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**Tracking the Invisible Hand: Convergence
of Double Auctions to Competitive
Equilibrium***

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Abstract

Economics is the science of want and scarcity. We show that want and scarcity, operating within a simple exchange institution (double auction), are sufficient for an economy consisting of multiple inter-related markets to attain competitive equilibrium (CE). We generalize Gode and Sunder's (1993a, 1993b) findings for a simple market to multi-market economies, and explore the role of the scarcity condition in convergence of economies to CE. When the scarcity condition is gradually weakened by allowing arbitrageurs in multiple markets to enter speculative trades, prices still converge to CE, but allocative efficiency of the economy drops.

Optimization by individual agents, often used to derive competitive equilibria, are unnecessary for an actual economy to approximately attain such equilibria. From the failure of humans to optimize in complex tasks, one need not conclude that the equilibria derived from the competitive model are descriptively irrelevant. We show that even in complex economic systems, such equilibria can be attained under a range of surprisingly weak assumptions about agent behavior.

Tracking the Invisible Hand: Convergence of Double Auctions to Competitive Equilibrium

1. INTRODUCTION

Economics is the science of want and scarcity. We show that want and scarcity, operating within a simple exchange institution (double auction), are sufficient for an economy consisting of multiple inter-related markets to attain competitive equilibrium (CE). Gode and Sunder (1993a, 1993b) reported similar findings for a single market. We use multi-market economies to generalize their results and to explore the role of the scarcity condition in convergence of economies to CE. In a second set of detailed experiments, scarcity condition is gradually weakened by allowing arbitrageurs in multiple markets to enter speculative trades. With relaxation of scarcity condition, prices still converge to CE, but allocative efficiency of the economy drops.

Double auction is often used to organize stock and commodity markets. The idea of want is implemented in our experimental economies by the willingness of agents to exchange what they have for more. The idea of scarcity is implemented by restricting their actions to the set defined by the resources. Within the opportunity set defined by these two constraints, individual agents behave randomly. There is no memory, learning, optimization, evolution, or selection of individuals over time. Rules of the double auction mechanism, in conjunction with individual actions, yield the market outcomes. The following experiments are designed to explore whether and how the constraint of opportunity sets of agents can transmit derived demand and supply functions across markets, and how well CE predicts the prices and allocations in such economies.

2. MARKETS

As shown in Figure 1, there are m markets labelled 1 through m . In the first market, a number of buyers with exogenously specified demand functions (see below) can buy goods. In the last, m^{th} , market, a number of sellers with

exogenously specified supply functions (specified later) can sell goods. The first and the last markets are linked through $(m-1)$ mutually exclusive sets of arbitrageurs (see below) who can sell in market i and buy in the adjacent market $(i+1)$, $i = 1, 2, \dots, (m-1)$.

Insert Figure 1 here

All markets are double auctions. Any buyer can submit a bid (to buy) a single unit of the good at any time in one market in which it is assigned to the buyer role. For a bid to be valid, two conditions must be fulfilled. First, the bid must exceed any existing bid that may be present in that market. Second, the originator of the bid must have the ability to settle the transaction at that bid, if it were to take place at that price. In other words, the proposed transaction must be in the opportunity set of the trader. Similarly, any seller can submit an ask (to sell) a single unit of the good at any time. Again, for an ask to be valid in a market, two analogous conditions must be fulfilled: the ask be lower than any existing ask in that market, and the proposed transaction should not lie outside the opportunity set of the trader who makes the offer.

A higher bid becomes the current bid and a lower ask becomes the current ask in the market. Current bid and ask are the only ones standing in the market at any time; all superseded bids and asks are canceled, i.e., there is no queue. If the current bid and the current ask cross at any time, a transaction is immediately executed. The transaction is recorded at the mean of the crossing bid and ask.

The markets are open for a specified period of time. In case of a single machine simulation each market is open for a specified number of cycles. Time, or the number of cycles, is chosen so doubling it does not result in any additional transactions. In each cycle, one of the $(m+1)$ groups (buyers, sellers, or $m-1$ sets of arbitrageurs) is picked randomly, with equal probability, and then one of the traders within that group is picked randomly, again with equal probability. If the trader is a buyer (seller), a bid (ask) is solicited. If the trader is an arbitrageur, *both* a bid and an ask are solicited.

Exogenous Buyers

There are a total n buyers in Market 1, each with the right to buy one unit. Redemption value of the i^{th} buyer is v_i , and without loss of generality, we shall assume that the buyers have been indexed so that $v_i > v_{i+1}$, $i = 1, 2, (n-1)$. Collectively, v constitutes the market demand function in market 1. The right to buy a single unit restricts the opportunity set of each buyer to a single purchase

transaction; redemption values limit the opportunity set of buyer i to transactions at or below price v_i .

We implement the idea of opportunity set-constrained zero-intelligence buyer as follows: until buyer i is able to buy this unit, it generates a uniformly and independently distributed random number in the range $(0, v_i)$ every time it has an opportunity to submit a bid. Alternatively, the idea can be implemented by letting each buyer generate a uniformly and independently distributed random number in the range $(0, M)$, M being some arbitrary upper limit, and allowing the market to reject those bids that fall beyond the ability of the buyer to settle the transaction (i.e., greater than v_i). As soon as the buyer exhausts its right to buy a single unit by entering in a transaction, it stops making further proposals. This constraint, too, can be implemented at either the individual level or at the market level by letting the market reject proposals that fall outside the opportunity sets of their originators.

Exogenous Sellers

Sellers are defined analogously to buyers. There are a total of n sellers, each with the right to sell one unit. Cost of the i^{th} seller is c_i , and without loss of generality, we shall assume that the sellers have been indexed so that $c_i > c_{i+1}$, $i = 1, 2, \dots, (n-1)$. Collectively, c constitutes the market supply function in the m^{th} market. The right to sell a single unit restricts the opportunity set of each seller to a single sale transaction; costs limit the opportunity set of seller i to transactions at or above price c_i .

We implement the idea of opportunity set-constrained zero-intelligence seller as follows: until seller i is able to sell this unit, it generates a uniformly and independently distributed random number in the range (c_i, M) , M being an arbitrary upper limit, every time it has an opportunity to submit an ask. Alternatively, the idea can be implemented by letting each seller generate a uniformly and independently distributed random number in the range $(0, M)$, and allowing the market to reject those asks that fall beyond the ability of the seller to settle (i.e., less than c_i). As soon as the seller exhausts its right to sell a single unit by entering in a transaction, it stops making further proposals. This constraint, too, can be implemented at either the individual level or at the market level by letting the market reject proposals that fall outside the opportunity sets of their originators.

Arbitrageurs

Figure 1 shows the configuration of markets, exogenous buyers, exogenous sellers and arbitrageurs. There are $(m-1)$ sets of arbitrageurs, each includes a

traders. The first set sells to the exogenous buyers in market 1, and buys from the second set of arbitrageurs in market 2. The second set buys in market 3 from the third set of arbitrageurs, and sells in market 2 to the first set of arbitrageurs, and so on, until the $(m-1)^{\text{th}}$ set of arbitrageurs buys from the exogenous sellers in the m^{th} market and sell to the $(m-1)^{\text{th}}$ set of arbitrageurs in market $(m-1)$. Each arbitrageur is permitted to engage in an unlimited number of purchase and sale transactions within the constraints of its opportunity set.

The opportunity set constraints on the arbitrageurs must be placed to subject them to a market discipline similar to that imposed on the buyers and the sellers. This constraint can be defined in terms of money or units of goods. For now, we choose to impose an opportunity set constraint on all arbitrageurs by requiring them to make only those bids and offers that can be immediately and simultaneously executed at a profit. Simultaneous purchase and sale transactions hold their inventory at zero at all times, and shield them from any risk of price shifts.

