# Markups in Double Auction Markets

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**Abstract**

We study the continuous double auction market with simulated traders using various markup rules. A higher markup trades off increased profitability against reduced probability of a transaction. The tradeoff in Nash equilibrium turns out to be remarkably close to the most efficient tradeoff. This may partially explain the "mysterious" efficiency of double auction markets.

*Key words:* Markup; Simulations; Continuous double auction

*JEL classification:* D40; C72

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## 1. Introduction

The continuous double auction (CDA) is the premier market format. It allows traders to make public committed offers to buy and to sell, and allows traders to accept offers at any time during a trading period. Variants of CDA markets prevail in most modern financial exchanges and are featured options on B2B Internet sites. Numerous laboratory studies beginning with Smith (1962) show that CDA markets are extraordinarily efficient even though each trader has little knowledge of the circumstances of the market. Smith (1982) calls this finding a major "scientific mystery." A substantial theoretical literature has attempted to solve the mystery, but so far with limited success.

Gode and Sunder (1993) developed automated agents to probe the inner workings of the CDA. They find that even random offers to buy (bids) and to sell (asks) produce highly efficient outcomes in CDA markets. The main requirements are that traders are persistent, and the asks involve only non-negative markups over the sellers' costs and the bids involve only non-negative markdowns from the buyers' values. Gjerstad and Dickhaut (1998) and Cliff and Bruten (1997) created adaptive agents that can adjust markups (and markdowns) in response to previous transactions, and their CDA simulations come closer to approximating human behavior .

The goal of the simulations we present below is not to approximate human behavior, but rather to gain insight into how traders' profit motive influences the performance of CDA market, and thus to obtain new clues regarding Smith's mystery. The profit motive is captured in a simple but not unrealistic markup rule: each trader chooses some target profitability $m$ and uses it to determine his/her offers to buy or to sell. Thus a buyer's offer to buy (bid) is a linear function of his value, a seller's offer to sell (ask) is a linear function of her cost. The computer simulations allow us to dissect market efficiency and other market outcomes such as transaction volume, average transaction price, and price dispersion. In particular, we seek answers to two questions.

1. Do traders' markups influence the performance of a CDA market? If so, which markups produce the most efficient outcomes?

2. Under various specifications of the game played in CDA markets, what are the Nash equilibrium markups, and how do they compare to the efficient markups?

The paper is organized as follows. In Section 2 we sketch the algorithms used in our CDA simulations, and define the performance measures and the markup rules. Section 3 presents results when all traders use the same markup. We show that the efficient markups in the CDA are positive, explain why, and present results on trading volume, average price and price dispersion. Section 4 allows different traders to use different markups. Nash equilibrium markups are found in a two-cartel game and in the full game with $M$ buyers and $M$ sellers. The last section summarizes and suggests future research. An Appendix contains the flow chart of our simulation program applied Matlab software.

## 2. Specifications

The participants or *traders* in the market simulations are $M$ automated buyers and $M$ automated sellers. The baseline, called the *thick* market, is $M = 100$. Two alternatives are a *thin* market with $M = 4$, and a *medium* market with $M = 12$.

The market is open for $T > 0$ periods, e.g., $T = 1000$ in the baseline. At the beginning of each period, every buyer $i$ is privately endowed with a valuation $v_i$ independently drawn from a distribution on (0, 200). The valuation applies to a single indivisible unit of the good. Likewise, each seller $j$ is endowed with the capacity to produce a single indivisible unit of the good at a cost $c_j$ independently drawn from a distribution on [0, 200]. In the baseline, both buyers and sellers draw from the same uniform distribution.

The algorithm for the continuous double auction (CDA) market may be described briefly as follows (see the Appendix for a more detailed flow chart).

- Initially in each period all buyers and sellers are active.
- In each cycle within a period, an active buyer or seller is selected randomly. A selected buyer submits a bid according to equation (1) below. Similarly, a selected seller submits an ask according to equation (2).
- A new bid goes into the bid queue that is sorted from the highest to the lowest. A new ask goes into the ask queue that is sorted from the lowest to the highest. The *best bid* is the highest in the bid queue, and the *best ask* is the lowest in the ask queue.
- Whenever the best bid is equal to or higher than the best ask, there is an immediate transaction at a price $p$ that is equal to the best bid or the best ask, depending on which offer came first.

- A transaction removes the best buyer and the best seller from their queues, and they become inactive for the remainder of the period. The new best bid is the highest remaining in the bid queue, new best ask is the lowest remaining in the ask queue.
- Then a new cycle begins with another randomly selected buyer or seller.
- Cycles continue until no active seller will ask a price lower than any active buyer will bid. Then the period ends and market outcomes are recorded.
- Finally, outcomes are averaged over all periods.

### 2.1. Outcome variables

When a buyer $i$ transacts at price $p$, his profit (or surplus) is $v_i - p$. Likewise, when seller $j$ transacts at price $p$, her profit (or surplus) is $p - c_j$. Profit is 0 for buyers and sellers who do not transact in a given period. *Buyers' surplus* in a given period is the sum of profits earned by all buyers that period, and *sellers' surplus* is the corresponding sum of all individual seller profits. *Total surplus* is the sum of buyers' surplus and sellers' surplus. *Transaction volume* is the number of transactions in a period. In a CDA market, different transactions may have different prices. Within each period we track the mean and standard deviation of prices. We report the *average price*, the mean transaction price averaged over all periods. The standard deviation is a measure of absolute price dispersion, but we focus mainly on (relative) *price dispersion*, defined within each period as the standard deviation of price divided by the mean, i.e., the coefficient of variation, and averaged over all periods.

