Draft: Comments welcome

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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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 at each round 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 item prices to help solve package allocation problems of this sort. One approach attempts to find 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 prices are additive and anonymous – the same for all bidders. If goods are not substitutes, then non-anonymous, bidder-specific package prices to support an efficient assignment still exist and one can try to find the item prices that best approximate those. This is the approach taken by the RAD design of DeMartini, Kwasnica, Ledyard, and Porter (1999).

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 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.

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

Our theorems apply to a wide class of dynamic package auctions in which the payments by bidders for their assignments are the highest bids they make during the auction for their packages. The theorems do not assume that item prices guide the bidding nor do they restrict in any way the dynamics of how bids are solicited. For example, the theorem applies to the ascending proxy auction of Ausubel and Milgrom (2002), even though that design does not use 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. The seller's revenue is $\max_x \sum_{j\in N} \beta_j(x_j)$.

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 $\pi_j = v_j(\bar{x}_j) - \beta_j(\bar{x}_j)$ denote bidder *j*'s profit from the auction assignment.

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.

Theorem 1. Consider any auction in class *A*. If, for all sets of bidders *S* and all $i \in S$, $v_i(x_i(S)) - \beta_i(x_i(S)) \le \pi_i$, then the final allocation $(\bar{x}, \beta(\bar{x}))$ is a core allocation.[2]

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

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

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. **QED**

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

Proof. The total value of the final goods assignment is

$$\begin{aligned}\sum_{j \in N} v_j(\bar{x}_j) &= \sum_{j \in N} \beta_j(\bar{x}_j) + \sum_{j \in N} \pi_j \\ &\ge \sum_{j \in N} \beta_j(x_j(N)) + \sum_{j \in N} \pi_j \\ &\ge \sum_{j \in N} v_j(x_j(N))\end{aligned} \tag{2}$$

The first equation follows from the definition of π_j; 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 achieve 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 ($\beta_j(x_j) \ge v_j(x_j) - \pi_j$), and (3) encourage losing bidders to bid all the way up to their full values ($\beta_j(x_j) = v_j(x_j)$) for the relevant packages. For theorem 2, the "relevant package" for any bidder *j* is $x_j(N)$; for theorem

[2] The sufficient condition used in theorem 1 can be weakened to require the inequality only for "relevant" sets of bidders *S*. A set of bidders is relevant if removing the constraint corresponding to the seller and this set of bidders would change the core.

1, the relevant packages also include $x_j(S)$ for all relevant sets of bidders S (as defined in footnote 2)

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 set of 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 could 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 successes. Comparisons between those earlier results and ours are limited because certain details of the auction rules, the bidder interfaces, and valuations and bid data were not reported.

These initial experimental results are suprising and point to the CCA as a promising design. 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 – many fewer than the more than 1,000 licenses offered in the actual auction. Nevertheless, 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 explore systematically even a hundred dimensional subspace of the full set – an impractically hard task – would require imposing hundreds of thousands of restrictions on the set of possible bidder values. While it is possible to explore some interesting special cases of this problem with an experiment, the only hope of generality lies in identifying a theory to extrapolate from the observations of a tiny fraction of the possibilities.

Theorems 1 and 2 identify bids whose presence necessarily lead to efficient outcomes or core outcomes. We can use the theorems to examine whether those bids are more or less likely to be made in alternative auction mechanisms. 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. Heuristically, item prices determined using the CCA rule encourage bidders to specify packages using items of relatively low marginal value. 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. Information that bidders receive about the status of their bids, such as whether the bids are provisional winners, and opportunities that are lost if bidders with provisional winning bids fail to make new bids, can all affect the likelihood that the conditions are satisfied.

How might bidders know which packages are relevant? In our experiments, 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 reported 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 and 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.[3]

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,

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

then the bidders most often choose bids at each round that are highly ranked by X. Previous package auction experiments have not reported in detail what sorts of decision support was provided to bidders; that is an important omission.

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

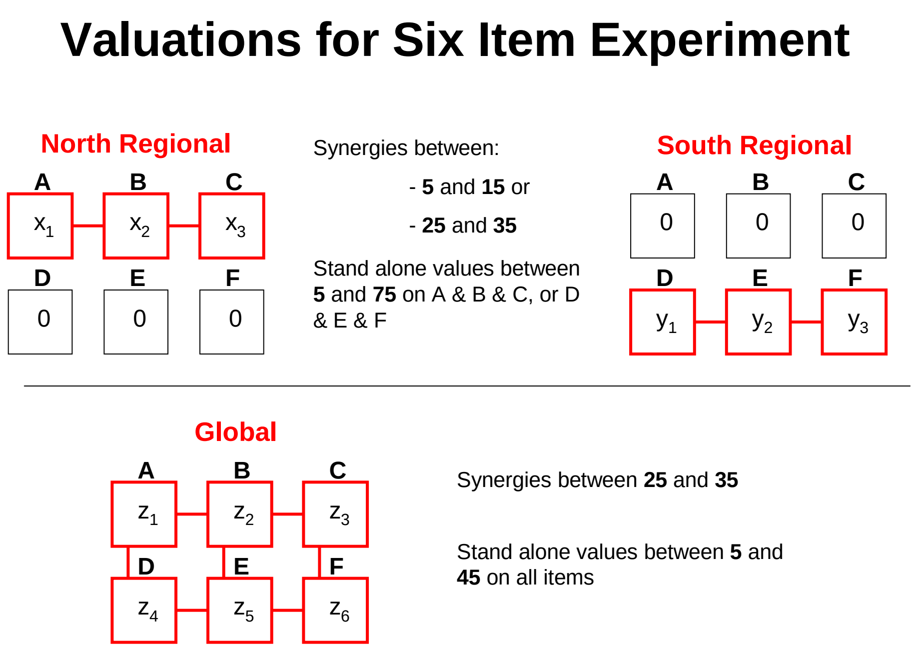
Yet another special issue in package auction experiments concerns what to measure. Previous experiments invariably report some measure of the efficiency of the experimental outcome. Sometimes, comparative revenues are also reported, but there is typically no standard by which to determine whether revenues attain a reasonable level. 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, including ones in which simulations showed the simpler simultaneous ascending auction performed better than the combinatorial clock auction.

I Experimental Design and Procedures

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 (see Figure 1A in the Appendix for the four item case). 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.



The stand alone values for the regional bidders were integer values consisting of iid draws 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 [25, 35]). Thus, synergy values were the same between all pairs of items, with stand alone values varying between items. The same synergy regime was in place for both regional bidders and was announced prior to each auction. The stand alone values for the global bidder were integer values consisting of iid draws 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 stand alone values for the global bidder meant that they had to rely more on the synergies inherent in their global structure for profits, as opposed to the regional bidder who relied more on their higher average stand alone values. Finally, roles as a regional or global bidder changed randomly from auction to auction as did bidders valuations.

Two types of auctions were explored. A continuous clock auction (CCA) permitting package bids and a simultaneous ascending auction (SAA) in which individual items were auctioned of simultaneously, each in its own market. In both, a "bid" is a vector of quantities representing an offer by a bidder to buy at the quoted prices.

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 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 the 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 stand alone values.

The auction proceeds in 25 second rounds during which subjects could submit as many package bids as they wished. Bidders submit demands for packages, with the bid for each package consisting of the sum of item prices in the package. Following each round, *tentative* winning bids were determined by a computational algorithm designed to maximize seller revenue.[4] The algorithm looks at all current bids as well as all past bids to find the combination of bids that maximizes seller revenue. The price associated with any quantity bid is that determined in the round in which the bid was originally placed.

[4] Ties or 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.