Figure 1 illustrates simple constraints imposed on arbitrageurs to implement the idea of scarcity. Consider the first set of arbitrageurs who buy in Market 2 and sell in Market 1. Let b_1 be the current bid in market 1 and let a_2 be the current ask in market 2. Knowing that they can sell immediately in Market 1 at b_1 , they submit a bid in Market 2 which is a uniformly distributed random variable between 0 and b_1 : $b_2 \sim U(0, b_1)$. Similarly, knowing that they can buy immediately in Market 2 at a_2 , they offer in market 1 a price above a_2 : $a_1 \sim U(a_2, M)$. More generally, the opportunity set constraints for an arbitrageur in set i can be stated as follows:

$$b_{i+1} \sim U(0, b_i), \text{ and} \\ a_i \sim U(a_{i+1}, M).$$

Arbitrage With Zero Inventory

Since arbitrageurs can hold no inventory, any transaction in any market must be immediately followed by complementary transactions in all other markets so a unit of good is transferred from the only net source of goods (the exogenous suppliers) to the only net buyers (i.e., the exogenous buyers.) Under these conditions, it makes no difference whether there are only one or more arbitrageurs in each set. To simplify things, we have reduced the number of arbitrageurs, a , in each set to one. The arbitrageur in set 1, for example, bids in market 2 below the bid it observes in market 1, and asks in market 1 more than the ask it observes in market 2. Thus, it remains entirely within its opportunity set, eliminating any risk of a loss. It can enter into a transaction in one market knowing full well that it can profitably execute the other side of the transaction at

any time. Depending on the degree of patience we wish to endow into these arbitrageurs, the second side of the transaction could take place immediately at the mean of bid/ask in the appropriate market, or the arbitrageur could be permitted to engage in further bidding, using the first transaction price as the limit. In the spirit of their zero intelligence, we model the arbitrageurs to be impatient, and take the former of these two options.

3. EXPERIMENTAL DESIGN

The experimental design is shown in Table 1. The number of markets (m) takes three different values--two, five and ten. In the two market economy, sellers sell to a set of arbitrageurs in market 2 who, in turn, sell to the buyers in market 1, or buyers purchase from arbitrageurs in market 1 who, in turn, purchase from sellers in market 2. Similarly, buyer and sellers in the five-market economy are linked through four different sets of arbitrageurs, and in the ten-market economy by nine sets of arbitrageurs.

Insert Table 1 here

The number of buyers and sellers is set at 100. Each buyer has the right to buy up to one unit of the good from arbitrageurs in market 1. The redemption value of the good for the first buyer, v_i , is 125, and declines in steps of 1 to 26 for the last buyer. Similarly, each seller has the right to sell one unit. The cost of this unit for the first seller, c_i , (incurred only if the unit is sold) is 5, and rises in steps of 1 to 104 for the last seller. These market demand and supply functions are shown in the upper panel of Figure 2.

Insert Figure 2 here

Competitive equilibrium price of these economies is 65, and the volume is 60-61. The sum of consumer and producer surplus is 3660. If the profits of all traders in the economy add up to 3660, the economy will be 100 percent efficient in extracting the surplus. Given the symmetrical supply and demand functions, the equilibrium distribution of this surplus is equal between the buyers and the

sellers. Since arbitrageurs are present, we expect them to capture some of these profits.

4. ECONOMIES UNDER OPPORTUNITY SET CONSTRAINT

Price convergence

The middle column in Figure 3 shows the paths of prices for the three economies corresponding to the cells in Table 1. Prices are plotted vertically against the transaction sequence number. Each graph was chosen arbitrarily from a collection of 10 different runs of the same economy for each cell in Table 1. In the right column, we plot the price of each transaction number in each of the markets.

o

Insert Figure 3 here

In all three economies the sequence of transaction prices in each markets gets gradually and noisily closer to the equilibrium price (represented by a horizontal line).

These results show that the competitive equilibrium price is a good predictor of the tendency of prices. In analytical models, equilibrium is arrived at by assuming that a large number of price-taking agents engage in profit maximizing behavior. Empirically, the equilibrium price so derived is a good predictor of the tendency of prices in an economy consisting of several interrelated markets that operate under continuous double auction trading mechanism populated by a small number of agents who make random ask and bid decisions within the boundaries defined by their opportunity sets.

Number of transactions

Competitive equilibrium prediction of transaction volume is 60-61. This prediction is quite accurate. As can be seen from figure 4, with two markets the number of transactions (62 to 65) slightly exceed the competitive equilibrium. In 5-market economies, most of the markets in most of the ten replications have exactly the number of transactions predicted by the competitive model. When the number of markets increases to 10, the number of transactions (58-59) is slightly under the CE prediction of 60. The amount of time allowed to the markets has been established so that doubling the amount of time does not result

in any further transaction. Perhaps one or two additional transactions might have occurred with a much larger increase in time permitted for each run.

Insert Figure 4 here

Efficiency

Efficiency measures the extraction of social surplus. Following Smith (1962), efficiency of a market is the total profit actually earned by all traders divided by the maximum total profit that could have been earned by all traders. Participants in a fully efficient system will extract the theoretical maximum social surplus.

Using this measure we observe relatively high efficiencies, even as the number of markets increases. Average efficiency across 10 runs for 2, 5, and 10 markets is 98.2, 99.7 and 99.6 percent respectively (see figure 5). As Gode and Sunder (1993b, 1993c) explain, a small loss of efficiency occurs because double auction has no recontracting. Therefore, intramarginal buyers and sellers have a nonzero probability of being replaced by extramarginal buyers and sellers, reducing the amount of surplus extracted through the trading process.

Insert Fig. 5 here

5. RELAXING THE OPPORTUNITY SET CONSTRAINT

Can the convergence of our experimental economies close to CE be attributed to the imposition of opportunity set constraint on trader behavior as we have implied so far? One way of answering this question is to relax the opportunity set constraint, and compare the behavior of such economies to the benchmark behavior described above. We designed and ran a larger set of economies shown in Table 2 for this purpose.

Insert Table 2

Arbitrageurs' Inventory

Recall that the opportunity set constraint means that no trader can make proposals from which it cannot turn a profit if it were accepted by some counterparty. For arbitrageurs, this constraint required them to trade simultaneously in two markets, buying in one and selling in the other. Arbitrageurs never held any inventory. Holding inventory means taking the risk of incurring loss on a trade, and thus violating the opportunity set constraint.

We parametrized relaxation of the opportunity set constraint in the form of the units of inventory the arbitrageurs were permitted to hold. The absolute magnitude of the arbitrageurs inventory constraint L was allowed to vary from 1 and 4; the larger the value of L , greater is the violation of the opportunity set constraint.

In order to permit the arbitrageurs to hold inventory, the auction procedure was modified. Recall that in opportunity set-constrained economies, whenever an arbitrageur entered into a transaction in any market, a chain of complementary transactions in all other markets were immediately executed because no arbitrageur could hold any long or short positions. For example, in a ten-market economy, if bid in market 4 exceeded ask in that market, a transaction in market 4 was accompanied by a transaction between high bidders in market pairs (4-3), (3-2), and (2-1) and between low askers in market pairs (4-5), (5-6), (6-7), (7-8), (8-9), and (9, 10). In other words, a unit was transferred all the way from the low asker in market 10 to the high bidder in market 1. When inventory is permitted, these immediate complementary transactions in other markets of the economy are not necessary, and are dropped. In the context of our example, a cross between high bid and low ask in market 4 resulted in the high bidder and the low asker changing their inventory positions by +1 and -1 respectively.