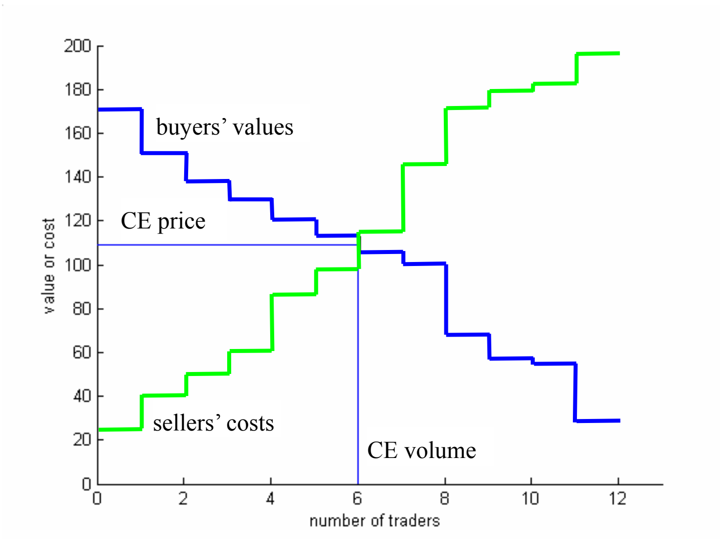


Fig. 1 Competitive Equilibrium (CE) in a market with $M$=12 buyers and sellers

Efficiency is the key performance variable. It is defined as the total surplus as a percentage of the maximum feasible surplus, given the specific cost and value realizations that period. Figure 1 illustrates the computation. The realized buyer values are sorted from highest to lowest and graphed as a stair-step demand curve, and the realized seller costs are sorted from lowest to highest and graphed as a supply curve. Their intersection defines the competitive equilibrium (CE) price and trading volume.[1] Since realized buyer values and seller costs are drawn randomly at the beginning of each period, the CE price is usually different each period and the CE volume often also differs. Each period we record the ratio of transaction volume to CE volume and the

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[1] With stairstep supply and demand curves, there can be a range of CE prices when the curves intersect on a vertical segment. Alternatively, when the intersection is on a horizontal segment, there can be a range of CE volumes.

ratio of average price to CE price, and we report the T-period averages.

In Figure 1, CE volume is 6 and CE prices lie in the interval [105.2, 112.6]. As explained in every Principles of Economics text, the total surplus (buyers' surplus plus sellers' surplus) is maximized in CE and is represented by the area between the demand and supply curves to the left of their intersection. CE total surplus is 465.0 in Figure 1. If the realized total surplus were 429.5 in a particular period, then efficiency would be (429.5/465.0)$\times$100% ≈ 92.4%. If the realized transaction volume were 5 that period, then the ratio of transaction volume to CE volume would be 5/6 ≈ 0.833. If the realized average price were 104.9 that period, then the ratio of average price to CE price would be (104.9/((105.2+112.6)/2)) ≈ 0.963.

### 2.2. Markup rules

The baseline trader algorithms (or the standard markup) use a specific value $m \in [0,1]$ that determines bids $b_i$ and asks $a_j$ according to the formulas:

$$b_i = v_i \times (1-m) \text{, and} \tag{1}$$

$$a_j = c_j \times (1+m) . \tag{2}$$

For example, if $m = 0.3$, then each buyer bids 30% below his own value and each seller asks 30% above her own cost. Thus, to the extent that $m > 0$, traders underreveal their true willingness to transact, in order to improve the profitability of their transactions.

These linear bid and ask functions (or constant markups) can be justified by noting that most complicated (and all non-monotone) functions are dominated. As noted in Cason and

Friedman (1999), linear functions are very close approximations to Bayesian Nash equilibrium behavior in related games, and constant markups are simple and attractive heuristics for humans that are quite common in practice.

Figure 2 illustrates the impact of markups. The solid lines show true demand and supply in a very thick market, and the corresponding dashed lines show the demand and supply revealed in bids and asks generated by equations (1)-(2) when $m$ = 0.3. In a Call Market (CM), the bids and asks of all traders are gathered at the same time and cleared at a uniform price that matches supply and demand. Point M indicates the resulting price and transaction volume.

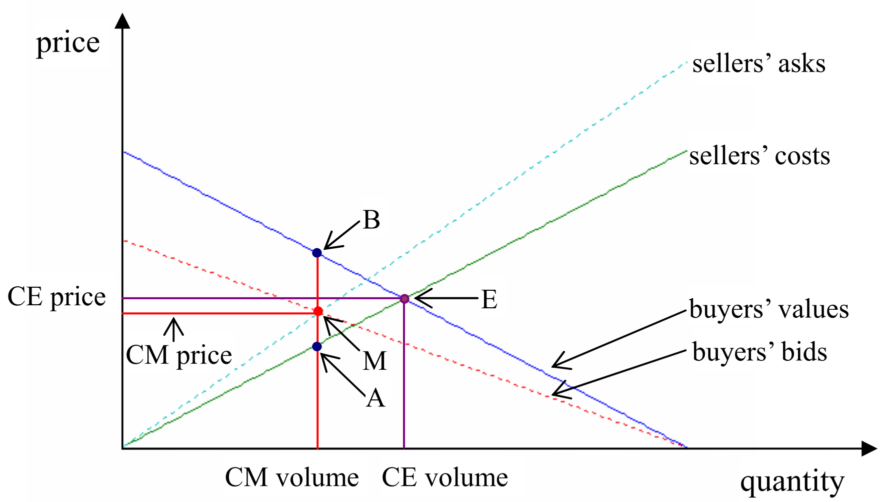


Fig.2 True and revealed demand and supply when $m$ = 0.3

Clearly the realized surplus (the trapezoidal area between true demand and supply to the left of line segment AB) is less than maximal due to the so-called deadweight loss triangle (△EAB). Indeed, as shown in Figure 3, efficiency in the CM declines to 0 as $m$ increases to 1. Sellers' surplus (defined as a fraction of CE sellers' surplus) declines smoothly but buyers' surplus increases slightly at first.