Price increases between rounds were 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). (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. Thus, by looking at which items had price increases for the current round, bidders could determine which items bidders were actively competing for. For items with a zero price increase, either no one wanted the item or there was a single provisional winner currently demanding that item. Prices for all items started at 5.[5]

In each round tentative winning bids were automatically reentered, but not counted as new bids, so that any bidder content with their tentative winning bid (which they alone were aware of) did not need to bid again. Those bidders not satisfied with their tentative winning bids, or who had no tentative winning bids, were, of course, permitted to enter new bids. 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."[6] 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: These auctions also proceed by rounds, with each round lasting for 25 seconds. Like the CCA auction bids could be made for packages of items but unlike the CCA, there was no guarantee of getting an all-or-nothing result. Prices of each item were computed separately, with prices increasing by 5 ECUs in each auction period for which

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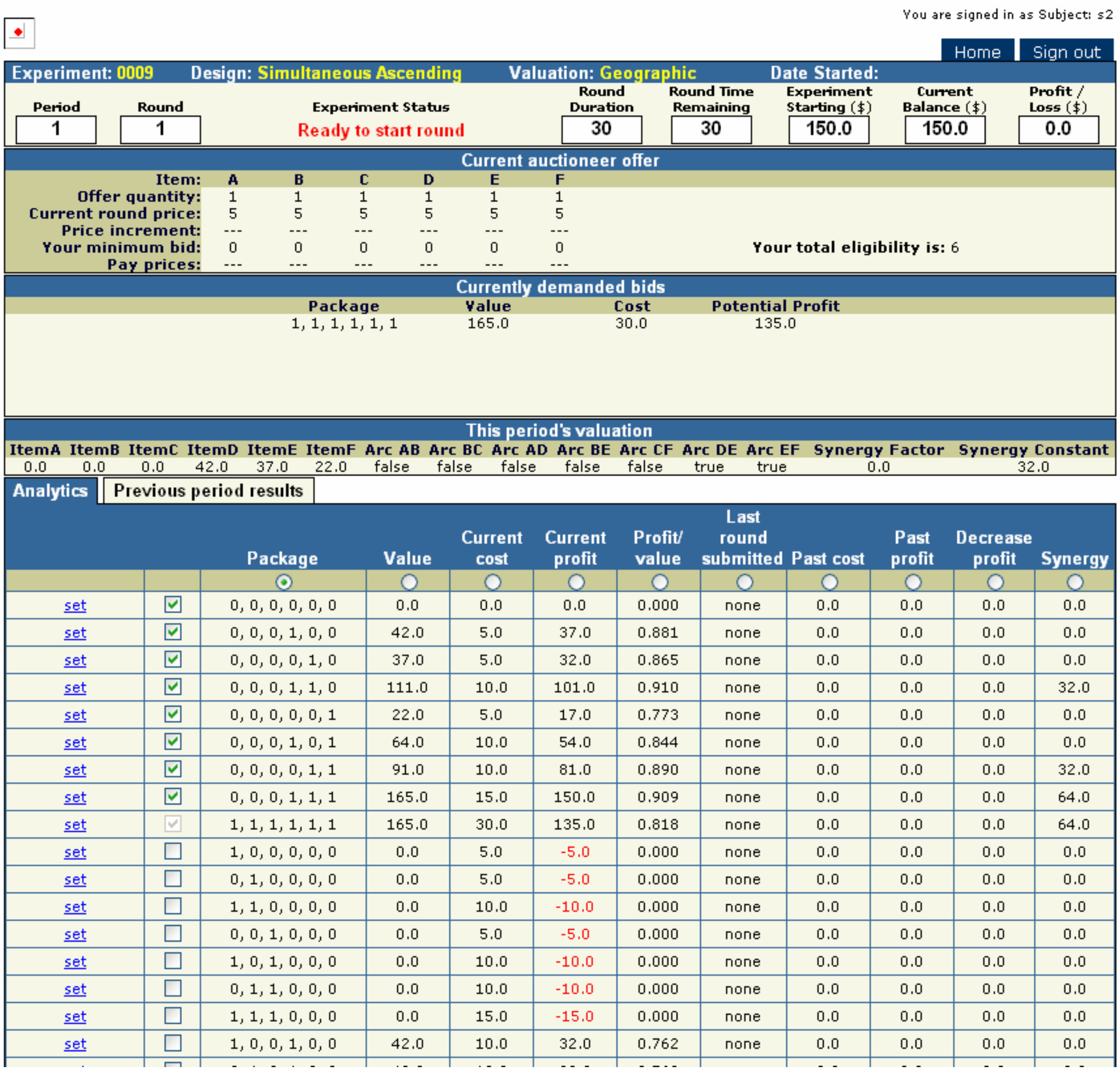
[5] Thus, prices were weakly increasing from round to round, unlike RAD (Kwasnica et al., 2005) or the FCC"s Modified Package Bidding.

[6] In a mechanism design problem the instructions to subjects are just as much a part of the mechanism as the rules of the auction. In this experiment we are interested in designing a mechanism with favorable properties, so that instructions of this sort are totally appropriate rather than requiring subjects to discover these properties on their own

there as 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 stand alone values for an individual item in order to capture the possible synergies associated with getting complimentary items, bidders were exposed to possible losses, paying more for one or more items than their stand alone values. With strong complementarities between items, this "exposure problem" is considered one of the major drawbacks to the SAA auction. Our SAA auctions have a number of similarities to the procedures used by the FCC for selling spectrum (air wave) rights with the key exception that bids automatically increased by a fixed amount in each period with excess demand rather than bidders deciding how much to bid (given some minimum bid increment). Thus, there is no scope for "jump bids."[7]

Figure 2 provides a sample screen layout for the SAA auctions. Like the CCA auctions, to bid on a set of items a subject only had to click "set" next to the set of items they were interested in. However unlike the CCA, they could only make one such bid as there was no opportunity for package bids.

[7] In its auction 73, however, the FCC adopted a similar rule with no scope for "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

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

1. *Eligibility 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 "Currently demanded bid" which was the default bid for that round if no new bid was posted. Our initial set of SAA auctions had a default bid of zero demand for all items at the start of each round, meaning that bidders needed to be proactive in each round to keep their eligibility up. After

looking at the data from these sessions we changed procedures, so that each auction started with a default bid of one unit for each and every item. After this first round of bidding, the default bid was the bid in the previous round. Further, any time a new bid was entered that reduced a bidder's eligibility, the bidder was notified of this on its computer screen and required to confirm the bid. Reasons for this change and the impact on the auction outcomes will be reported in the results section.