Also recall that whenever an arbitrageur was picked (randomly) to make a proposal, it entered a bid as well as an offer in the appropriate markets. In a second modification, when a trader hit the limit of its long position in the market in which it was allowed to buy, it could no longer submit a bid in that market. Similarly, if an arbitrageur hit the limit of its short position in the market in which it was allowed to sell, it was no longer allowed to submit an offer in that market. Whenever a binding inventory constraint prevented an arbitrageur from submitting a proposal, another arbitrageur from the same set was picked randomly to submit that proposal. This meant that we could no longer assume a single arbitrageur in each set. Therefore Table 2 shows our 3x4x3 design (number of markets $m = 2, 5, \text{ or } 10$; inventory constraint $L = 1, 2, 3,$

or 4; and the number of arbitrageurs $a = 5, 25, \text{ or } 50$). As before, we conducted 10 replications of each cell in the table.

Multiple, distinct arbitrageurs within each group allowed the possibility that some members of a group might hold positive inventory while the others hold short positions after the m markets close. To clear this inventory, we considered opening a set of $(m-1)$ subsidiary markets for a specified period of time (or for a specified number of cycles in case of a single machine simulation). In each of these markets, arbitrageurs within the same set could trade with one another subject to the same set of double auction rules. These subsidiary markets, analogous to after-the-hours crossing networks operated by the New York Stock Exchange, Instinet, and many other exchanges, would, in principle, enable the individual arbitrageurs to clear their inventories at the end of each period. But, as we shall see, hardly any trades occur in these subsidiary markets. (In future work we plan to eliminate the price discovery function in the subsidiary markets, and use them purely for the purpose of clearing arbitrageurs' inventories at closing price).

Arbitrageurs

The market-based constraints on arbitrageurs described in Section 4 had to be modified to take into account their inventory positions. In the following explanation of how arbitrageurs function under the relaxed opportunity set constraint, we shall focus on the first and the last set (who deal with the exogenous buyers and exogenous sellers respectively), and then on one of the intermediate sets of arbitrageurs. Each arbitrageur is permitted to engage in an unlimited number of purchase and sale transactions within the constraints of its opportunity set. When buying to increase their inventory, arbitrageurs use borrowed funds that must be paid back through subsequent inventory liquidation. Similarly, when selling to expand their short position (negative inventory), arbitrageurs use borrowed goods that must be returned through subsequent purchases to liquidate the short position. (The subsidiary market described above would have served this function of settling up the accounts among each set of arbitrageurs at the end of each period).

The opportunity set constraints can be defined in terms of money or units of goods. For now, we choose to impose an opportunity set constraint on all arbitrageurs by requiring them to hold their long or short inventory positions to no more than L units. In other words, an arbitrageur can take any inventory position from $-L$ to $+L$. This limit represents the extent to which arbitrageurs can borrow to finance their trading activity. This constraint is analogous (but not identical) to the single unit constraint imposed on our buyers and sellers.

In addition to the inventory constraint, the arbitrageurs must also be subject to a constraint on their bids and asks in a manner similar to the constraint on the range of bids of buyers and asks from sellers. These constraints can be specified as follows:

Let I_i be the inventory position of arbitrageur i from the first set of arbitrageurs at any time during trading. Consider the following cases:

$I_i = 0$: Since it has no inventory, this arbitrageur can bid as well as ask at the same time. Its asks (in market 1) must be constrained from below by the current ask in market 2 at the time: $a_1 \sim U(a_2, M)$. Its bids (in market 2) must be constrained from above by the current bid in market 1 at the time: $b_2 \sim U(0, b_1)$.

$I_i = +L$: Since it has reached its upper inventory limit, this arbitrageur cannot bid in market 2 but can still asks in market 1. It will be selling from its inventory. Let p be the price of the lowest cost unit in its inventory. It must not propose to sell below this cost. Therefore: $a_1 \sim U(p, M)$. When it does sell from inventory, it is assumed that the lowest cost unit is sold first.

$I_i = -L$: Since it has reached its lower inventory limit, this arbitrageur can bid in market 2, but cannot ask in market 1. Let p be the price of the highest priced unit in its short position. It must not propose to buy units at a price above p . Therefore: $b_2 \sim U(0, p)$. When it does buy to cover a short position, it is assumed that the highest priced unit is covered first.

$-L < I_i < 0$: Since it has negative inventory, but has not reached the limit on its short position, this arbitrageur can bid as well as ask at the same time. However, its sales will add to its short position, and therefore its asks in market 1 must be constrained from below by the current ask in market 2: $a_1 \sim U(a_2, M)$. Its purchases will liquidate its short position. If p is the price of the highest priced unit in its short position, its bids (in market 2) must be constrained from above by p : $b_2 \sim U(0, p)$.

$0 < I_i < +L$: Since it has a positive inventory, but has not reached the limit on its long position, this arbitrageur can bid as well as ask at the same time. However, its sales will be from inventory. If p is the price of the lowest cost unit in this inventory, it must not propose to sell below this cost in market 1: $a_1 \sim U(p, M)$. Its purchases will increase its long position and it must not propose to buy at a price above the current bid in market 1: $b_2 \sim U(0, b_1)$.

For the second set of arbitrageurs, the same rules apply by increasing the subscripts of asks (a_i) and bids (b_i) by one. The same procedure continues until we reach the last, $(m-1)^{\text{th}}$, set of arbitrageurs. Figure 1 schematic still applies except that it does not graphically depict the constraints based on the price of units in arbitrageurs' inventories.

For each value of m and a , there are four cells in Table 2, one for each of the values of inventory constraint on the arbitrageurs, $L = 1, 2, 3,$ and 4 . (Opportunity set constrained economies of the previous section have been labelled as $L = 0$). As explained above, arbitrageurs' inventories must remain within the range $-L$ to $+L$.

As before, all these economies have 100 buyers and 100 sellers. Seller costs vary from 5 to 124 and buyer values vary from 125 to 26 in steps of 1. Competitive equilibrium price of these economies is at 65, and the volume is 61-62.

Prices

Figures 6A, 6B and 6C show the prices paths for different multi-market economies, one from each cell of columns $L=1$ and $L=3$ of Table 2. Again, each graph was chosen arbitrarily from a collection of 10 different runs of the same experiment.

Insert Figures 6A, 6B, and 6C here

Two features of these graphs are worth noting: (1) in all cases, the sequence of transaction prices in each markets gets gradually and noisily closer to the equilibrium price (represented by a horizontal line); and (2) the larger the number of markets, tighter is the *appearance* of convergence. The first result can be confirmed from the graphs. The second relates to the particular market mechanism we used to which we return in Section 6.

Number of Transactions

When $L > 0$, results for the 2-market economy are essentially unchanged. In some runs a market might allow for a number of transactions slightly above the number observed with no inventory. As the number of markets (and therefore the number of groups of arbitrageurs) increases, the competitive equilibrium quantity still is an excellent predictor of volume in markets 1 and m . However, in the intermediate markets, the trading volume increases with the number of markets, the number of arbitrageurs and the limit on inventory arbitrageurs are allowed to hold. Prices are consistently close to the CE prediction, but the quantities traded are not. Allowing arbitrageurs to take long or short positions increases the trading volume as should be expected. But the number of arbitrageurs is not a neutral variable, either. In the intermediate markets the number of transactions increases with the number of arbitrageurs. The highest

trading volume occurs in the markets near the center of the chain as can be seen in Figures 7A and 7B.

Insert Fig. 7A and 7B here

In summary, relaxing the opportunity set constraint on arbitrageurs affects the number of transactions among arbitrageurs but it does not affect the high predictive power of the competitive equilibrium model in the markets of final sellers or buyers.