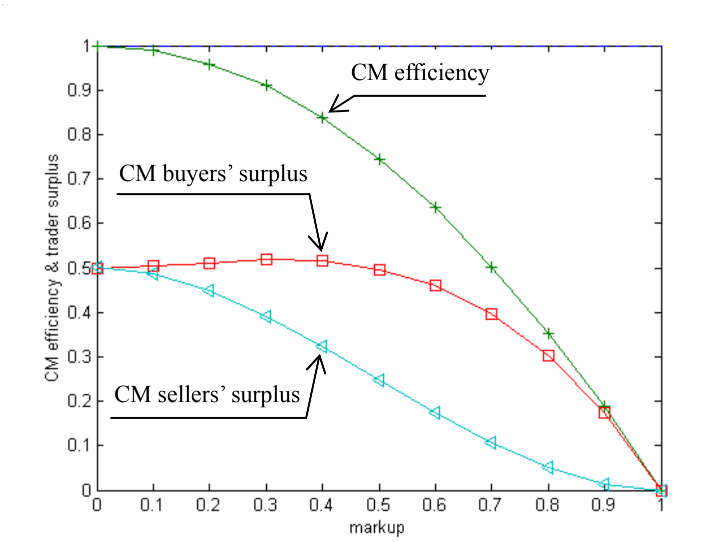


Fig.3. Call market (CM) efficiency and surplus

The reason for this "buyer bias" asymmetry can be seen in Figure 2 and equations (1)-(2). When $m$ is near 1, then all bids are near 0, while asks are evenly spread between 0 and 400. Since transaction prices can't exceed the highest bid, the prices are quite low. Hence the transactions that do occur are much more profitable for buyers than sellers.

The asymmetry led us to consider two alternative markup specifications: exponential and shift. Exponential markups replace the factors $1\pm m$ in (1)-(2) by $\exp(\pm m)$. This sort of markup is used in Cason and Friedman (1999) and it implies that even at $m=1$ the bids are about 37% of true value, not 0%, while asks are about 270% of true cost, not 200%. We also considered shift markups, in which $b_i = v_i - 100 \times m$ (truncated below at $b_i = 0$) and $a_j = c_j + 100 \times m$. We will note when these alternatives produce qualitatively different results from the baseline specification (1)-(2).

## 3. Results with Uniform Markups

Recall that efficiency is maximized in the call market (CM) at $m$=0, where buyers and sellers fully reveal true values and costs and competitive equilibrium (CE) is achieved. One might think that the same would be true in the Continuous Double Auction (CDA) market, but Figure 4 shows otherwise. As $m$ increases from 0 to 0.3, efficiency increases! The Figure shows that sellers' surplus as well as buyers' surplus increases at first. Of course, as $m$ increases further, eventually transaction volume dries up and efficiency declines.

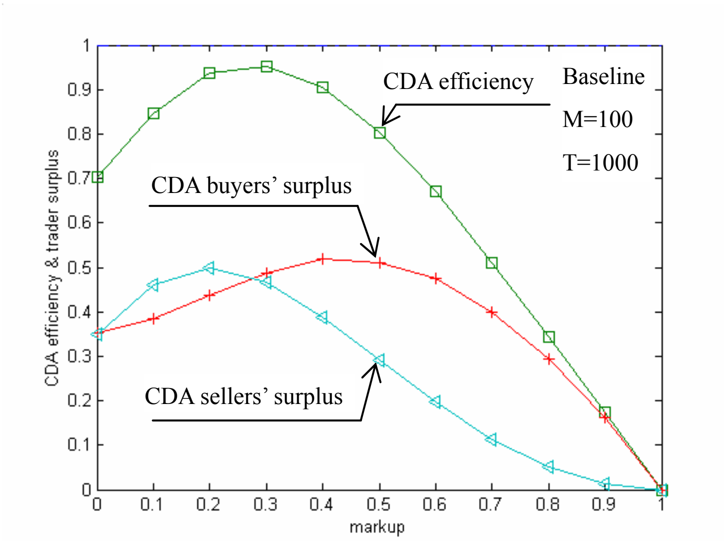


Fig.4. Continuous Double Auction (CDA) market efficiency and surplus

Figure 5 helps explain what is going on. Traders who transact in CE (viz, buyers with values $v_i$ above the CE price $p^*$ and sellers with cost $c_j$ below $p^*$) are called intermarginal (IM); the other traders are called extramarginal (EM). In CE, by definition, all transactions are between IM buyers and IM sellers. When an IM buyer or seller fails to transact, there is a loss of total surplus equal to that trader's CE profit, viz, $v_i - p^* > 0$ for an IM buyer ($T_4$ in Fig.5), and $p^* - c_j > 0$ for an IM seller ($T_5$ in Fig.5). The sum of such losses is called *V-inefficiency* (VI). Formally,

$$VI = \{ \sum_{i \in IMBN} (v_i - p^*) + \sum_{j \in IMSN} (p^* - c_j) \} / CETS \ , \tag{3}$$

where IMBN is the set of intermarginal buyers who do not trade, IMSN is the set of intermarginal sellers who do not trade, and CETS is the CE total surplus. All losses in the Call Market with $m > 0$ are of this sort.