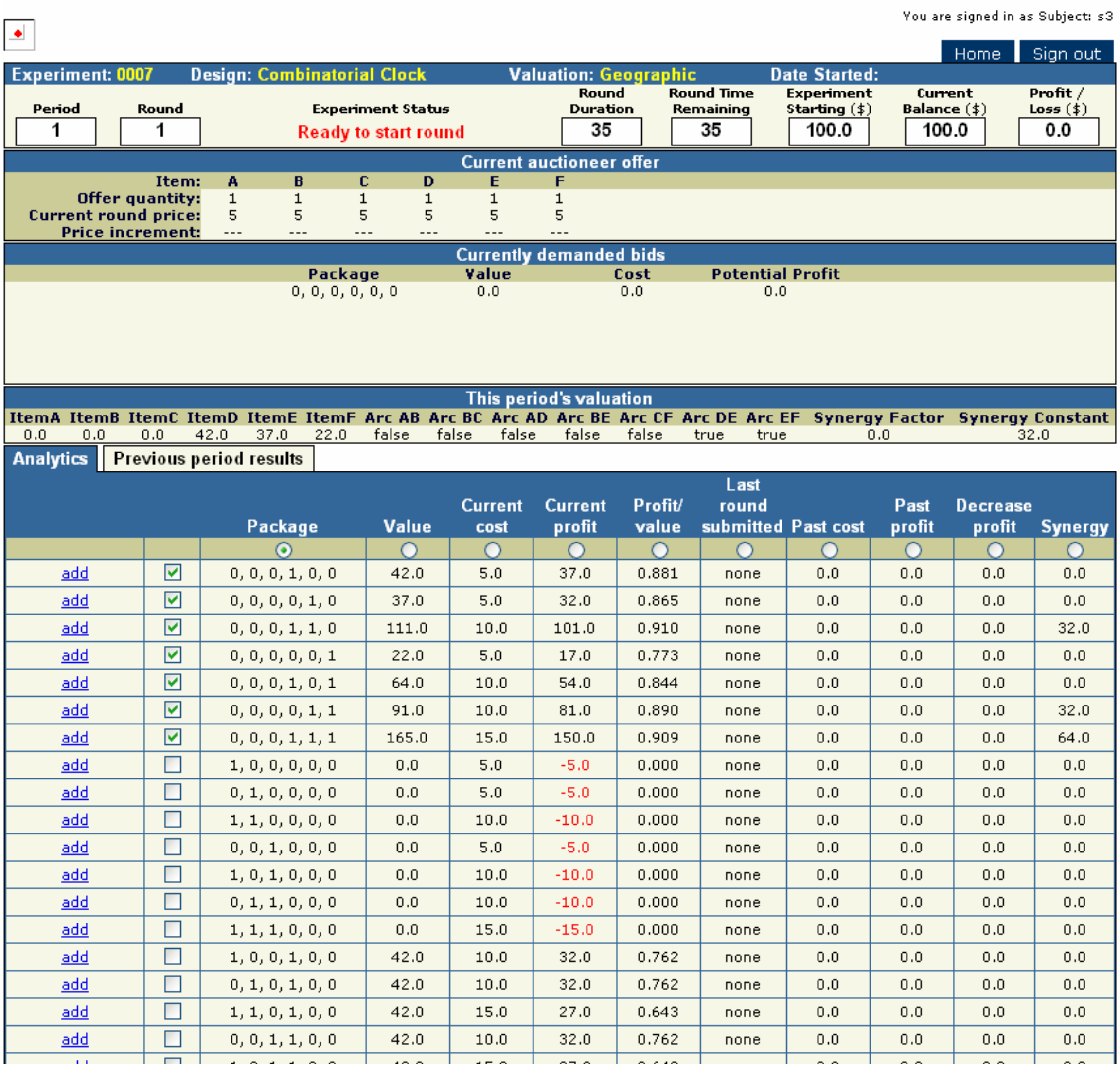
3. *Minimum bid requirements:* Once there was no longer any excess demand for an item, the current high bidder for that item was required to maintain their bid for the item, with this minimum bid requirement in effect unless someone else topped that bid. This minimum bid requirement held regardless of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

4. P*rice rollback rules:* Given the indivisibilities inherent in the fixed price increase rule, near the end of an auction it would not be unusual for several bidders to drop their demand for an item at the same time, moving from excess demand to zero demand, resulting in unsold items with their large negative impact on efficiency. The following price rollback rule procedures dealt with this problem, thereby eliminating unsold items[8]: A*ll* bids in the round for which demand for *any* item went from excess demand to zero were cancelled. The computer randomly assigned the item(s) in question to one of the bidders who had bid on them in the previous round at the previous round's price (the *Pay price*). The bidder assigned the item had a minimum bid requirement for that item with the same requirements as in (3) above. The auction round that was cancelled then repeated itself with the Pay price applying to the bidder randomly assigned the item, with anyone else wanting to outbid the current winner paying the Current round price, i.e., the same price as in the round where demand for the item went to zero.[9] In addition, the default bid in the do-over round reverted to what it was at the start of the cancelled round so that eligibility was restored. The auction then continued in the usual way.

[8] There was a small glitch in the price rollback implementation that resulted in a single unsold item in three of the 216 four unit SAA auctions conducted. This was corrected in the six item auctions.

[9] By separating the Pay price from the Current price, bidders never pay more than what they bid for the item. At the same time, the Current price is higher, so the tentative losing bidder needs to pay more in order to outbid the tentative winner.

Computer Interface and Aids for Subjects: Auctions with multiple items and synergies between those items 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 provide 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.



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

The important thing to note here are the aids provided to bidders with 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 items/package they were interested in. Further, to make sense of the large number of possibilities, the subjects were provided with a number of sort options were provided using different criteria - value, current cost, current profit, etc. In addition, for the regional bidders, checks were initially placed next to all the packages containing only those items with positive values (in this case packages containing only items D, E or F). 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.[10] Regardless of the sort option chosen, the value of the items in each package, its current cost, current profit, etc., were updated at the end of each auction round. Further, all bids in previous rounds received a check mark, with bidders able to delete the check mark on any package simply by clicking on the little box with the check.

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 of auctions was a training session where subjects were introduced to the experimental procedures and computer interface followed by three dry runs, which was about all we could complete 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 the session two earnings withheld until completion of session three. Subjects were paid a flat $10 for participation in the initial training session. Given the complicated nature of both auctions, subjects were permitted to take the instructions home with them if they wanted to. Earnings in session 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) and were converted into dollars so as to achieve or exceed these projected earnings. 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.

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[10] This double sort routine is important since it essentially allows subjects to disregard dominated packages in terms of their profitability. Automatically checking of these packages for regional bidders was only initiated with the six item auctions, and was not present in the four item auctions. In the four item case bidders could effectively see all the packages on a single screen so the issue of possibly mistakenly choosing dominated packages was not as severe.

As noted, each auction consisted of three bidders. Subjects' roles as a regional or global bidder were randomly determined prior to each auction, as were the bidders in their auction group. There were no subject numbers provided on computer screens which, until the end of the auction, only reported a bidders own outcome. Each experimental session was designed to have five or more auctions with exactly the same private valuations going on at the same time, only moving on to the next auction after the last group had finished. 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. At the end of each auction, subjects saw the allocation of units to bidders in their auction 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. Bidders never saw or knew any other bidders' valuations.

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.[11]

Subjects participated in either a series of CCA or SAA auctions. Each auction session consisted of a parallel series of auctions with common valuations. 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. In each set of four (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"

[11] Four item auctions, which were conducted first, had fixed round times of 25 seconds. The change was necessitated by the higher number of rounds anticipated in the six item auctions.

valuations – several cases where straight forward 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 straight forward 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.[12]

It became immediately apparent in the pilot sessions that subjects did not consistently follow straight forward bidding. Still, the simulations guided our choices among various cases given the limited number of auctions we could actually conduct. It also let us choose some auctions satisfying each of the criteria described above. So if, for example, bidders did not follow straight forward bidding in the SAA auctions, the global bidder would more than likely have to suffer losses to obtain all the items while achieving 100% efficiency if their regional bidders played reasonably aggressively.

Table 1 lists the auction sessions conducted with the number of subjects in each session, along with the number of auctions in each session.[13] Subjects were recruited through e-mail lists of students taking economics classes in at the Ohio State University in academic year 2006-07.[14] Average earnings per subject were $145 for those completing all three sessions, including the $30 show up fee and the $10 payment for session one. Average minimum earnings per subjects completing all three sessions were $81, with average maximum earnings of $236.

[12] Although the simulations were based on random draws, the instructions were clear not to suggest that bidders' valuations were randomly drawn.

[13] 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 the two auction relatively complicated mechanisms, and implementing them in the software, as one of the major outputs of this project.

[14] 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., in press).

II. 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 arise out of a mechanism like the one described in the introduction, in which bidders adopt something close to *dynamic profit target strategies*. In pure form, these strategies are ones in which (1) bidders set and revise profit targets during the auction and make all bids for relevant packages which, if they become winning, will result in profits exceeding the target and (2) bidders reduce profit targets when they have no provisionally winning bids, with the target levels eventually reaching zero for losing bidders. If bidders behave that way, outcomes in the CCA will necessarily be efficient, revenues will be at core levels, and the vector of bidder profits will lie in the core. If failures to achieve core outcomes result from situational blocks to these profit-target bidding strategies, then the CCA should exhibit low efficiency and low revenue in the same experimental trials, so positive correlations being efficiency and revenue, both suitably normalized, are expected.

In contrast, for the SAA, the exposure problem could drive a negative correlation between revenues 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 the individual items in an 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 implement dynamic profit-target strategies are several. One of these 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 in those rounds may continue to rise and, by the time the bidder is again placing bids, it may have already missed its last opportunity to place 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. (The SAA4 auction data are, for the moment, restricted to those auctions where the default bid was 1, 1, 1, 1.) Efficiency is calculated by taking the difference between actual surplus (S_{actual}) and the surplus resulting from a random allocation (S_{random}) and the dividing through by the difference between the maximum possible surplus (S_{max}) and the (same) random allocation.[15] 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.