Efficiency

The last four columns of Table 3 show that when short selling and long buying are allowed, efficiency drops sharply as inventory limit and the number of markets is increased. In 5 arbitrageur economies, efficiencies drop from 99.2, 81.8 and 48.1 percent (for 2, 5 and 10 markets with an inventory limit of 1) to 83.8, 58.1 and 28.8 when the inventory limit is raised to 4. In 25 arbitrageur markets, these drops are from 96.9 to 86.0, 60.3 to 56.7, and 18.9 to 14.8. In 50 arbitrageur markets, these changes are from 94.6 to 88.3, 41.1 to 54.9, and 19.0 to 7.8 respectively.

Insert Figure 8 here

6. TRACKING THE INVISIBLE HAND

How and why the relaxation of the opportunity set constraint causes efficiency to drop so sharply? Answers to this question may help demystify the magic invisible hand often associated with markets.

Movement of Units Across Markets and Efficiency

When a chain of transactions starts in some market (i.e., a new unit of the good is exchanged for the first time, perhaps only nominally), three scenarios could occur. In the first scenario, the starting trade can occur in the first market. The exogenous buyer buys at some price below its reservation price and therefore makes a potential profit on the trade. It is prudent to call this *potential* profit because the unit purchased cannot yet be delivered to the buyer by the arbitrageur of Set 1; the latter sells this unit but may not itself have the unit to deliver from its inventory. At this point the profit of the arbitrageur who sells the unit is

indeterminate until it actually buys the unit from someone else. In fact the profit of all arbitrageurs who hold inventory in any market remains indeterminate until the short sale is covered at the time this unit is actually sold by a seller in market m . No increase in allocative efficiency can occur until the unit traded is transmitted right across the m markets of the economy, since arbitrageurs have no consumption value for the unit.

In the second scenario, the starting point is at the m -th market, so that a seller actually sells one unit to an arbitrageur of set $(m-1)$. This case is exactly analogous to the preceding paragraph. Again, no social surplus is extracted until all links in the chain of transactions that transmit this unit right across the m markets are executed.

The third possibility is that trade starts between two arbitrageurs in a market different from 1 and m . In this case also, no net surplus is extracted at the time of the transaction. In summary, as long as this unit does not reach *both* end markets, i.e., as long as the unit actually is not sold by an exogenous seller *and* bought by an exogenous buyer, nothing can be added to the measure of efficiency. Only those units that have both a seller in market m and a buyer in market 1 should enter our computation of efficiency.

This helps understand why efficiency drops dramatically with relaxed opportunity set constraint when the number of markets and arbitrageurs increases. Recall from Section 5 that with the relaxation of the opportunity set constraint, our arbitrageurs acquire speculative inventory positions, but they cannot liquidate these inventory positions at a loss. They can only sell their positive inventory at prices above what they paid for it, and buy out of their short positions at prices below what they received for short sales. The combined effect of allowing them to acquire speculative positions, but not allowing them to liquidate these positions at a loss is that some units get stuck in the hands of the arbitrageurs, and do not contribute to efficiency. Under these market rules, all transactions initiated in some market do not necessarily reach both ends of the economy to the exogenous buyers and sellers.

Arbitrage and Transactions Volume

Recall that we have m markets. In market 1 each buyer cannot buy more than one unit even if arbitrageurs can take short and long positions. Therefore, the number of transactions cannot exceed the number of buyers. In market 2, the number of units that arbitrageurs can buy cannot be greater than the number of units that can be sold to the buyers in market 1 (i.e. exactly the number of buyers) plus the amount of stock that they are allowed to have. Therefore, the number of transactions has to be less than or equal to the number of transactions in the

previous market plus the inventory they are entitled to hold. In market 3 the same argument applies. The number of transactions cannot be greater than the number of transactions in market 2 plus the amount of inventory that arbitrageurs are allowed to hold. Therefore in market $k = 1, \dots, m$, the number of units traded cannot be greater than $n + (k - 1) a L$.

If we start looking at the market transactions from the other end, from market m downstream, we observe a similar pattern. In market m , each seller cannot sell more than one unit. The number of transactions, therefore, cannot exceed the number of sellers. In market $m-1$, the maximum numbers of units that arbitrageurs can sell is equal to the number of units that can be bought from sellers in market m (i.e., exactly the number of sellers in market m) plus the amount of short selling that they are allowed to do. Therefore, number of transactions has to be at most equal to the number of transactions in the previous market plus the number of units they are entitled to short sell. And so on. Therefore in market k , the number of units traded cannot be greater than $n + (m - k) a L$.

Consequently, the maximum number of units that can be bought keeps increasing upstream from market 1 to market m , while the maximum number of units that can be sold keeps increasing downstream from market m to market 1. The number of transactions in every market has to be less than or equal to the smaller of the two. This limit is lower at the end markets than in the middle markets, which helps to explain the single-peaked shape of the graph of transaction volume across m markets in Figures 7A and 7B.

This also explains why the upstream arbitrageurs hold mostly short positions and downstream arbitrageurs tend to hold long positions. Since the long and short positions of arbitrageurs are held in different markets, opening up local subsidiary markets at the end of the session (in which arbitrageurs within a group can trade with each other) do not see much action.

Link Between Transaction Volume and Price Convergence

The above analysis also helps explain why prices appear to converge more spectacularly to the competitive equilibrium price when there are more markets than when there are fewer of them. With more markets, the number of transactions in the middle markets is larger than in the end markets. The double auction institution used in these simulations determines that prices in the middle markets must be between a smaller interval centered around the equilibrium price, as can be observed in figures 3 and 6. Therefore more transactions occur in the middle markets and this happens at prices that are close

to the CE price¹. In addition, end markets which start at prices further away from equilibrium, converge very quickly terminating early. This gives the look of sharp convergence.

Efficiency drops with increased number of markets in the economy because fewer transactions get through. Fewer transactions get through a longer chain of markets because there is greater opportunity for units to get trapped in arbitrageurs' inventory in a longer chain of markets. Why are more units trapped when the number of arbitrageurs increases or when the short and long selling allowed is increased?

As the number of arbitrageurs increases (and the number of buyers stays the same), the probability that an arbitrageur who has purchased one unit cannot sell it at a price above its purchasing price also increases. Why is this so? The probability that an arbitrageur gets another chance to make a proposal in the market after its purchase decreases as the number of arbitrageurs increases. Therefore, with large numbers of arbitrageurs operating in the same market, when its turn arrives again, he may very well find that the reference bid on which the arbitrageur based its purchase may have been substituted by another one. If the new bid were higher, this would allow it to sell anyway. But the average bid declines in the later part of the period just as the average offer rises. This happens because a buyer with a high reservation price and a seller with a low cost is more likely to succeed early in the market.² Since at any moment of time all bids have to be below the remaining reservation prices, bids will tend to become lower. A similar argument explains why asks tend to become higher and why an arbitrageur that has short sold one unit may discover when its turn to purchase one unit arrives, that current asks are above the price at which he short sold the unit. In addition, the larger is the inventory allowed, the greater is this effect. The result being that as the number of markets, arbitrageurs and inventories increases, the larger is the difference between the number of transactions occurring in the different markets of one economy.

Therefore, as the number of markets in the economy increases, the number of commitments made by arbitrageurs that cannot be met grows as well. The interesting part being that, in spite of this, the number of commitments to sell made to the buyers in market 1 and the number of sales made in market m , are close to the number of transactions predicted by the competitive equilibrium

¹ In all these examples the short selling and long buying allowed is symmetrical. When it is not, an asymmetry is observed in the number of transactions that occur upstream and downstream as the previous explanation leads us to expect.

² There is an "efficient order" (see Wilson (1985) but obviously not due to any impatience.

model. Moreover, prices tend to converge towards the vicinity of the CE price. To put it bluntly, as the number of markets in the economy increases, relaxation of opportunity constraint can cause it to become deadlocked. Commitments to sell are made at a price too low, and commitments to buy are made at a price too high, so that no subsidiary market can be of any help. And yet, even in such an economy, the CE model is a good predictor of prices in all markets and of quantities in the end markets, even if no actual units of the good are exchanged.