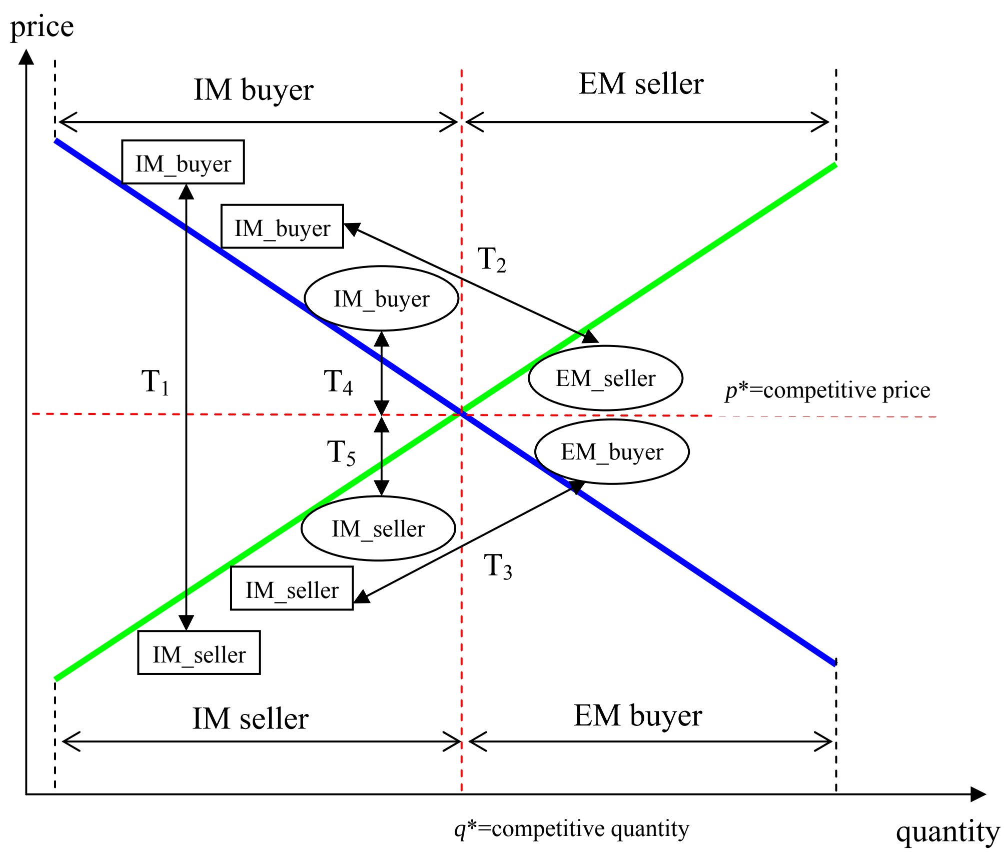


Fig.5 Schematic diagram for inefficient transactions in the CDA

But another sort of loss is possible in the CDA: an EM trader may transact, creating an overall loss equal to her (negative) profit at CE price $p^*$. For example, when EM buyer $i$ trades with an IM seller ($T_3$ in Fig.5), there is a loss of total surplus equal to $p^* - v_i > 0$. Likewise, when EM seller $j$ trades with an IM buyer ($T_2$ in Fig.5), the total surplus decreases by $c_j - p^* > 0$. The sum of such losses in a market period is called the *EM-inefficiency* (EMI). Thus

$$EMI = \{ \sum_{i \in EMBT} (p^* - v_i) + \sum_{j \in EMST} (c_j - p^*) \} / CETS , \tag{4}$$

where EMBT is the set of extramarginal buyers who trade, and EMST is the set of extramarginal sellers who trade. Unwinding the definitions, one can verify that

$$\text{CDA efficiency} = 1 - EMI - VI . \tag{5}$$

That is, the realized CDA surplus plus the losses due to EMI and VI sum to the CE total surplus.[2]

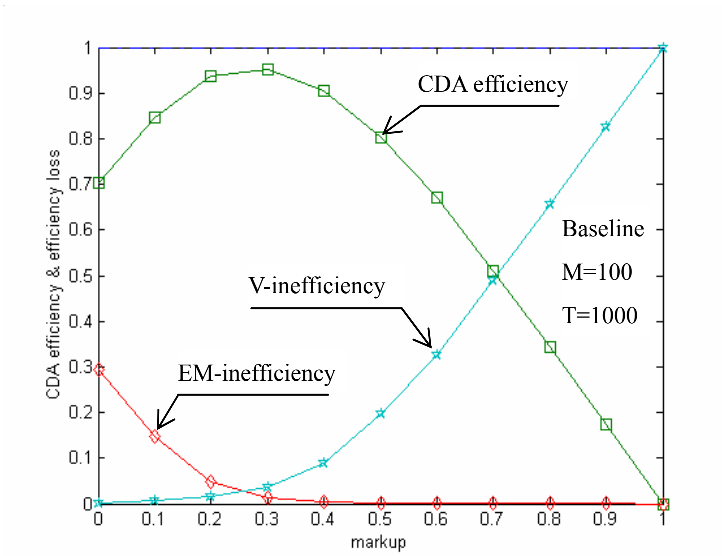


Fig.6 Efficiency loss in CDA market

Figure 6 shows that EM-inefficiency is maximized at $m = 0$ in a thick CDA market. It

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[2] Two slightly different conventions for decomposing efficiency losses can be found in Rust et al. (1993) and Cason and Friedman (1996).

decreases fairly quickly towards 0 as *m* increases. For the same reasons as in the CM market, V-inefficiency rises at an increasing rate in *m*: with larger markups, fewer bids fall below asks and transaction volume goes to zero as *m* increases to 1. The Figure shows that the sum of EM- and V-inefficiency is minimized at $m$ = 0.3, so by (5) efficiency is maximized at that point.

Fig.7 bolters this explanation by dissecting transaction volume. Normalizing CE volume to 1.0, the Figure shows that CM volume (which automatically excludes EM traders) declines steadily as markup *m* increases. CDA volume also decreases, but starts out substantially higher.

