself.

Some hypotheses about how bidders respond to exposure risk can be ruled out. Extreme aversion to losses from the exposure problem would cause bidders not to bid much above their standalone values. If bidders had bid up to their standalone values and stopped, revenue as a percentage of minimum revenue in the core would have been low –

[34] The impact on bidder participation would appear to be best measured in an experiment by giving subjects the option of which auction to participate in, a CCA or SAA, with the same underlying valuations in the two cases.

36.0% and 36.8% – for the SAA6 and SAA4 auctions respectively. This compares with actual revenue of 89.4% and 100.3% for the SAA6 and SAA4 auctions, so the extreme exposure aversion hypothesis is not consistent with the experimental outcomes.

Another hypothesis, more consistent with the experimental outcomes, is that some bidders were largely unconcerned about the exposure problem, bid aggressively, and suffered losses on that account. As previously reported, global bidders frequently suffered losses, particularly when the efficient outcome calls for regional bidders to win all licenses.[35]

Conclusion 6: Subjects were not much deterred by the exposure problem with many bidding aggressively, seeking the potential profits offered by large synergies in these auctions. The effect of this behavior in those SAA auctions in which the efficient outcome called for the regional bidders to win all the items was reduced efficiency, reduced profits for regional bidders, and losses for global bidders.

Individual Bid Patterns: Subjects' bidding behavior in the CCA auctions exhibit at least three consistent characteristics. These characteristics can be used to help simulate predicted outcomes for various environments. They also affect the ability of the auction to approach core allocations and hence to achieve efficient outcomes and competitive revenues for the seller.

First, subjects typically do not place bids in rounds in which they are provisional winners. This effect is most pronounced in later rounds when the auction had a greater chance of ending: In auction rounds 11 and above, no new bids are submitted in 94.9% (89.8%) of all rounds in which global (regional) bidders were provisional winners in CCA4 auctions, with the percentages for CCA6 auctions 88.1% and 85.4% for global and regional bidders, respectively.[36] Reasons for these high frequencies of not bidding are threefold: (i) Subjects typically bid on only a fraction of the packages they are eligible to

[35] In a Bayes-Nash equilibrium, no class of risk-neutral bidders can lose money on average, so some have suggested that inexperienced student bidders in our experiments were simply making mistakes. To take that hypothesis seriously and evaluate its implications for high stakes auctions, one needs to ask: what sort of mistakes? In single-unit private value clock auctions, student subjects typically bid up to, but not above, their private values. The problem faced by student bidders in these SAA auction experiments is that the exposure problem cuts two ways – if global bidders bid aggressively to capture the synergies, they will suffer losses in some significant portion of the space of values. If they bid cautiously to avoid the possibility of losses, they will suffer missed profit opportunities. In an analysis not reported in detail here, we find that bidders adopt various strategies and both kinds of mistakes are present.

[36] For rounds 1-10 the corresponding percentages are 81.1% and 88.0% for global and regional bidders in CCA4 auctions and 63.6% and 71.1% for global and regional bidders in CCA6 auctions.

bid on even when they are *not* provisional winners (see Table 3 below), (ii) bidding on packages as a provisional winner can extend the auction and/or raise prices on provisionally winning bids, and (iii) given the bid patterns, more often than not provisionally winning bidders were already winning on their highest valued package. On this last point, in rounds 11 and higher, provisionally winning bidders who did not place new bids were already provisional winners on their highest valued package in 68.8% (72.2%) of all cases for global (regional) bidders in the CCA4 auctions and for 69.5% (58.5%) of all cases for global (regional) bidders in the CCA6 auctions. Looking at those cases in which the provisionally winning bidder did not bid and were not winning on their most profitable package, the profit difference between the package they were holding and their best alternative averaged 31.1 (13.2) ECUs for global (regional) bidders in the CC4 auctions, and 54.7 (13.5) ECUs in the CCA6 auctions.

Second, looking at rounds in which bidders were *not* provisional winners, bidders bid on only a small fraction of the profitable packages they were eligible to bid on, with most of these bids directed at the most profitable or second most profitable packages available. Table 3 summarizes these data. In the CCA4 auctions, on average global bidders bid on 21-24% the profitable packages they were eligible to bid on. In rounds 1-5 when the number of packages earning positive potential profits was at its maximum, global bidders bid on an average of 3 packages per round. For the CCA6 auctions the percentage of profitable packages global bidders bid on dropped substantially, averaging between 12-14%, as there were now far more potentially profitable packages available. As such even though global bidders more than doubled the average number of packages bid on in rounds 1-5, the percentage of packages bid on was almost halved relative to the CCA4 auctions. For regional bidders, there were negligible differences in the percentage of profitable packages bid on between CCA4 and CCA6 auctions, averaging in the neighborhood of 31% to 37% in both cases.