7. CONCLUSIONS

There is order in the economic world. What are the roots of this order? Since Adam Smith, economists have generally accepted that this order is the result of the individual striving for self-interest. We often suppose that the absence of order in individual behavior will be reflected in the behavior of the aggregate economy.

The natural world shows order as well. For example, the shape of catenary, the trajectory of the rays of light across media of different densities, and the spherical shape of a droplet of oil in water¹, all are ordered by the principle of least action. So one could, perhaps, entertain a view, antithetical to Smith's, that spontaneous order could arise in the economy just as it does in nature.

Our experiments do not seem to favor either of these two extreme explanations for the source of order in the economy. Order arises in our markets without individual rationality. The scarcity constraint, of which the real world has plenty, imposes order on an otherwise random system.² Our conclusion that scarcity is the source of this order is confirmed by evidence that order progressively breaks down as the scarcity constraint is relaxed in the economy. Efficiency of the economy tumbles under random bidding in double auction as the number of arbitrageurs, markets and inventories increase. With a sufficiently large number of arbitrageurs, markets and inventories, commitments cannot be met. And yet, all in all, one hypothesis dear to economists seem to be sustained all along. The hypothesis that prices and quantities tend to converge to the level at which supply equals demand. The

¹ Spontaneous order appears also in complex biological systems as D'Arcy Thompson illustrated many years ago.

²Becker (1962) showed that agents who choose randomly within their opportunity set defined by the budget constraint give rise to a downward sloping demand and upward sloping supply function.

predictions of the law of supply and demand are accurate, even if agents act randomly in markets interrelated in a complex manner, as long as the agents want to exchange and they trade within some bounds.

Our data show that the price that equates supply and demand is descriptively relevant, but it has little to do with rationally. This issue has been a challenge in economics (Simon 1978). The behavior of individual “human subjects in the laboratory often violate the canon of rational choice when tested as isolated individuals,... in the social context of exchange institutions serve up decisions that are consistent (as though by magic) with predictive models based on individual rationality” (Smith 1991), and “In spite of its mathematical complexity, the competitive model is very crude when placed in the context of... interactive markets and behaviors. Nevertheless, if the assumptions of the model are applied with an “as if” interpretation the resulting model is very powerful. ... In essence, the mathematical problem was solved quickly and without all the relevant information existing in a single place. ... Some sort of parallel processing appears to be taking place but its form remains a mystery” (Goodfellow and Plott, 1990)¹.

Our experiments are a step in the direction of resolving this mystery. They indicate that there is no substantial mathematical problem that needs to be solved in the process of bidding and asking. The substantial mathematical problem was “solved” in ours, as well as in Goodfellow and Plott and many other experiments, when we gave agents their reservation prices and unit costs (in terms of aggregates, once we provided the market supply and demand). As it were, the real action is off the stage. Given market supply and demand, want (i.e., bidding, asking and exchanging) and scarcity (i.e. opportunity sets) combined with the appropriate institutional mechanism do the trick. This trick consists in funneling transaction prices towards the CE price, not in parallel processing any complex mathematical problem. Nor is there, obviously, any sort of learning process that eventually guides agents towards behavior that constitutes an “as if” complete information Nash equilibrium.² Except for a trivial case, a certain degree of heterogeneity of reservation values is necessary for funneling to occur. Random bidding generates heterogeneity in decision making. A fair degree of heterogeneity is required for well behaved aggregated demand curves with irrational subjects (see, e.g. Trockel, 1984, and Hildenbrand, 1994), an intuition that Cournot and Marshall already had.

¹ Also see Plott (1986, p.306), and D. Friedman and J. Rust (1993, p. xix).

²See Friedman (1993), p. 15

If buyers are enticed to buy but are constrained to do it at prices below some reservation price, sellers are enticed to sell but are constrained to do it at price above some specified cost, and arbitrageurs have similar constraints, then there is price convergence towards the price at the intersection of the frontiers of the reservation prices and marginal costs, known as demand and supply. Remarkably, it is so even in complex environments with many intermediate markets and arbitrageurs entitled to hold short and long inventory positions. It indicates that the constraint of the opportunity sets is capable of transmitting demand and supply across markets in the form of derived demand and supply. It underscores the power of the venerable law of supply and demand, independent of whether the aggregate demand and supply are the result of rationality at the individual level.

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Figure 1
 Arrangement of Markets, Buyers, Sellers, Arbitrageurs, and Their Opportunity Sets

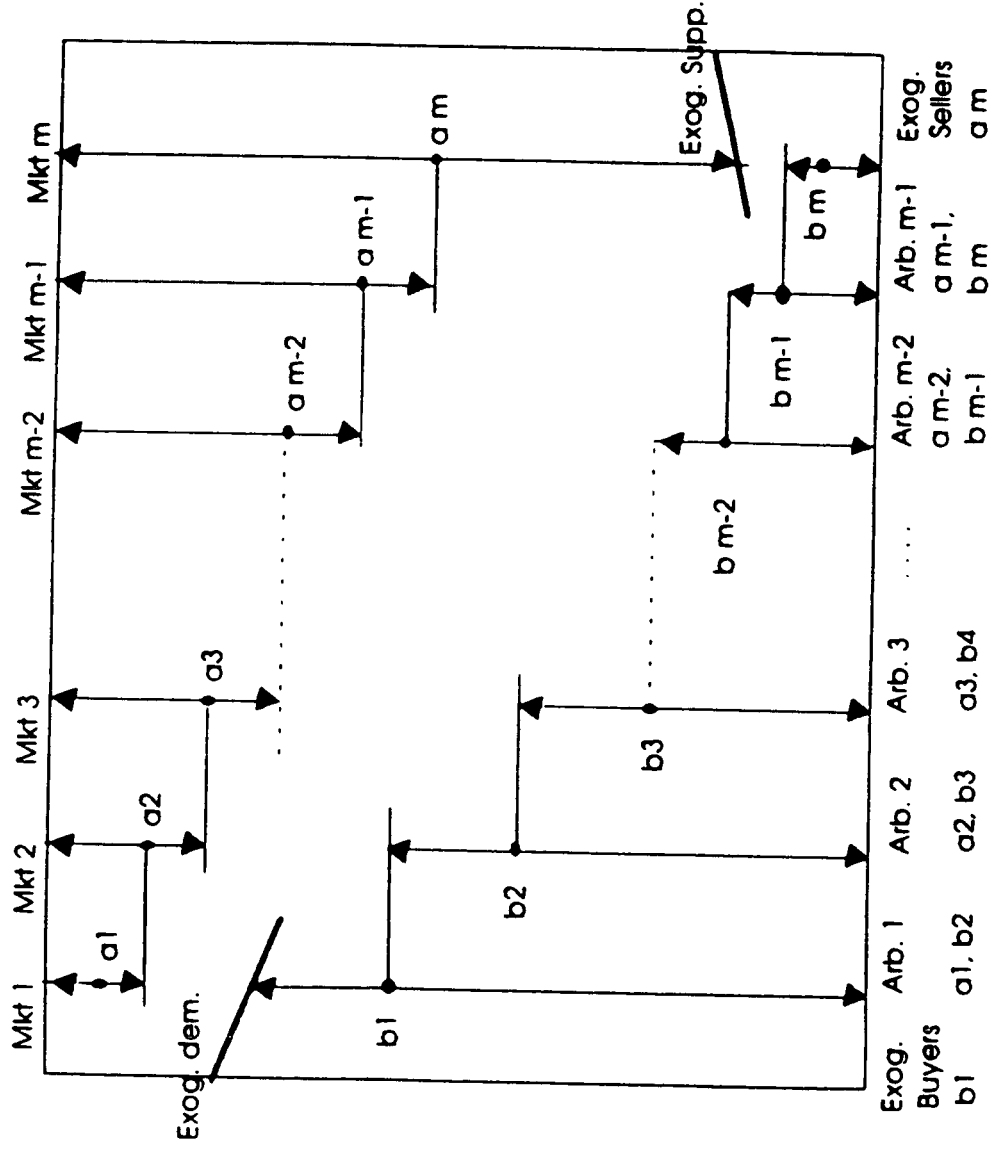
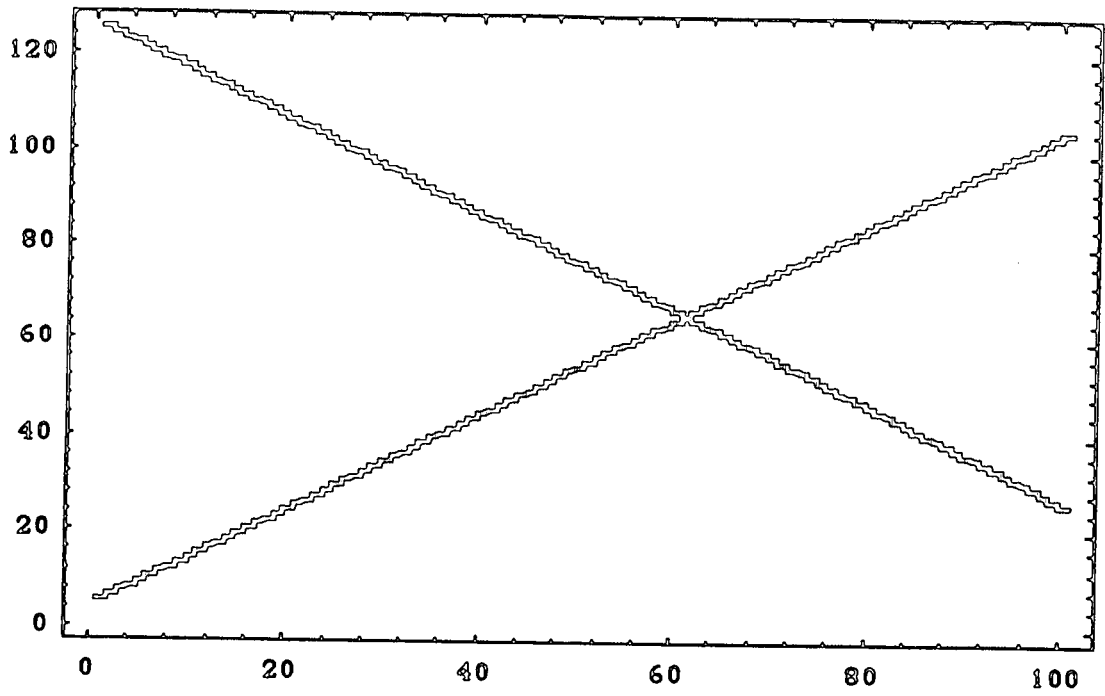