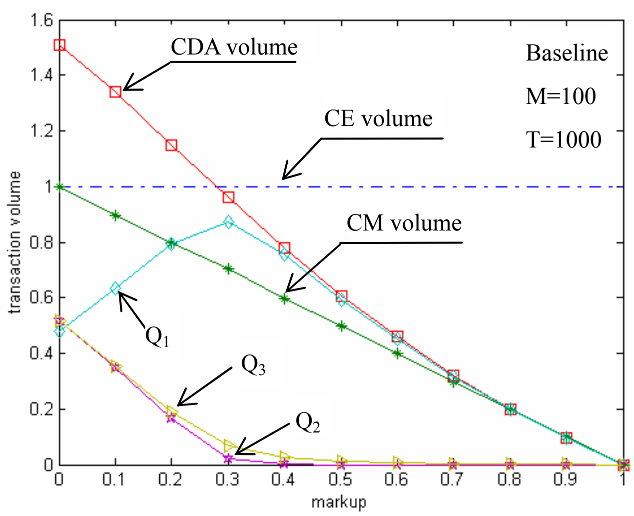


Fig.7 Effect of markup on transaction volume

Figure 7 decomposes transaction volume into three components,

$$\text{CDA volume} = Q_1 + Q_2 + Q_3 \,, \tag{6}$$

where $Q_1$ = the normalized number of transactions between IM buyers and IM sellers, $Q_2$ = the normalized number of IM buyers trading with EM sellers, and $Q_3$ = the normalized number of EM buyers trading with IM sellers. As markup *m* increases, the efficiency-enhancing volume $Q_1$ increases at first and then follows the CDA volume, while the efficiency-impairing trades ($Q_2$ +

$Q_3$) decrease quickly.

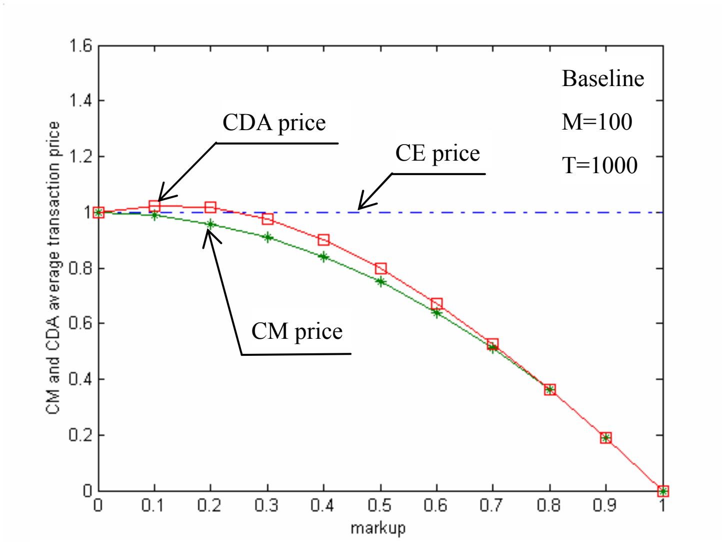


Fig. 8. Effect of markup on average transaction price

Fig. 8 examines average transaction price, normalizing CE price to 1. The (uniform) CM price decreases gradually from 1 to 0 due to the buyer bias described earlier. The CDA average transaction price increases slightly at first, and then decreases gradually with $m \in [0.1, 1]$. Thus the CDA slightly attenuates the buyer bias overall, and reverses it slightly for small markups.

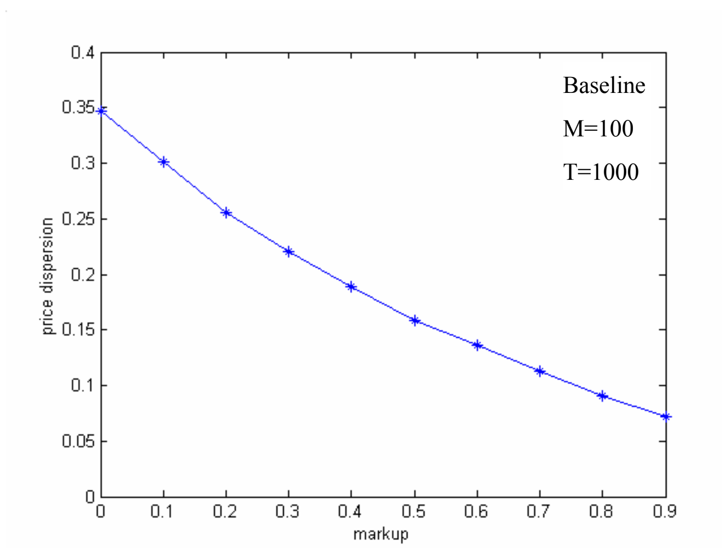


Fig.9. Effect of markup on price dispersion

Finally, Figure 9 shows that as markup $m$ increases, the standard deviation of CDA price decreases even faster than the average transaction price, resulting in decreasing price dispersion.

The results are fairly robust to variations from the baseline simulation. Efficiency is maximized in a thin CDA market ($M$ = 4) at $m$ = 0.1, and in a medium market ($M$ = 12) at $m$ = 0.2. Efficiency is maximized with exponential markups and with shift markups at the same values of $m$ as in standard markups for all three markets (thick, medium and thin). The buyer bias disappears with shift markups but is only slightly attenuated with exponential markups.

## 4. Results with Heterogeneous Markups

### 4.1 Two cartel game

As a preliminary exercise, suppose that $m=m_b$ for all buyers $i$ in equation (1) while $m=m_s$ all sellers $j$ in equation (2). A fanciful interpretation is that all buyers belong to a cartel, and all sellers belong to a second cartel, and the members of each cartel agree on a common markup. Formally, the first player B chooses $m_b$ from the set {0.0, 0.1, 0.2, … , 0.9, 1.0} and the second player S simultaneously chooses $m_s$ from the same set. The payoffs are respectively buyers' surplus and sellers' surplus, computed numerically by averaging across periods.

Does this two-player game have a Nash equilibrium in pure strategies? Figure 10 shows that it is a dominant strategy in the baseline market for the buyer cartel to set $m_b$ = 0.5, because that maximizes profit in a CDA market for each seller cartel choice $m_s$ in [0, 1].