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.[16] 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% of auctions with high complementarities. There are some subtle differences between our implementation of the CCA auction and these other experiments that no doubt account for some of these differences; e.g., Brunner

[15] 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.
[16] Unless stated otherwise, all statistical tests reported will use nonparametric (two-tailed) Mann-Whitney tests.

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 bidders conditionally winning bid. This would require bidding on the package with the largest number of items a bidder is interested in, in each round, to maintain maximum eligibility. We had no eligibility requirements in our CCA auctions.[17]

As important, if not more important, to the differences in efficiencies reported are bidders underlying valuations. Our simulations showed that in auctions where the efficient allocation required all bidders to get at least one item, efficiency was relatively low in the CCA auctions with straight forward bidding.[18] Although it is clear that bidders did not practice straight forward bidding (see below for details on this), the CCA auctions had a particularly difficult time achieving high efficiency rates in these cases, to the point that the SAA actions performed significantly better in these cases[19]: Using efficiency in each individual auction as the unit of observation, average efficiency was 89.2% (0.021) in the CCA6 auctions in which the efficient allocation required all bidders to get at least one item compared to 94.4% (0.024) in the SAA6 auctions ($p < .01$). And average efficiency was 90.9% (0.028) in the CCA4 auctions in which the efficient allocation required all bidders to get at least one item compared to 92.7% (0.027) in the SAA4 auctions ($p < .10$).[20] Note that these reduced efficiencies can *not* be attributed to unsold units in the CCA auctions as there were very few cases where this occurred: 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.[21]

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[17] A further illustration of the importance of procedures is discussed in Appendix A to this paper, where we report the results for the SAA4 sessions which employed a default bid of no bid at the start of each round of bids.

[18] With straight forward bidding, subjects bid on *the single* package yielding the highest return in the current auction period *and bid only on that package*.

[19] 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.

[20] 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.

[21] The rollback rules essentially eliminated any unsold items in the SAA auctions. We say essentially since there were 3 four item auctions in which there was one unsold item as a consequence a minor flaw in the rollback algorithm. This was corrected in the six item SAA auctions.

A second subset of auction valuations that are 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.[22] 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) SAA4 auctions. This translated into substantially higher efficiencies in these CCA auctions than in the corresponding SAA auctions.[23] 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 SAA4 auctions the 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. 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 the threshold problem, and that, absent any overlapping demands, there were no fitting problems for the regional bidders in these experiments.

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 that 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

[22] In multi-unit sealed bid auctions this is an issue as well, but for somewhat different reasons (see Cantion and Pesendorfer, 200x and Chernomaz and Levin, 2007 for an experiment dealing with this issue).

[23] 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).

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.

Using average revenue (as a percentage of the minimum revenue in the core) 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.[24] 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 periods in SAA6 auctions.[25] Part of the reason for this is that bidders, particularly the global bidder, frequently suffered losses in the SAA auctions (in 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 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,

[24] Unless stated otherwise all references to average revenue here are in terms of averages as a percentage of minimum revenue in the core.
[25] This rarely happens in the CCA auctions – occurring once in the four and six item auctions respectively.

potential losses (which it looks like it did). As such, we do not feel comfortable pooling the average period revenues between the four and six item auctions.

Comparing revenues using each individual auction as the unit of observation, average revenue is 91.8% (0.012) of minimum revenue in the core for the CCA6 auctions versus 89.4% (0.024) in the SAA6 auctions, which differences are not statistically significant at conventional levels ($p > 0.10$). But average revenue is significantly higher in the four item SAA auctions: 100.3% (0.021) of minimum revenue in the core for the CCA4 auctions versus 93.9% (0.015) in the SAA4 auctions ($p < 0.01$). Normalizing 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%; $p < 0.01$). These results are consistent with the notion that with increased synergies, the exposure problem becomes more severe in the SAA auctions, leading to more cautious bidding and lower revenue compared to the CCA auctions which eliminate the exposure problem.

There are no directly equivalent revenue results from other multi-unit demand auctions against which to compare these revenue 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.[26] They find that revenues are significantly higher in their version of the CCA auction than the simultaneous multi-round (SMR) auction employed in the FCC auctions (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. But these differences

[26] They 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 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.

are not so large as 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. 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 per capita for the SAA6 auctions and -6.6 versus 15.63 for the SAA4 auctions. In contrast, for the CCA6 auctions, regional and global bidder profits per capita 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 bidders do worse 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 and did the same in 35.8% of the SAA6 auctions compared to 5.3% of the regional bidders. Finally, part of the reason for the negative average profits for global bidders in the SAA4 auctions has to do with the smaller profit opportunities for global bidders in these auctions as measured by the substantially lower profits for global bidders in the CCA4 auctions as well.

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. We suspect that part of the reason for these differences has to do with differences in CCA procedures between our experiment and Brunner et al. Under their procedures provisional winners are not announced following each round of bidding, whereas in our design they are. The failure to announce provisional winners in each round more than likely results in bidders competing against themselves at times. In our design bidders would only wind up competing against them self if they placed overlapping bids relative to a provisionally winning bid, with the latter is relatively unlikely to occur in later auction periods, when final prices are set.

There is, however, a downside 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.[27] The second is potentially more damaging, as it permits bidders to tacitly collude, stopping bidding early on if all bidders achieve reasonable profits. This happened in one of the over one hundred CCA4 auctions. In this case bidding 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.[28] 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. The downside of not reporting provisionally winning bids in the CCA auction is that a bidder can wind up competing with himself, which could result in lower participation in field settings, with its adverse impact on revenue.

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: The "core" in a package auction can be understood as the set of "competitive outcomes" (Ausubel and Milgrom (2002). This subsumes several other familiar conditions such that any core outcome is (i) efficient, as otherwise the coalition of the whole could, hypothetically, deviate to a preferred outcomes, (ii) entails no losses for any bidder, since otherwise that bidder could, hypothetically, deviate to a preferred outcome, and (iii) generates revenue for the seller at least as large as the minimum revenue in the core as otherwise a coalition of the seller and certain buyers could,

[27] Our instructions pointed this out to subjects.

[28] 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 stand alone 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.

hypothetically, deviate to a preferred outcome. Because the mechanisms for our combinatorial auctions are simplified ones and the allocations problems under investigation are challenging ones, it comes as no surprise that outcomes are less than fully efficient and that the core allocations are hard to achieve. However, the above considerations would lead us to guess that for easy cases identified by the ability of bidders to find deviations that cause (i) and (ii) to be satisfied, bidders might also find the deviations to support (iii) as well. As such we look for correlations among the magnitudes of these three conditions for the CCA auctions, as well as for the corresponding SAA auctions. These are reported in Table 2.

Looking at the CCA auctions first, there is a reasonably strong positive correlation between efficiency loss and the ratio of revenue loss to minimum revenue in the core (0.358 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, as is to be expected.[29] 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., the larger bidder profits are in any given auction, the less the efficiency losses for the CCA4 auctions. Bidder profits normalized by the value of the efficient allocation are positively correlated with the ratio of revenue loss relative to minimum revenue in the core, with this positive correlation more pronounced in the CCA6 auctions.

Similar correlations are reported for the SAA auctions, with the exception that there are no significant correlations between revenue loss and efficiency loss in either of the SAA4 auctions. This in turn might be explained by the price rollback rules employed. Recall that a price rollback occurs if following a price increase, the auction moves from excess demand for an item to zero demand. In this case the item in question is randomly allocated to one of the bidders demanding it in the previous round of the auction. While this insures at least some positive revenue for the seller, and eliminates the sharp drop in efficiency resulting from not having sold the item, this random allocation

[29] 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 xx.

disrupts the positive correlation between revenue losses and efficiency losses found in the CCA auctions, where such random allocations do not occur.

Rounds to Auction Completion: The average number of rounds to completion were 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.[30] 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.

Conclusion 4: There were no major differences in rounds to completion between the SAA and CCA auctions.