[Insert Table 3 here]

Of the packages bid on, those attracting the most attention were, not surprisingly, the most profitable ones: the frequency of bidding on the most profitable package averaged between 60-70% for global bidders and 50-60% for regional bidders for the

CCA4 auctions. These percentages drop substantially for the second most profitable package averaging between 10-35% for global bidders and 20-30% for regional bidders, with lower percentages for less profitable packages.[37] There was more variability in the frequency with which subjects bid on the most profitable packages in the CCA6 auctions varying between 50-80% for global bidders and 60-90% for regional bidders. Here too there were substantial drop offs for both regional and global bidders in the frequency of bidding on the second most profitable packages. .

Third, Table 4 reports both the percentage of auctions in which higher profits were available to bidders when the auctions ended and the average level of these forgone (potential) profits. In cases where global bidders failed to win any items, they still had potentially profitable opportunities available in 4.5% and 9.4% of the CCA4 and CCA6 auctions respectively. For regional bidders, potentially profitable opportunities were available a little over 24% of the time in both cases. These differences between regional and global bidders, which are representative of a threshold problem, are statistically significant at the 1% level in a random effects probit, controlling for repeated measures for the same subject. If we eliminate gross outliers, the magnitude of the problem is much reduced as average foregone profits were 10.3 ECUs and 16.0 ECUs for regional bidders in CCA4 and CCA6 auctions, respectively. Generally, the failure to exhaust potentially profitable relevant bids contributes to either reduced revenue and/or lower efficiency.

[Insert Table 4 here]

There are no comparable differences between global and regional bidders when they are winning: the frequencies with which such bidders could bid for packages with higher potential profits were essentially the same for the CCA6 auctions and higher for global bidders in the CCA4 auctions. This reinforces the notion that what we are seeing for losing bidders represents a threshold problem. Here too after dropping gross outliers the magnitude of the potential forgone profits are relatively small.

[37] These percentages are independent of each other in that a bid on the second most profitable package is counted independently of whether or not a bid was placed on the most profitable package.

In terms of theorems 1 and 2, a condition for the auction mechanism to achieve an efficient or core outcome is that it encourages losing bidders to bid all the way up to their full values for relevant packages. The experimental evidence indicates that, most often, bidders at the last round exhausted the profit opportunities. The occasional failures contributed to reduced revenue and to less than fully efficient outcomes.

Two reasons why winning bidders stopped short of pursuing maximum possible profits suggest themselves: (i) given the complicated nature of the auction, winning bidders achieving a reasonable level of profits at auction's end did not want to "rock the boat" for fear of setting off new rounds of price increases (satisficing) and/or (ii) in these cases winning bidders were focused on the wrong packages, say because they were concentrating on named packages as opposed to those packages with the largest profits. We look at this last possibility next.

What cues did bidders use to choose which packages to bid on? In many cases, particularly early on, the most profitable package and the "named" package (all items for the global bidder and all positively valued items for the regional bidders) coincide. To determine the relative role played by named packages as opposed to potential profits in guiding bidding decisions, we focus on those cases where named packages were *not* the most profitable ones. Table 5 reports these data for the regional bidders. As shown, when there is a conflict between named packages and most profitable packages regional bidders clearly favor the more profitable package over the named package, typically by a ratio of two to one or more. Thus, regional bidders are sensitive to price signals, in both CCA4 and CCA6 auctions.

[Insert Table 5 here]

Table 5 leaves out data for global bidders as there were very few cases (2 for CCA4; 12 for CCA6) where the named package was *not* the most profitable package to bid on. Further, averaging over these few cases, the more profitable package was bid on more often (35.7% vs 64.3%), so it appears that global bidders were also guided more by price than the name in these cases.[38] But the real story here is the low frequency with which anything but the named package was most profitable. As such, in those cases

[38] 14.3% of the bids were for both the most profitable and the named packaged.

where the efficient allocation calls for all bidders to get at least one item (as well as those few cases where the efficient allocation calls for the global bidder to split items with one of the regional bidders), if bidders behave in the usual way, bidding only on their most profitable package, prices will fail to guide global bidders to their "relevant" packages. In these cases, the only way to achieve efficient or core allocations is if global bidders happen to bid on lots of packages, thereby bidding on the "relevant" ones by chance. That is, given that global bidders focused on their most profitable package to bid on, which in the overwhelming number of cases this corresponded to their "named" package, means that they were effectively engaged in straightforward bidding, which is bound to result in inefficiencies in cases where the efficient outcome calls for all bidders to get at least one item. This is an issue in package auction design that needs to be addressed in future research.