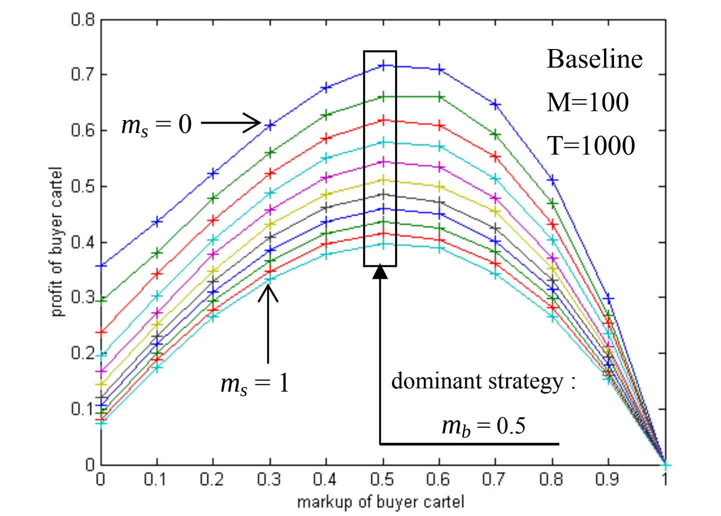


Fig 10 Dominant strategy for the buyer's cartel

In turn, Fig.11, shows that the best response for the seller cartel to the buyer cartel's dominant strategy is $m_s = 0.5$. As a result, we conclude that the unique Nash equilibrium for the baseline two-player game is ($m_b = 0.5$, $m_s = 0.5$). The two-player game is competitive in the sense that larger $m_s$ reduces B's payoff at each at each $m_b$, and larger $m_b$ reduces S's payoff at each $m_s$.

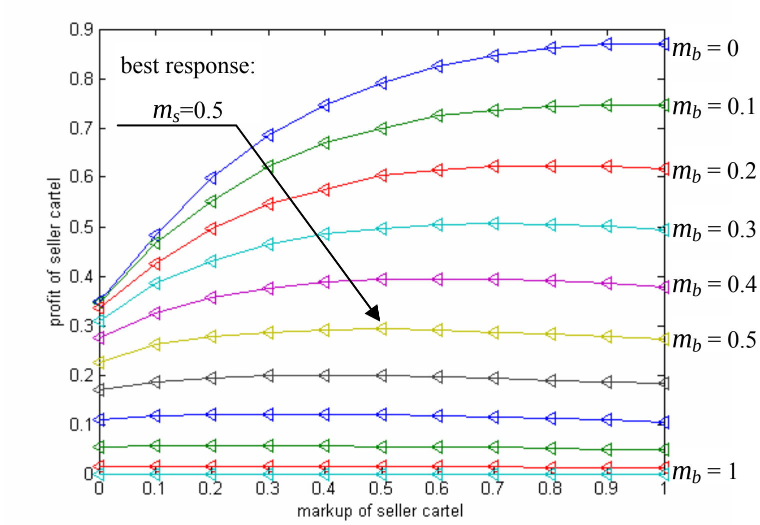


Fig 11. Best response for the seller's cartel

The same game can be played in the medium market ($M$ = 12) and has the same unique Nash equilibrium ($m_b$ = 0.5, $m_s$ = 0.5). In the thin market ($M$ = 4), the Nash equilibrium moves down to ($m_b$ = 0.4, $m_s$ = 0.4). With exponential markups, the Nash equilibrium markup of this two-cartel game is ($m_b$ = 0.7, $m_s$ =0.4) in a thick ($M$ = 100) market, ($m_b$ = 0.6, $m_s$ =0.4) in a medium market, and ($m_b$ = 0.5, $m_s$ =0.3) in a thin market. With shift markups, the Nash equilibria become ($m_b$ = 0.6, $m_s$ =0.6) in a thick market, ($m_b$ = 0.5, $m_s$ =0.5) in a medium market, and ($m_b$ = 0.4, $m_s$ =0.4) in a thin market.

### 4.2 The 2*M* - CDA Game

The more relevant game in an auction market allows each of the $M$ buyers and each of the $M$ sellers to simultaneously choose her own markup from the same set {0.0, 0.1, 0.2, … , 0.9, 1.0}. In a symmetric Nash equilibrium in pure strategies, each buyer chooses the same $m_b$ and each seller chooses the same $m_s$. Do such equilibria exist?

To find out, we numerically compute the payoffs to a "deviator" buyer who tries all possible markups, while all the other buyers (the "regular buyers") use a common markup $m_b$ and all sellers use a common markup $m_s$. The deviator's profit depends sensitively on his value $v_i$. Numerical explorations confirm that averaging profit over the distribution of values (uniform over [0, 200]) can be closely approximated by a simple average of profit for values {180, 160, 140, …, 20}. Similarly, we compute the payoffs to a "deviator" seller who tries all possible markups, while all the other sellers (the "regular sellers") use a common markup $m_s$ and all buyers use a common markup $m_b$ by averaging realized profit over costs {20, 40, 60, …, 180}.

Figure 12 shows the results for a thick ($M$ = 100) CDA market averaged over 1000 periods when $m_s$ = 0.3. Note that when the regular buyers' margin is $m_b$ = 0.3, the deviator buyer's best response is also $m$ = 0.3.