Figure 2. Exogenous supply and demand



Equilibrium Price = 65
Equilibrium Quantity = 60-61

For economies with no inventory, 100 buyers and 100 sellers

Figure 3. Price paths for one replication from each cell of Table 1 and average of 10 replications

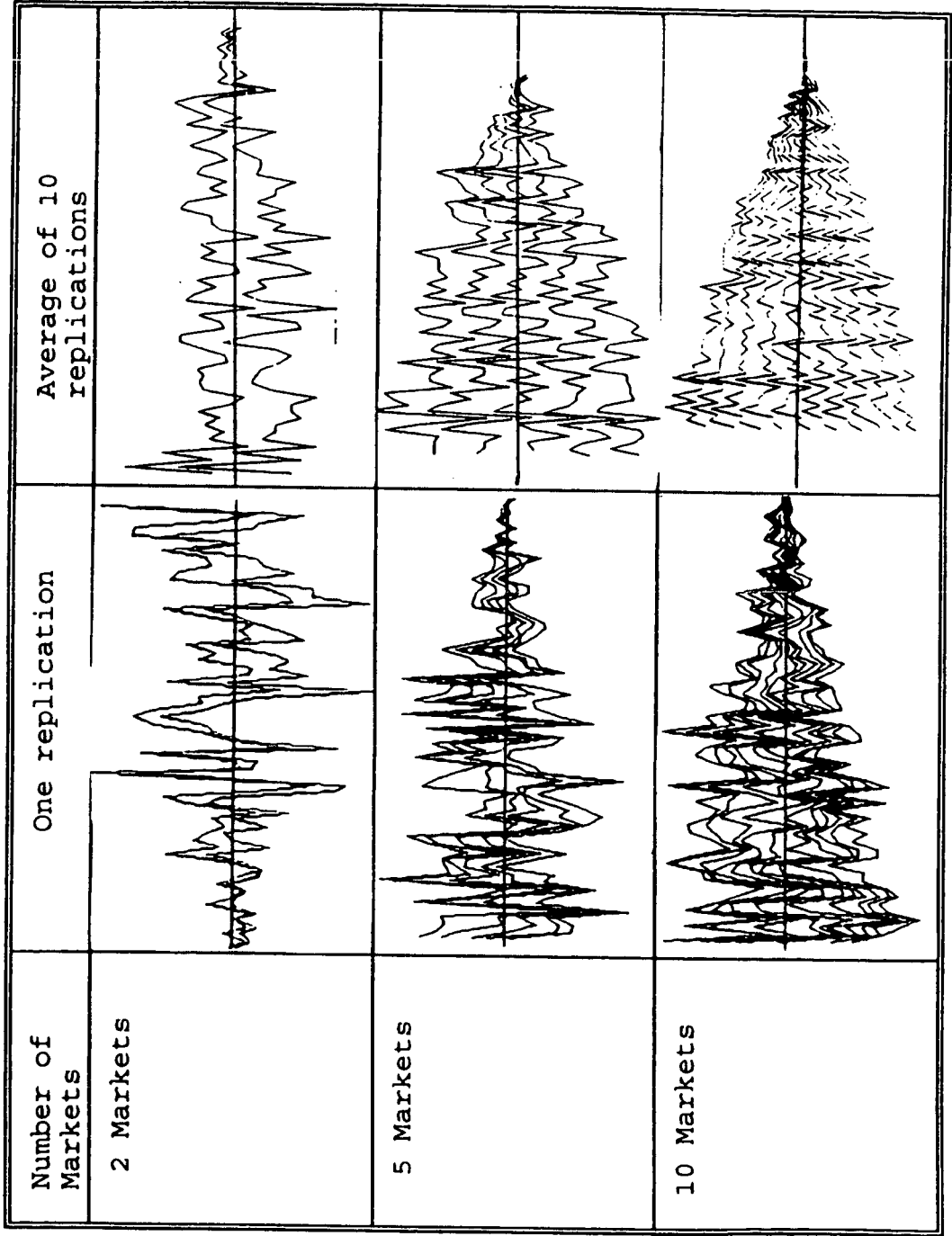


Figure 4. Transactions volume in each replication (in each replication, the volume is the same in all markets)