Exposure Problems in SAA Auctions: The SAA auction present 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 stand alone value of the items that they actually get. This in turn may inhibit bidder aggressiveness which, along with the potential negative impact on participation, is the primary benefit of package bidding. While the impact on bidder participation cannot be measured here, we can look for its impact on bidder behavior in the SAA auctions.[31] It is quite difficult to come up with an accurate measure of the impact of the exposure problem in terms of inhibiting aggressive bidding. As already noted, it appears to have had some impact in reducing revenue relative to minimum revenue in the core 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 how extreme the problem was in the SAA auctions.

At one extreme the exposure problem might have caused bidders to not bid above their stand alone values, or not to bid very much above their stand alone values. If bidders had bid up to their stand alone values and stopped, revenue as a percentage of minimum revenue in the core would have been 36.0% and 36.8% for the SAA6 and 4

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

[31] 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, wit the same underlying valuations in the two cases.

auctions respectively. This compares with actual revenue as a percentage of minim revenue in the core of 89.4% and 100.3% for SAA6 and 4 respectively. Thus, by these measures at least, bidders were reasonably aggressive. Further, as already noted revenue as a percentage of minimum revenue in the core was only slightly smaller in SAA6 auctions compared to CCA6 auctions and were higher in the SAA4 auctions compared to the CCA4 auctions. Since there is no exposure problem in the CCA auctions, given that revenues were close to or higher in the SAA auctions, would leads to the same conclusion that the exposure problem was not a major factor in inhibiting bids in the SAA auctions. In fact the major impact of the exposure problem in the SAA auctions is how, as noted earlier, it contributed to the efficiency losses in auctions where the efficient outcome called for regional bidders to win all the items.

Conclusion 5: The exposure problem had little impact on the aggressiveness with which bidders pursued the profit opportunities inherent in the relatively large positive synergies in these auctions. However, it played a major role in contributing to the reduced efficiency in those SAA auctions in which the efficient outcome called for the regional bidders to win all the items, as global bidders aggressively pursued their profit opportunities only to win inefficient subsets of items because of bid requirement rules.

Individual Bid Patterns: Subjects' bidding behavior in the CCA experiments have some notable characteristics which can affect the efficiency of the outcomes as well as the revenue relative to minimum revenue in the core.

First, subjects typically do not place bids in rounds in which they are provisional winners, with this effect most pronounced in later rounds where the auction has a reasonable 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 are provisional winners in CCA4 auctions, with the percentages for CCA6 auctions 88.1% and 85.4% for global and regional bidders, respectively.[32] Reasons for these high frequencies of not bidding are three fold: (i) Subjects typically bid on only a fraction of the packages they are eligible to 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

[32] 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 aucitons.

this last point, in rounds 11 and higher, provisionally winning bidders who did not place new bids were already winning (provisionally) on their highest valued package for 68.8% (72.2%) of global (regional) bidders in the CCA4 auctions and for 69.5% (58.5%) of global (regional) bidders 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 20-30% the profitable packages they were eligible to bid on. In rounds 1-5 when the number of possible packages to bid on earning positive potential profits was at its maximum, global bidders bid on an average of 3 packages per round.

Third, packages bid on tended to be the most profitable ones, with the frequency of bidding on the most profitable package averaging between 67-74% for global bidders, dropping to between 10-35% for the second most profitable package.[33] Regional bidders bid on a higher percentage of the packages earning positive potential profits, averaging between 33-38% of these packages. Note that these higher percentages relative to global bidders reflects the fact that regional bidders had far fewer profitable packages to bid on. (Percentages for the regional bidders exclude packages containing items of zero value.) Here to packages bid on tended to be the most profitable ones averaging between 58-67% in each round, with the frequency of bidding on the second most profitable package dropping to between 17-32%. 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 to bid on,. The frequency with which global bidders bid on the most profitable and second most profitable packages did not change much relative to the CCA4 auctions, averaging 59-72% of the most profitable and 19-39% of the second most profitable packages. The percentage of profitable packages regional bidders bid on remained roughly constant relative to the CCA4 auctions, averaging between 32-36% of all such packages, with

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

between 65-68% of the most profitable packages and 33-46% of the second most profitable packages bid on.

The low numbers of profitable packages subjects bid on does not create a particular barrier to achieving very high efficiency and revenue relative to minimum revenue in the core in those cases where the underlying demand structure calls for the global bidder to win all items or for the regional bidders to split the items. In those cases, the only relevant coalition for the global bidder consists of that bidder alone and the only relevant coalition for the regional bidders consists of the two of them alone, so a core outcome is assured if each bidder bids on just its *one* relevant package. Moreover, the very setting of the auction tends to point the bidders to the right packages.

In contrast, in those cases where the efficient outcome calls for all bidders (both regional and global) to get one or more items, or to split the items between a regional bidder and the global bidder, the auction has much more work to do in helping bidders to identify the relevant packages. In these cases, it is helpful for bidders to bid on a larger number of packages as this will help them to hitt on the relevant ones. As such, it is hardly surprising to see the relatively large efficiency differences in CCA auctions between settings in which the efficient outcome calls for all bidders to get one or more items and settings in which the obvious coalitions are the only relevant ones.

Conclusion 6: Both regional and global bidders bid on only a small fraction of the profitable packages they were eligible to bid on when they were not provisional winners. Of those packages bid on, the most profitable packages were bid on most often by far. Provisionally winning bidders tended not to place any bids, particularly in later rounds when they tended to already be provisional winners on their most profitable packages. This bidding pattern can help to explain why efficiency tends to be significantly lower in the CCA auctions in which the efficient outcome calls for both regional and global bidders to get one or more items versus those in which either the global bidder should get all the items or the regional bidders should split the items.

SAA Auctions Requiring Proactive Maintenance of Eligibility Requirements: Our initial set of SAA4 actions required that in each round bidders needed to be proactive to maintain their eligibility. That is, if no bid was made, the default bid was zero demand for all items, which dropped that bidder from the auction. In looking a the data we identified a number of cases where bidders reduced their eligibility, or dropped out of the auction completely, well before prices reached their stand alone values, which makes little sense. This could easily be attributed to the complexity of the auction in conjunction with the relatively short time bidders had to place a bid and the default rule for maintaining eligibility. To test this and possibly correct the problem, we modified procedures so that the default bid was the bid in the previous period.[34] In addition bidders were notified when a new bid would reduce their eligibility, needing to confirm such a bid. These results are summarized below.

1. The change in the default bid had minimal impact on efficiency, with no significant differences in average efficiency between the SAA4 auctions where the default bid was zero on all items ($SAA4_0$) and the SAA4 auctions where the default bid was the bid in the previous round ($SAA4_1$): 86.2% (0.020) for the $SAA4_0$ auctions versus 87.2% (0.020) for the $SAA4_1$ auctions ($p > 0.10$).
2. Average auction revenue was substantially lower in the $SAA4_0$ auctions compared to the $SAA4_1$ auctions: 86.2% (0.015) as a percentage of minimum revenue in the core compared to 100.3% (0.021) ($p < 0.01$).
3. Total profits were substantially higher in the $SAA4_0$ actions averaging 21.3% (0.022) of total value at the efficient allocation versus 10.5% (0.028) for the $SAA4_1$ auctions ($p < 0.01$).

Conclusion 7: There are large differences in revenue and efficiency in the SAA auctions as a consequence of the default in each round, with minimal differences for economic efficiency. These large differences in revenue and profits as a function of something as seemingly simple as the default value for bids at the start of each round of the auction, are suggestive of the importance of the details of auction design in outcomes for these complicated environments.

[34] All SAA bidders started out with full eligibility on all items.