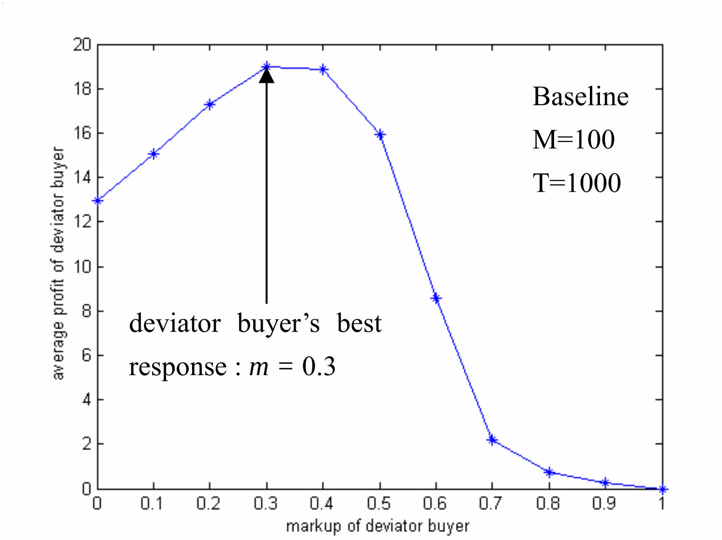


Fig.12 Deviator buyer's average profit with $m_b = m_s = 0.3$

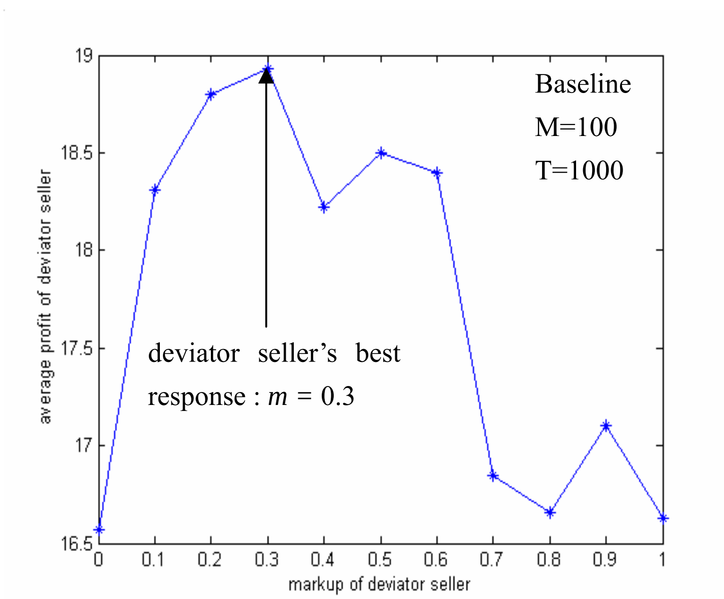


Fig.13 Deviator seller's average profit with $m_s = m_b$ =0.3

Figure 13 shows the deviator seller's average profit with different markup when regular sellers' markups and all the buyers' markups are 0.3. The best response for the deviator seller is also $m = 0.3$. Consequently, the symmetric Nash equilibrium for the 2*M*-player game is ($m_b = 0.3$, $m_s = 0.3$). Remarkably, this is also the most efficient markup choice in the baseline simulation, as seen in Section 3.

The Nash equilibrium markup of the 2*M*-player game turns out to be ($m_b = 0.3$, $m_s = 0.3$) both in medium and in thin markets with all three markup rules (baseline, exponential and shift). But in a thick CDA market with an exponential markup, the epsilon Nash equilibrium markup is ($m_b = 0.4$, $m_s = 0.3$).[3] In a thick CDA market with a shift markup, the Nash equilibrium markup is ($m_b = 0.4$, $m_s = 0.4$).

Table 1 summarizes market efficiency for differently chosen markups in all nine specifications. In thick and medium markets, the Nash equilibrium markups of 2*M*-player game deliver efficiency amazingly close to that of maximally efficient markups. The efficiency shortfall is less than 2.5% in all six cases. By contrast, Nash equilibrium in the 2-cartel game suffers efficiency shortfalls of about 15-20%, and full revelation ($m = 0$) in these CDA markets produces an efficiency shortfall of about 20-25%. In thin markets, the efficiency shortfalls of the

[3] In this case, the seller deviator earns 17.6, 18.0, 17.7, 17.7, and 16.2 respectively for $m_s = 0.1, 0.2, 0.3, 0.4$, and 0.5, while $m_b = 0.4$ is the best response for the buyer deviator. Hence $m_s = 0.3$ is part of an epsilon NE for epsilon = (18.0 – 17.7) = 0.3.

2$M$-player game widen somewhat, but still remain well below that of the 2-cartel game.

Table 1 Summary of Market Efficiency

| | | CM | CDA | | | |
|---|---|---|---|---|---|---|
| density | markup | $m = 0$ | $m = 0$ | $m$ = NE (2-cartel) | $m$ = NE (2$M$-player) | $m$ = most efficient |
| thick | baseline | 100% | 70.3% | 80.4% | 95.2% | 95.2% |
| | exponential | 100% | 70.3% | 80.5% | 94.2% | 95.4% |
| | shift | 100% | 70.5% | 77.6% | 94.8% | 96.2% |
| medium | baseline | 100% | 76.7% | 71.4% | 88.5% | 90.7% |
| | exponential | 100% | 76.3% | 75.4% | 88.7% | 90.7% |
| | shift | 100% | 76.9% | 78.6% | 92.3% | 92.3% |
| thin | baseline | 100% | 82.0% | 66.2% | 75.5% | 86.7% |
| | exponential | 100% | 82.0% | 68.1% | 76.7% | 86.5% |
| | shift | 100% | 82.3% | 69.2% | 79.3% | 87.8% |

In simulations not reported here, we also checked efficient and Nash equilibrium markups when the buyer values and seller costs were drawn from non-uniform distributions. With buyer values and seller costs drawn from the same truncated normal distributions centered at 100, the markups (both efficient and Nash equilibrium) tend to be smaller than those reported above. When the buyer distribution had a much larger mean than the seller distribution, the markups tended to be closer to those just analyzed. Efficiency at Nash equilibrium of the 2$M$-player game remains close to the CDA maximum.

## 5. Discussion

Our simulations of Continuous Double Auction (CDA) markets lead to the following main conclusions.