Conclusion 7: Provisionally winning bidders tended not to place new bids, particularly in later rounds when they were often provisional winners on their most profitable packages. When placing bids, both regional and global bidders tended to bid on only a small fraction of their profitable packages. Of those packages bid on, the most profitable packages were bid on most often. This bidding pattern, through the lens of our theorems, helps to explain why the CCA performs better than the SAA when the "relevant packages" correspond to the bidders' most profitable packages and worse than the SAA when the efficient outcome calls for both regional and global bidders to get some items.

IV. Conclusions

We have evaluated the potential of dynamic package auctions in general – and the combinatorial clock auction in particular – to lead to good outcomes in a class of package allocation problems. Our analysis of experiments by ourselves and others is informed by a pair of theorems, which assert that if all bidders bid as aggressively (that is, set low bid mark-downs) on the relevant packages as on the packages they acquire, then outcomes are efficient or, even more strongly, in the core. For core outcomes, the relevant packages that need to attract bids include the relevant packages for efficient outcomes, and more. The contest among the core-relevant packages is what drives revenues up to a competitive level for the seller.

For losing bidders, the conditions of the theorem mean that bids on the relevant packages should continue until the potential profits from winning have reached zero. In our experiments, many bidders meet that condition remarkably often, promoting good outcomes from the auction process. What is most interesting and informative about that is how this condition is met and why it is sometimes not met.

In principle, one way that bidders might bid sufficiently aggressively on relevant packages is to bid aggressively on *all* packages, but that is not what we find. Bidders in our experiments typically bid on just the one or two most profitable packages at each round and those packages often remained unchanged for many rounds during an auction. Given that behavior, another way the aggressiveness condition might be met is if the most profitable packages in each round are the relevant ones. That does describe what we find in many of the cases that lead to good outcomes. In cases where efficiency requires that every bidder should win some licenses, however, round-by-round profits in the CCA typically fail to guide bidders to the relevant packages and the result is inefficient auction outcomes.[39]

This analysis explains several of our main findings. One is that outcome efficiency was higher for the CCA except in cases where efficiency requires that all bidders win some licenses. In the non-exceptional cases, bidders who bid round-by-round on the most profitable packages were automatically bidding for the relevant packages. In these "easy" cases, revenues were high for the CCA, too, because bids on relevant packages led to competition that drove up prices. The SAA sometimes generated very high revenues, too, but with a very different logic. Due to an exposure problem in the SAA, revenues were sometimes very high, but in those cases the high revenues typically came at the cost of bidder losses and inefficient outcomes. Bidder profits were higher on average for the CCA, largely because bids on packages enable bidders to avoid losing money as they do in the SAA.

The relevant packages theory also helps to explain the correlations between revenue and efficiency, or more precisely between revenue shortfalls and efficiency shortfalls relative to the core standard. In cases where prices and profits guide bidders to

[39] If bidders bid for just one package at each round, then there is no ascending price algorithm that always guides bidders to bid on the relevant packages. Indeed, the amount of communication generally needed to find an efficient allocation in package auctions is so large that uniformly efficient outcomes is not a reasonable objective. Formal statements and proofs of these results are developed by Blumrosen and Nisan (2004) and Nisan and Segal (2006).

bid on relevant packages, both shortfalls are small, which tends to account for the observed correlation.

Other experimental findings include the observation that time to completion is about equal for the SAA and CCA design, that bidders in the SAA bid aggressively despite the exposure problem, and that provisionally winning bidders, when so informed, tended to make fewer bids. Only the last of these three observations is potentially relevant for making improvements to package bidding designs.

Although our experiments have focused narrowly on a particular mechanism and a small set of environments, the consistency of bidder behavior with a simple theory suggests a number of hypotheses, both about how the CCA will perform in various cases and about how the design we have tested might be improved. It seems that simulations, similar to ones that guided our selection of cases, can be useful. In these simulations, bidders bid at each round for their most profitable packages. The provisionally winning bidders in our CCA tended not to bid that way, but it is a reasonable hypothesis that, if provisionally winning bids are not reported back to bidders, then the simulations might predict performance with better accuracy.

The possibility that price-guided auctions could fail to direct bidders to relevant packages early enough in the auction is another feature that is relevant to guide design. One way to make relevant bids more likely is to make bidding easier, for example by implementing a richer bidding language. In our experiments, bidders had to express separate bids for each package in which they might be interested; this so-called “XOR” bidding language burdens bidders who want to make multiple bids. Alternative bidding languages could ease that burden and improve outcomes.