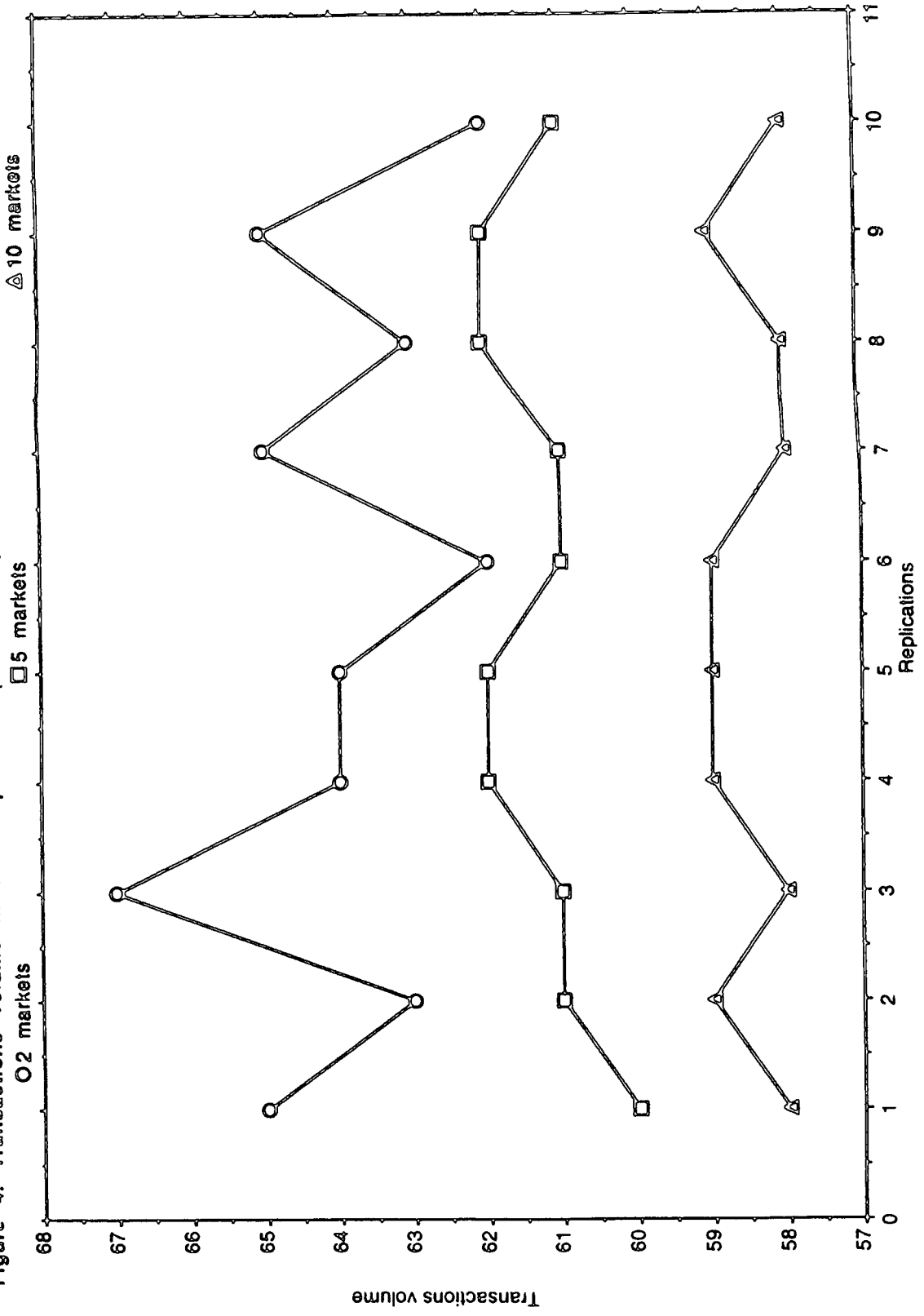


Fig. 5 Efficiency Distribution (Percentiles) in Economies with Different Number of Markets, $L=0$

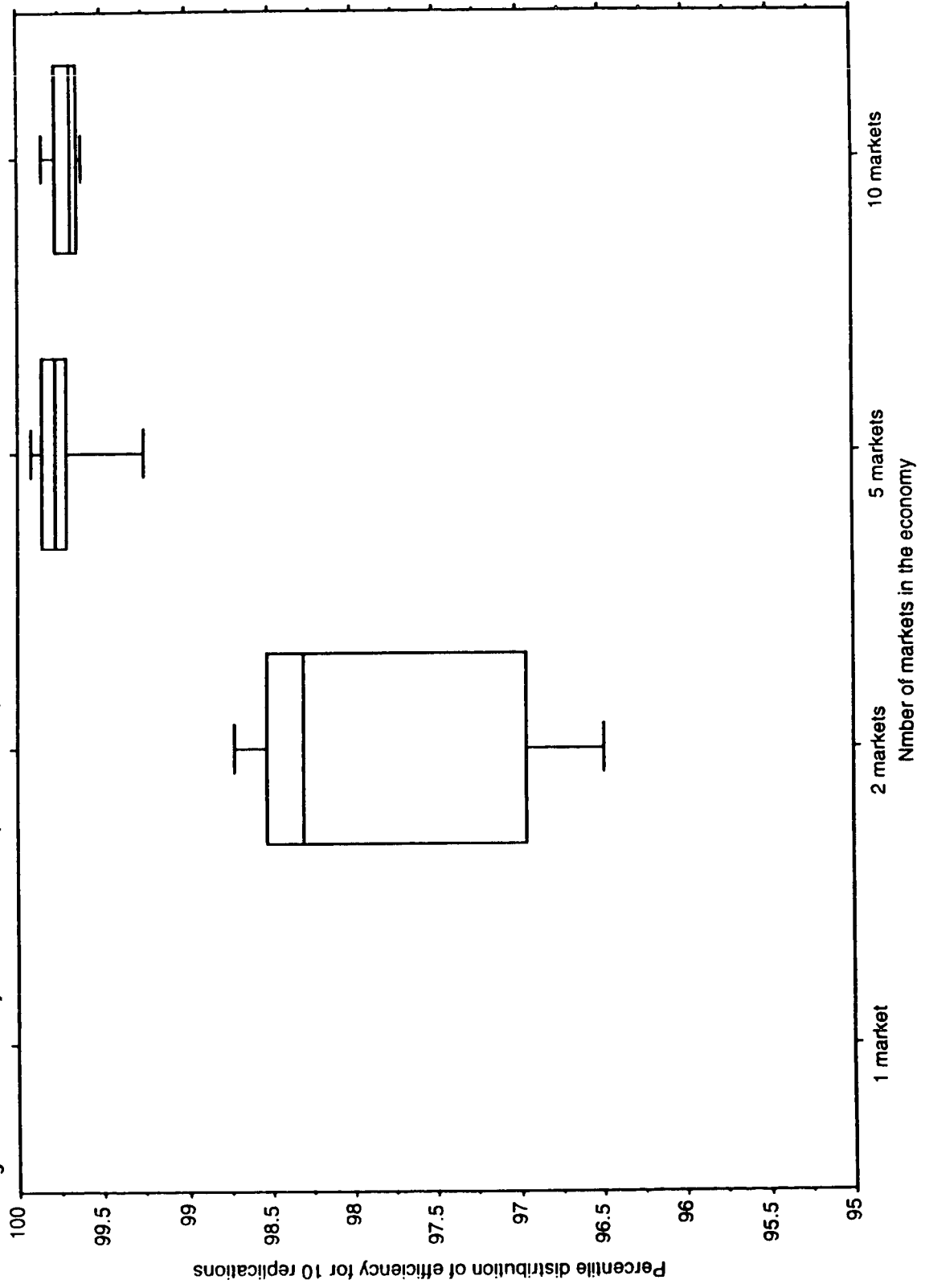


Figure 6A. Price paths for one replication from the cells of Table 2 corresponding to 2 markets
 $L=1, L=3$