1. As markup increases, EM-inefficiency (due to transactions involving extramarginal traders) decreases while V-inefficiency (due to missing intermarginal trades) increases. Their sum is minimized, and hence efficiency is maximized, at a 30% markup in thick markets with $M$ = 100 buyers and 100 sellers. In medium ($M$ = 12) markets, efficiencies are maximized at the 20% markup, while in thin ($M$ = 4) markets, the efficiencies are maximized at the 10% markup, and decline slowly as $m$ increases slightly. These results hold when all traders use the same value of $m$ under each of the three markup rules.

2. The symmetric pure strategy Nash equilibrium markup of the 2$M$-player game is at or near 30% for buyers and for sellers in thick, medium, and thin markets with all three markup rules. Consequently there is very little shortfall from maximal CDA efficiency.

All simulation evidence to date points to the same general conclusion: efficiency at Nash equilibrium in the markup games is surprisingly close to maximal. A possible interpretation is that the continuous double auction (CDA) market format is so efficient for a subtle reason. In increasing the markup, traders face a tradeoff between greed (larger profit if there is a transaction) and fear (a greater probability of failing to transact). This tradeoff in Nash equilibrium seems to parallel the tradeoff between EM-inefficiency and V-inefficiency in the CDA. Of course, the parallel fails in the call market (CM) and perhaps in other market formats.

In the baseline simulation as well as in the variants considered in this paper, each trader had to choose a markup that applied to any possible value or cost. That is, the trader has to commit to the markup before learning his value or cost that period. In future work, it might be worth considering nonlinear bid and ask functions, i.e., the markup is contingent on the realized value or cost. Indeed, the results of Friedman and Ostroy (1995) suggest that traders will prefer to have markup be an increasing function of value in CH as well as in CDA markets. It will be interesting to see whether Nash equilibrium behavior in this richer setting still leads to efficiency.

## Appendix. Flow chart for the continuous double auction market

[Insert Fig. A1 here]

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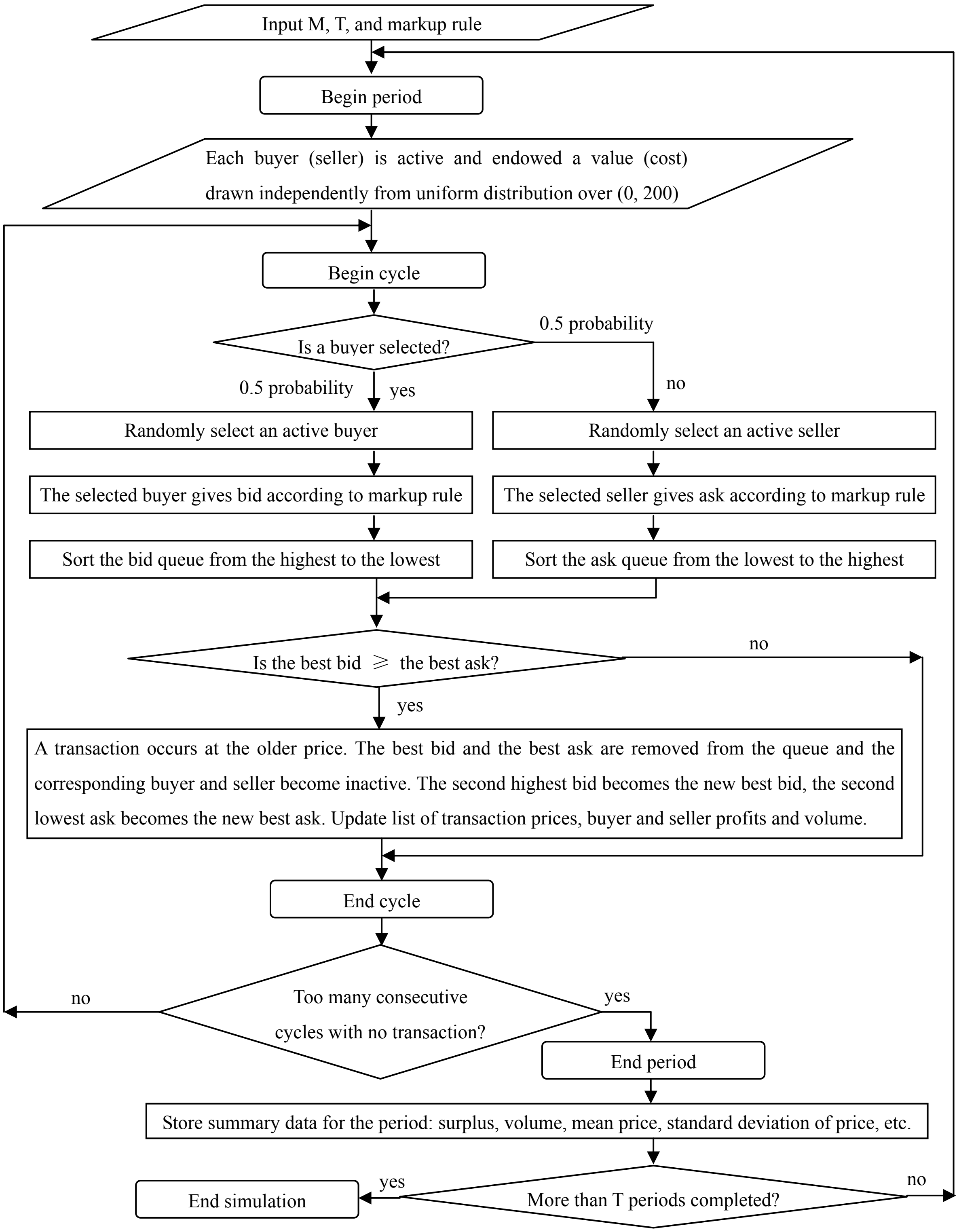


Fig. A1 Flow chart for the continuous double auction market