Another potential improvement is to allow bidders to add more bids later in the auction when the relevant packages become clearer. The recent spectrum auctions conducted by the British Office of Communications (Ofcom) allows “supplemental bids” to be made at the end of the clock stage of an auction when identifying relevant packages is presumably easier.[40]

The relationship between theory and experiment is a two-way street. In this paper, we use theory to explore and explain experimental outcomes. For the experiments reported, our analysis successfully identifies which environments are most likely to be problematic for the CCA; it points to the features of auction designs that might account for performance differences; it provides a revenue standard for package auctions, where none had been available to past experimenters; and it identifies correlations in outcome attributes. Plainly, the theory helped us to explain and predict experimental outcomes.

In the reverse direction, experiments influence theory. The theory reported here was inspired by the twin attempts to understand the surprising reported efficiency of CCA outcomes in early experiments and the puzzle of the extreme differences in performance across varied environments in our own experiments. That a theory derived to explain these observations also delivers insights into certain empirical correlations, points to relevant design details, and makes concrete predictions about the likely outcome of future experiments with different value profiles are clear benefits of the paired theoretical-experimental approach. It is an approach that we enthusiastically recommend.

[40] The Ofcom auction rules, which were proposed largely by Peter Cramton, combine the clock-proxy auction design of Ausubel, Cramton, and Milgrom (2005) with the minimum-revenue core-selecting auction of Day and Milgrom (2007).

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Table 1
Experimental Treatments

Session	Date	Number of Subjects Session 1	Session 2	Session 3
Combinatorial Clock Auction (CCA)				
4 items (number of auctions)	Feb./March, 2007	22 (3)	20 (9)	18 (8)
6 items (number of auctions)	May/June, 2007	19 (3)	18 (9)	16 (10)
Simultaneous Ascending Auction (SAA)				
4 items; default bid is (0,0,0,0) (number of auctions)	Feb./March, 2007	21 (3)	21 (9)	20 (10)
4 items; default bid is (1,1,1,1) (number of auctions)	May, 2007	21 (3)	20 (9)	19 (8)
6 items; default bid is (1,1,1,1,1,1) (number of auctions)	May, 2007	21 (3)	21 (9)	19 (10)

Table 2

Correlations Between Efficiency Loss, Revenue Loss and Profits

	CCA6 Auctions		SAA6 Auctions	
	Efficiency Loss[1]	Revenue Loss	Efficiency Loss[1]	Revenue Loss
Revenue Loss[2]	0.385***	----	0.092	-----
Bidder Profits[3]	-0.042	0.844***	-0.197**	0.929***
	CCA4 Auctions		SAA4 Auctions	
	Efficiency Loss[1]	Revenue Loss	Efficiency Loss[1]	Revenue Loss
Revenue Loss[2]	0.244**	----	0.009	-----
Bidder Profits[3]	-0.425***	0.558***	-0.551***	0.764***

** Significantly different from 0 at the 5% level.
*** Significantly different from 0 at the 1% level.
[1]Efficiency loss is the difference between full efficiency and realized efficiency. Realized efficiency is normalized relative to the expected value of a random allocation (see text).
[2]Revenue loss is the ratio of actual revenue to minimum revenue in the core.
[3]Bidder profits are calculated as the ratio of total bidder profits divided by the value of the efficient allocation.

Table 3
Percentage of Profitable Packages Bid on in CCA Auctions[a]

	Global Bidders			Regional Bidders[b]		
CCA 4 Auctions	Overall[c]	Most Profitable	2^{nd} Most Profitable	Overall[c]	Most Profitable	2^{nd} Most Profitable
Rounds 1-5	22.4% (3.0)	61.4%	34.8%	37.1% (1.1)	62.8%	31.1%
Rounds 6-10	21.2% (1.5)	69.3%	22.3%	32.2% (0.7)	52.2%	23.0%
Rounds 11-15	21.6% (0.5)	59.8%	21.7%	35.7% (0.6)	56.9%	20.1%
Rounds >15	23.8% (0.2)	64.0%	10.5%	32.9% (0.4)	47.3%	19.4%
CCA 6 Auctions						
Rounds 1-5	13.2% (7.8)	59.0%	38.0%	36.1% (2.4)	65.6%	45.7%
Rounds 6-10	12.1% (4.1)	52.4%	31.5%	31.8% (1.7)	61.9%	48.2%
Rounds 11-15	12.6% (1.0)	65.5%	34.6%	34.4% (1.0)	73.3%	47.9%
Rounds >15	12.4% (0.3)	82.8%	22.2%	36.7% (0.6)	89.0%	41.7%

[a] Rounds in which a bidder is a provisional winner and no bid is submitted are dropped from calculations. Otherwise bids of provisional winners are included. Data from last auction round are excluded as by definition there are no bids.
[b] Only includes packages where all items had positive value for regional bidders.
[c] Average number of bids in parenthesis.