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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

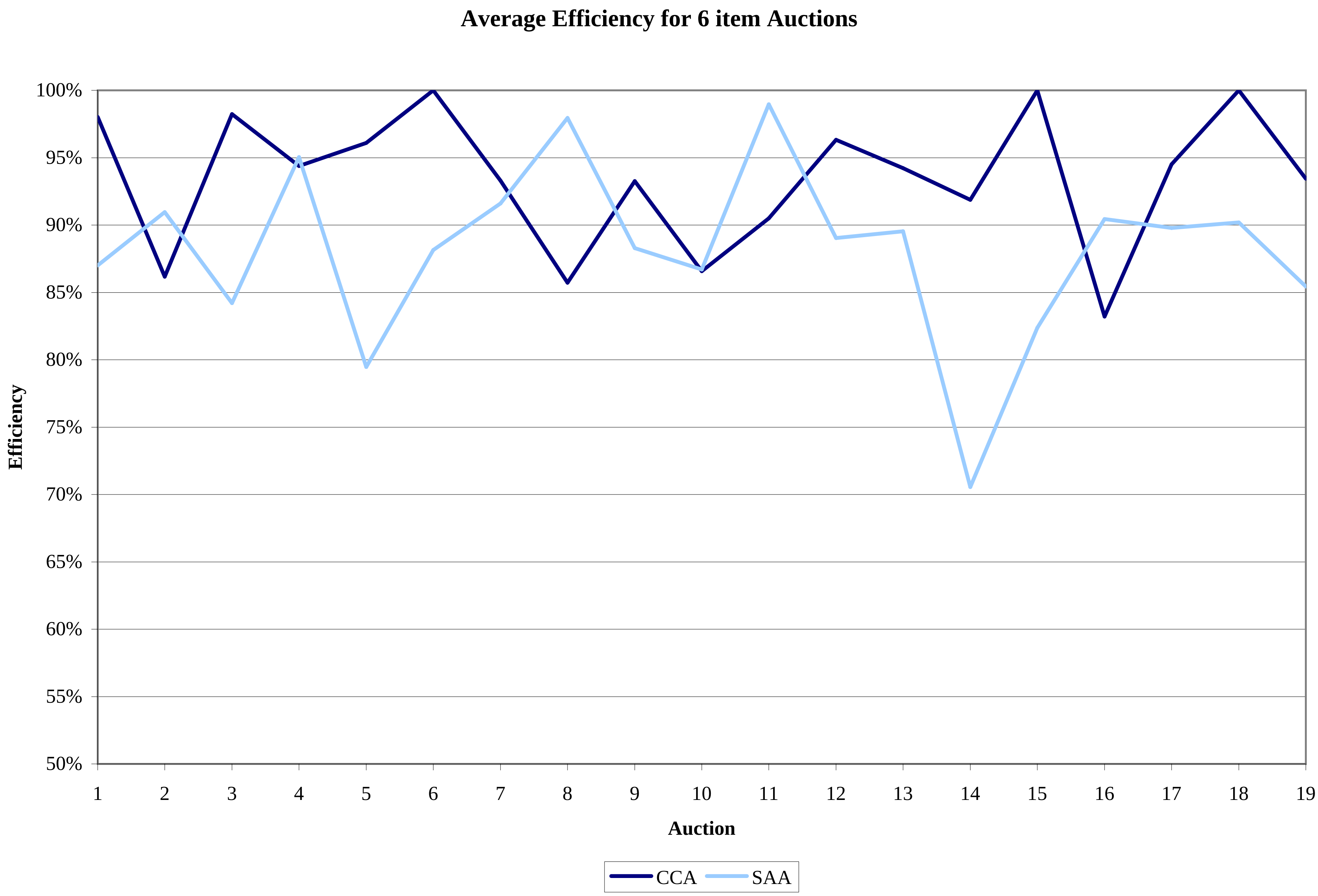
	CCA6 Auctions		SAA6 Auctions	
	Efficiency Loss[1]	Revenue Loss	Efficiency Loss[1]	Revenue Loss
Revenue Loss[2]	0.385***	----	0.092	-----
Bidder Profits[3]	-0.042	0.844***	-0.197**	0.929***
	CCA4 Auctions		SAA4 Auctions	
	Efficiency Loss[1]	Revenue Loss	Efficiency Loss[1]	Revenue Loss
Revenue Loss[2]	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	2nd Most Profitable	Overall[c]	Most Profitable	2nd Most Profitable
Rounds 1-5	22.3% (3.0)	66.5%	35.0%	37.1% (1.1)	66.5%	32.0%
Rounds 6-10	20.9% (1.5)	74.0%	21.5%	32.7% (0.7)	58.0%	23.0%
Rounds 11-15	19.8% (0.5)	68.0%	23.0%	35.7% (0.6)	61.0%	20.5%
Rounds >15	27.9% (0.2)	72.5%	10.0%	37.7% (0.4)	64.0%	17.0%
CCA 6 Auctions						
Rounds 1-5	13.1% (7.8)	62.5%	38.5%	36.3% (2.4)	68.0%	45.5%
Rounds 6-10	11.7% (4.1)	58.5%	30.0%	31.8% (1.7)	64.5%	43.0%
Rounds 11-15	12.7% (1.0)	67.0%	30.5%	34.5% (1.0)	67.5%	39.5%
Rounds >15	14.0% (0.3)	72.0%	19.0%	33.9% (0.6)	65.5%	32.5%

[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.