Table 4
Scope for Profits at End of Auctions

CCA4 Auctions	Bidder Type	Frequency Higher Profits were Available[a]	Average Foregone (Potential) Profits in ECUs[b]
Losing Bidders	Global	4.5% (3/66)	12.0 (7.6)
	Regional	24.4% (11/45)	10.3 (2.8)
Winning Bidders	Global	11.8% (4/34)	15.0 (6.0)
	Regional	5.2% (8/155)	5.4 (1.7)
CCA6 Auctions			
Losing Bidders	Global	9.4% (5/53)	4.5 (1.3)
	Regional	24.7% (19/77)	16.0 (3.4)
Winning Bidders	Global	9.8% (5/51)	26.3 (6.9)
	Regional	9.9% (13/131)	17.5 (5.0)

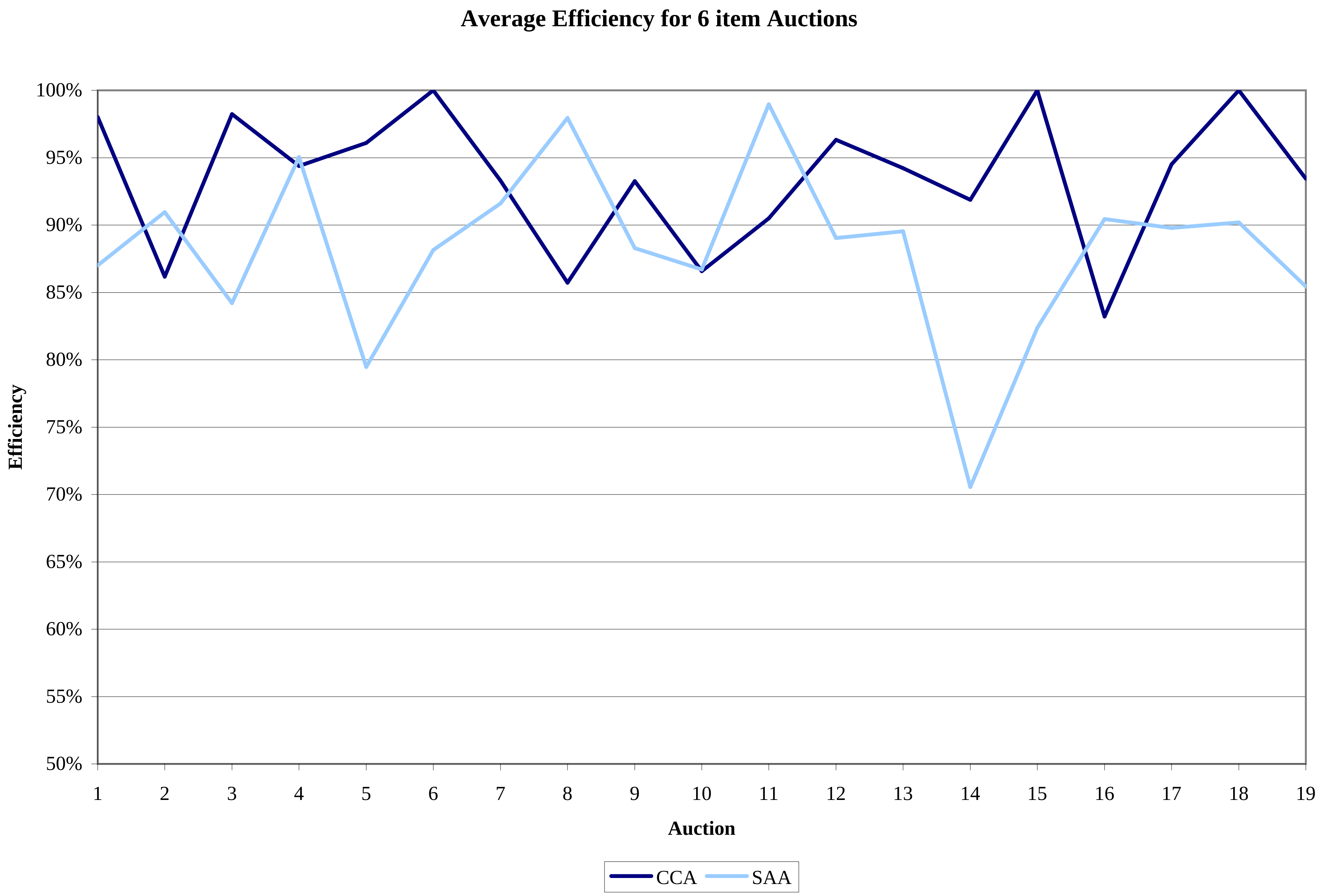
[a] Raw data in parentheses
[b] Standard error of the mean in parentheses. Eight outliers have been dropped from average foregone profit calculations, with minimum forgone profits of 76 and average forgone profits of 115.

Table 5

Package Bids in CCA Auctions when Named Package No Longer Most the Most Profitable Bid[a]

	Regional Bidders		
CCA 4 Auctions (number cases)	Named Package[c]	Most Profitable	Both
Rounds 1-5 (16)	31.3%	68.8%	25.0%
Rounds 6-10 (126)	25.4%	51.7%	14.3%
Rounds 11-15 (98)	19.4%	60.2%	10.2%
Rounds 16 – 20 (47)	17.0%	48.9%	4.3%
CCA 6 Auctions			
Rounds 1-5 (7)	28.6%	85.7%	28.6%
Rounds 6-10 (105)	57.1%	74.3%	40.0%
Rounds 11-15 (92)	37.0%	63.0%	23.9%
Rounds > 15 (21)	33.3%	66.7%	19.0%

[a] Observations for which named package is not profitable are dropped. When a provisional winner does not bid, or the auction is in the last round, observations are dropped.



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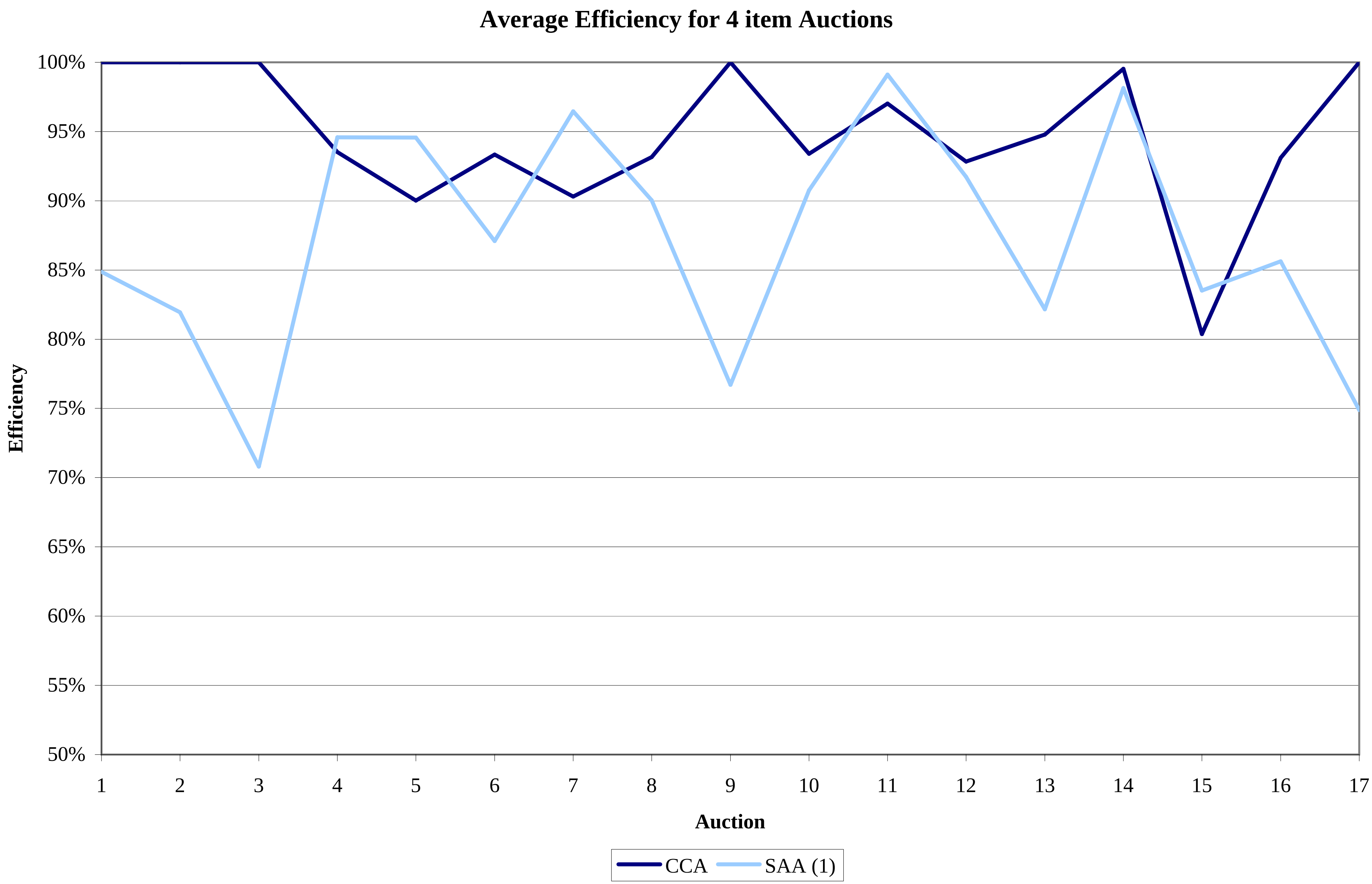
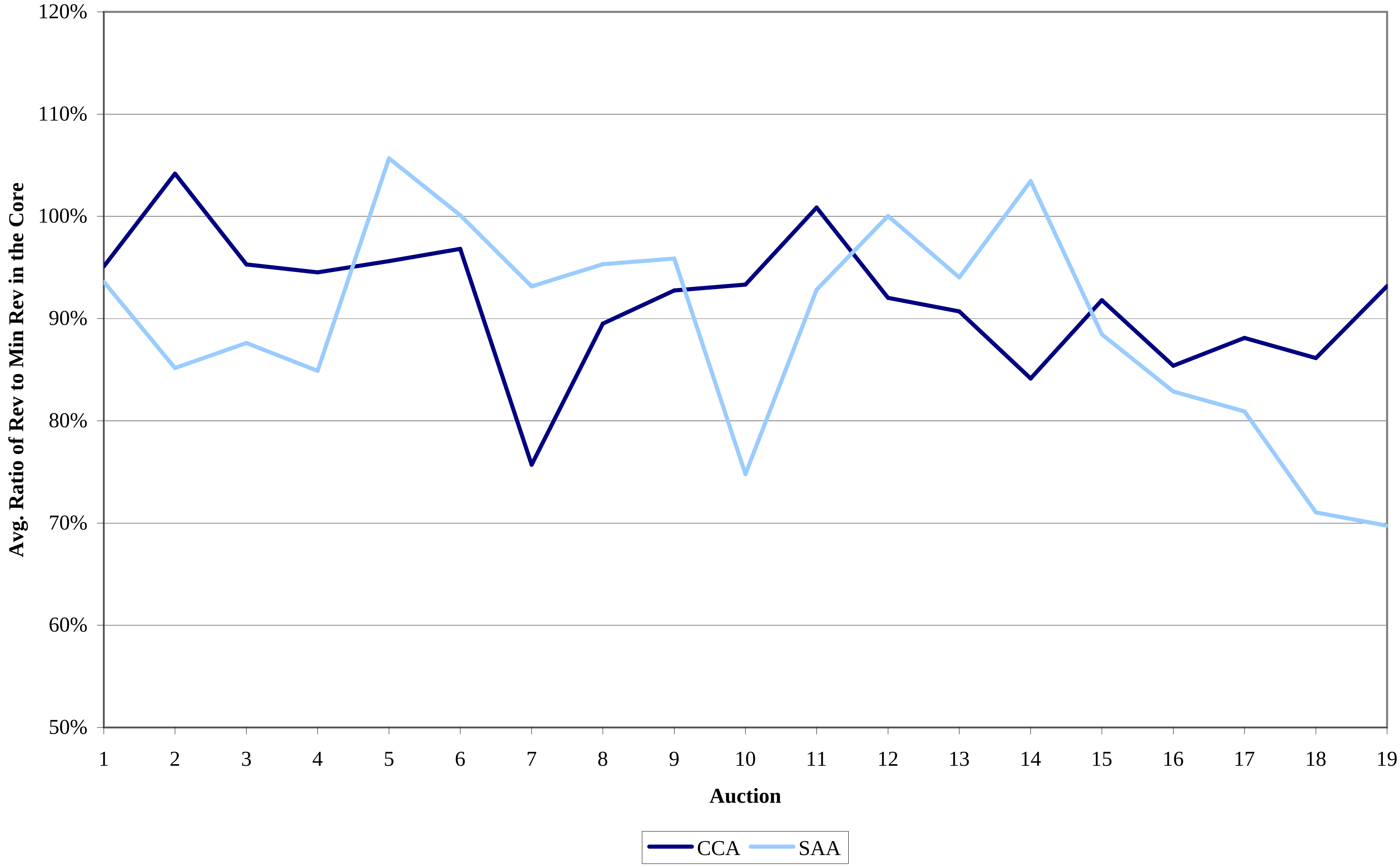


Note: Auction 7 Group 6 and Auction 13 Group 3 are excluded from the CCA calculations.