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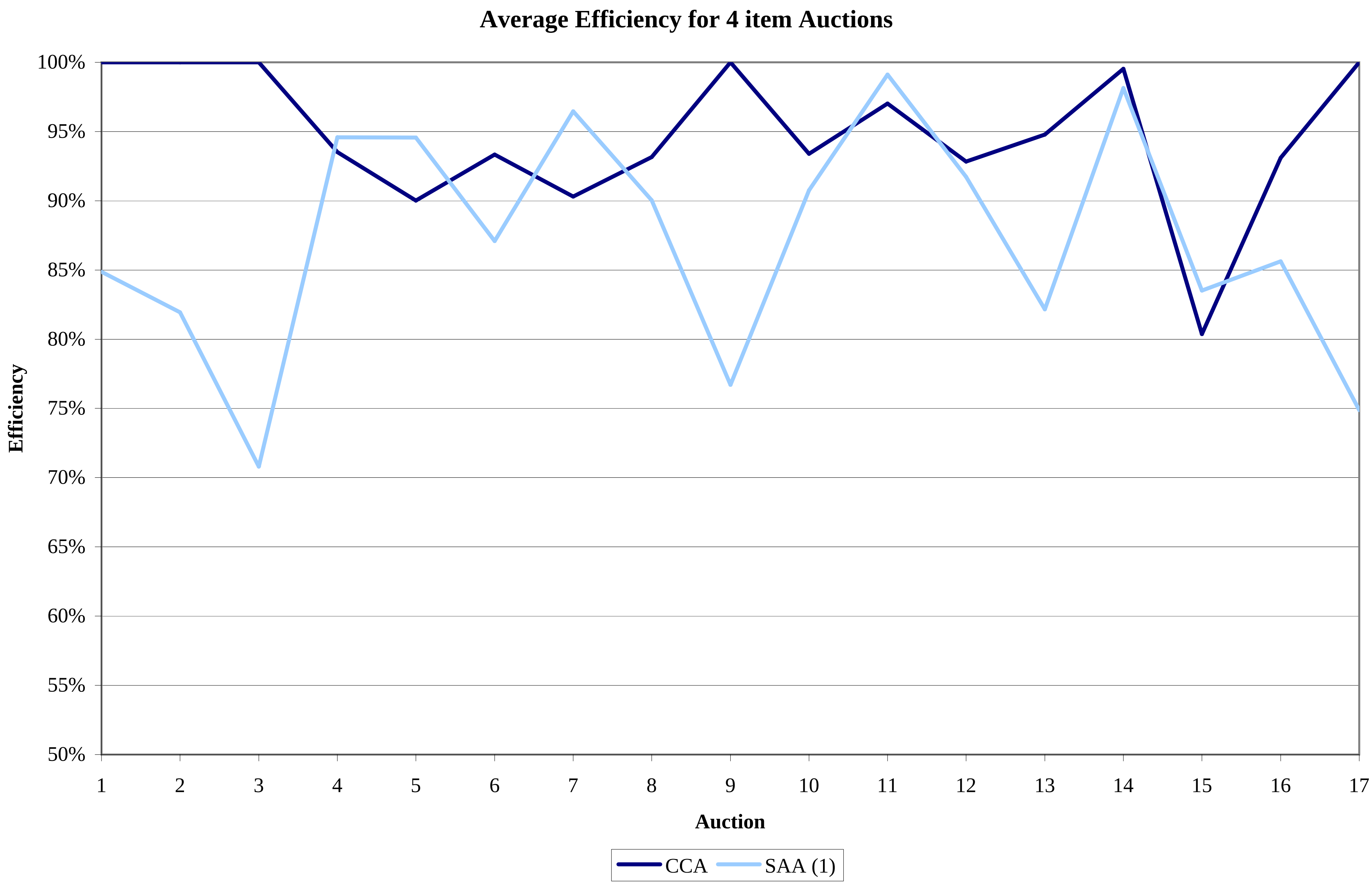
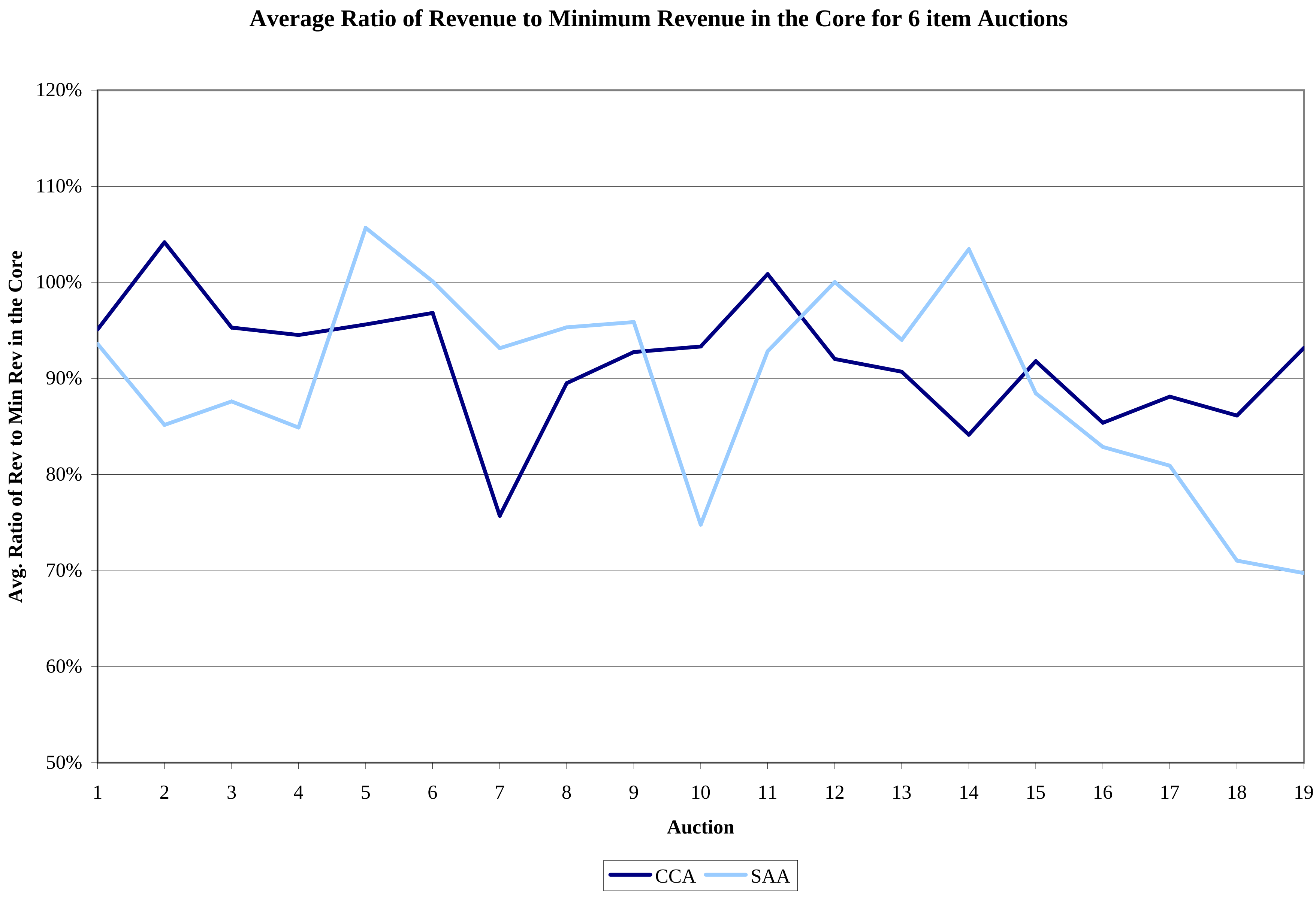


Note: Auction 7 Group 6 and Auction 13 Group 3 are excluded from the CCA calculations.



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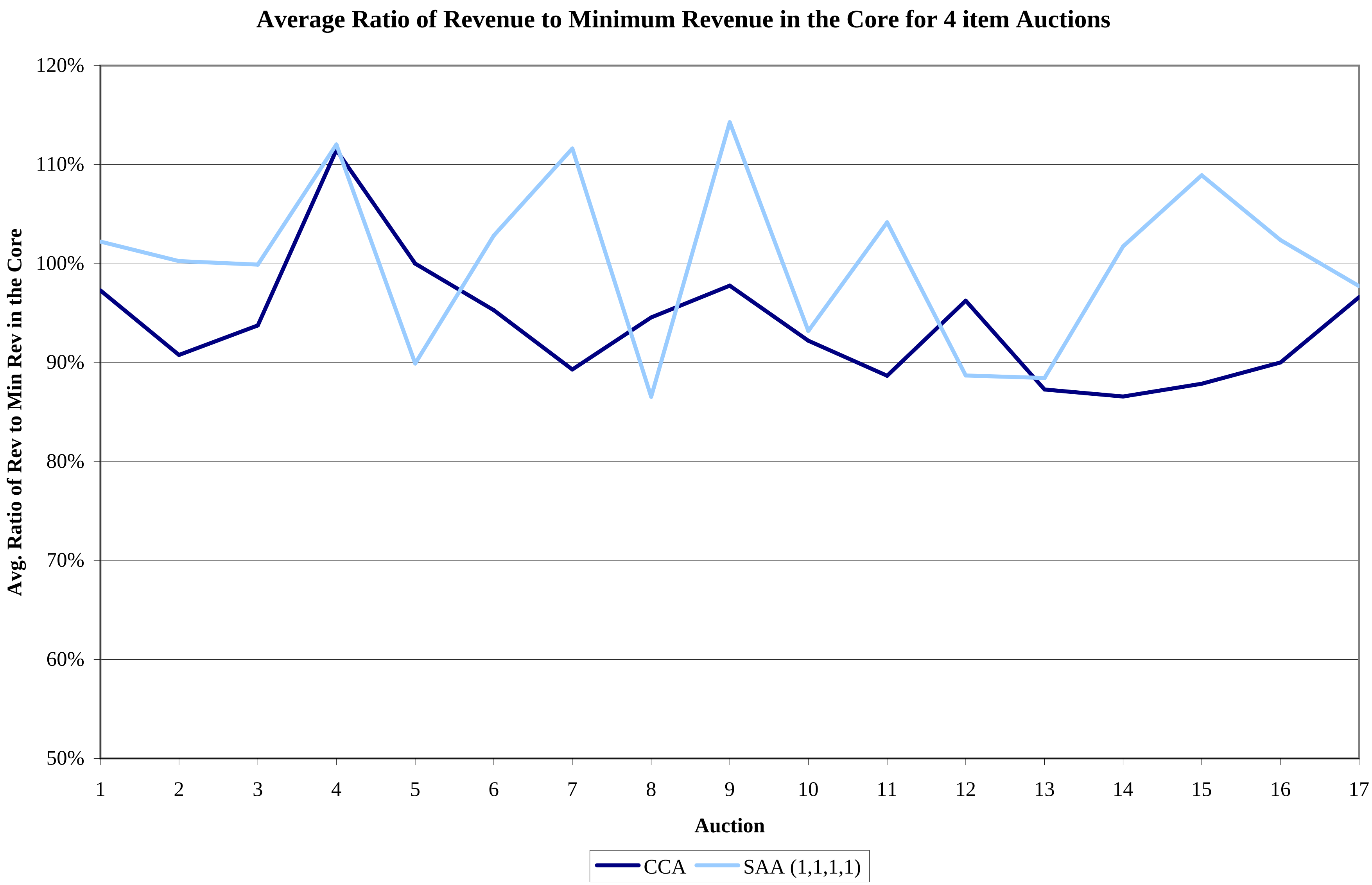