Average Ratio of Revenue to Minimum Revenue in the Core for 6 item Auctions



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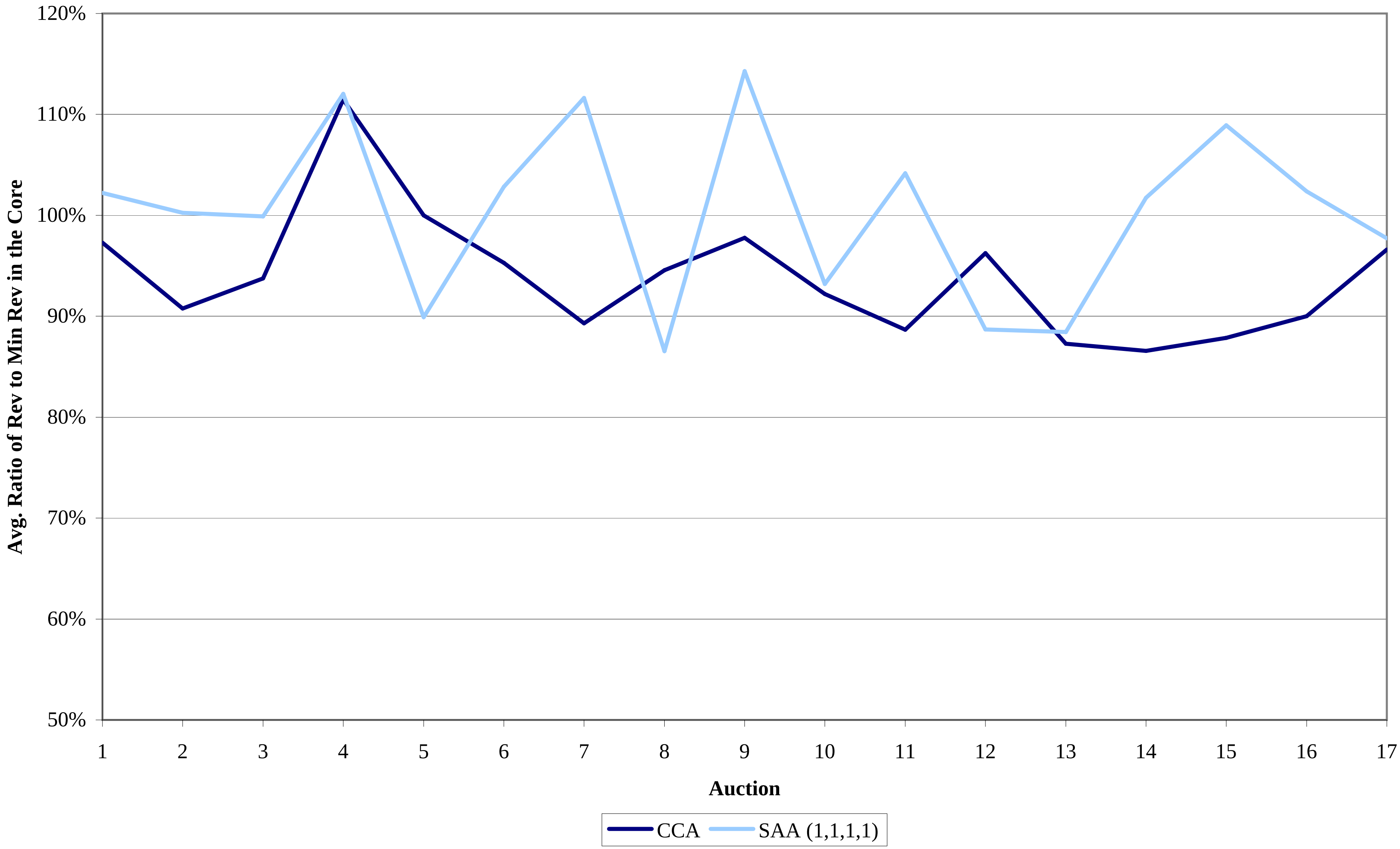
Average Ratio of Revenue to Minimum Revenue in the Core for 4 item Auctions



Note: Auction 7 Group 6 and Auction 13 Group 3 are excluded from the CCA calculations.

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