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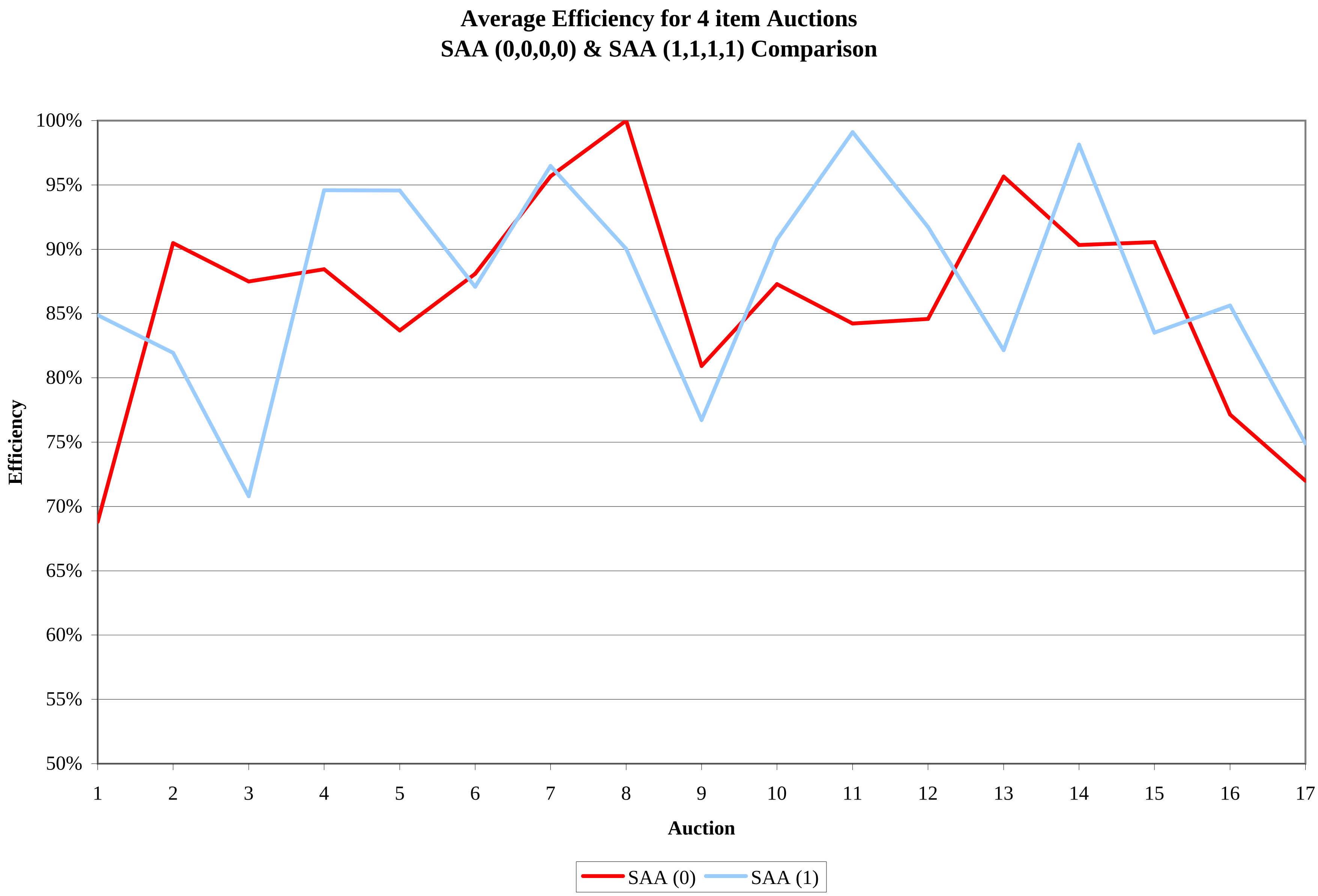

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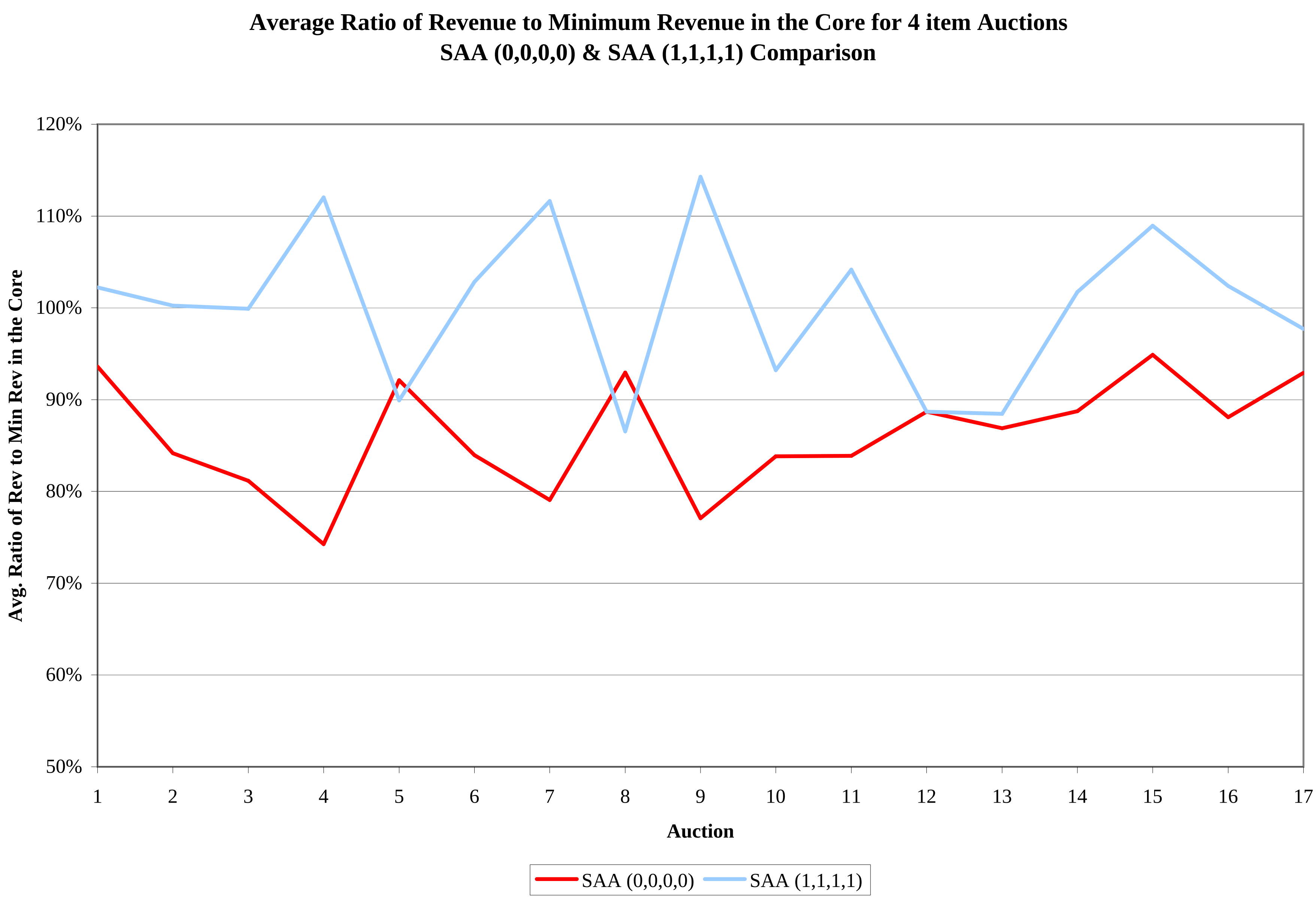

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