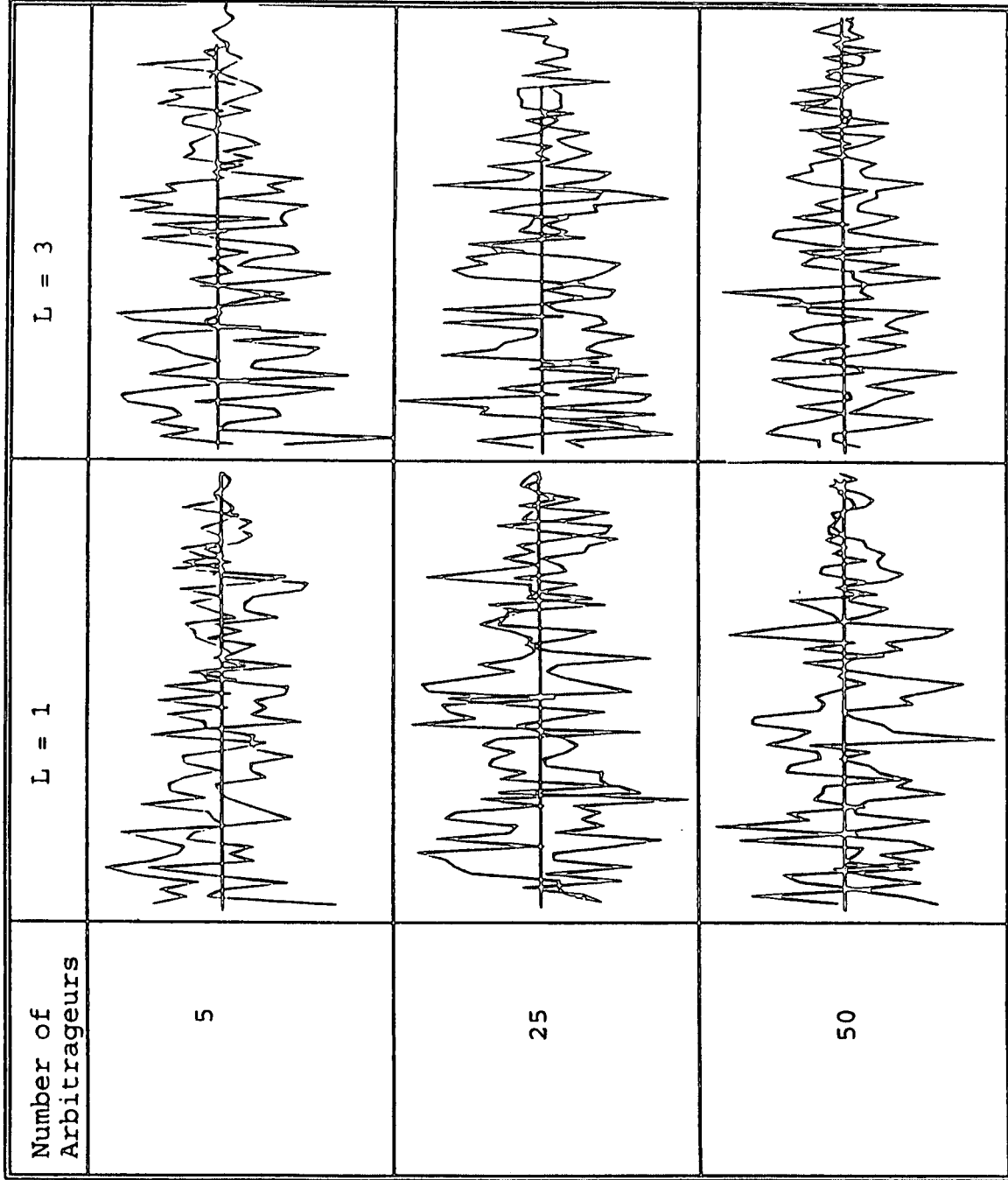


Figure 6B. Price paths for one replication from the cells of Table 2 corresponding to 5 markets $L=1$, $L=3$

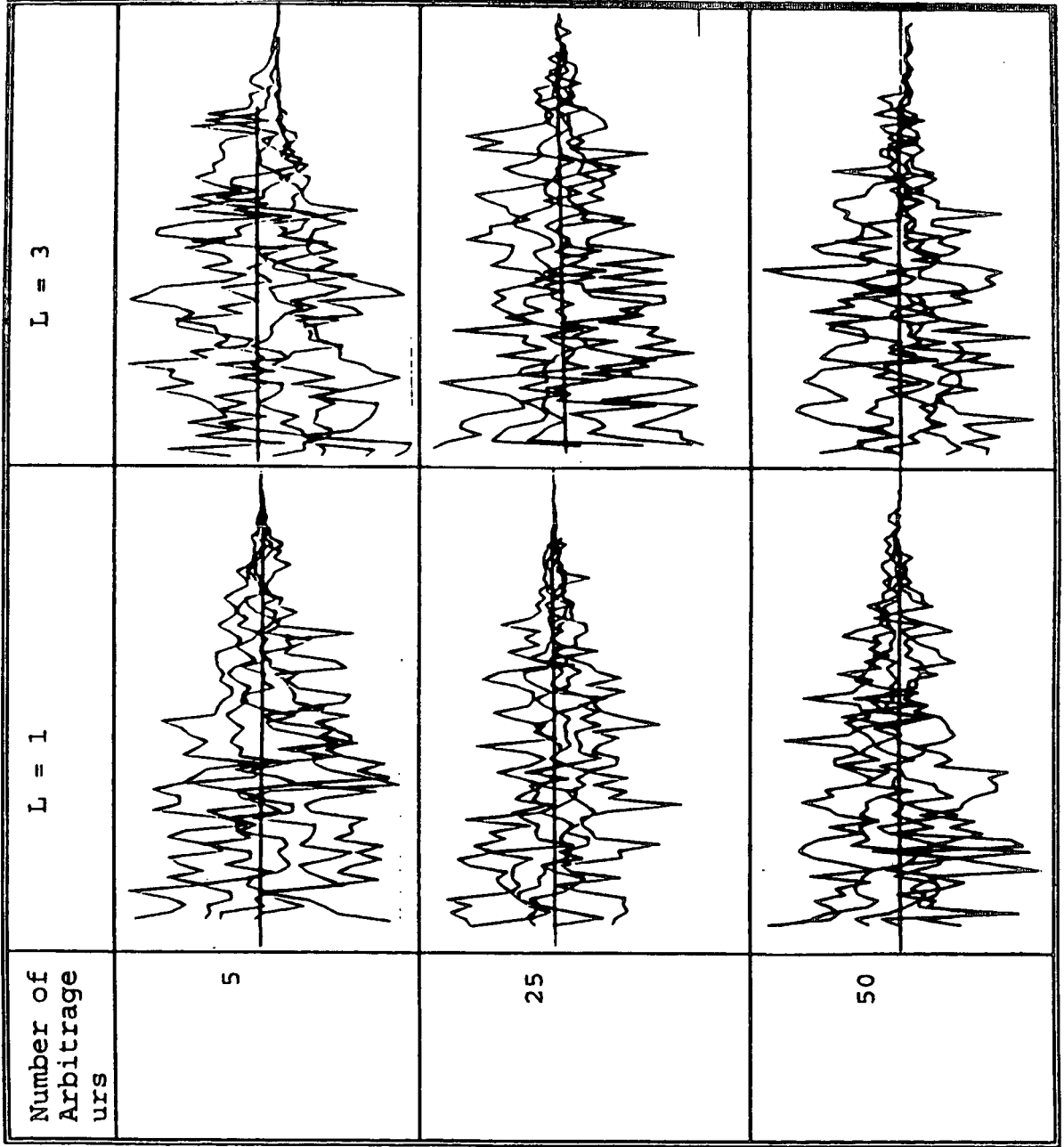


Figure 6C. Price paths for one replication from the cells of Table 2 corresponding to 10 markets $L=1$, $L=3$

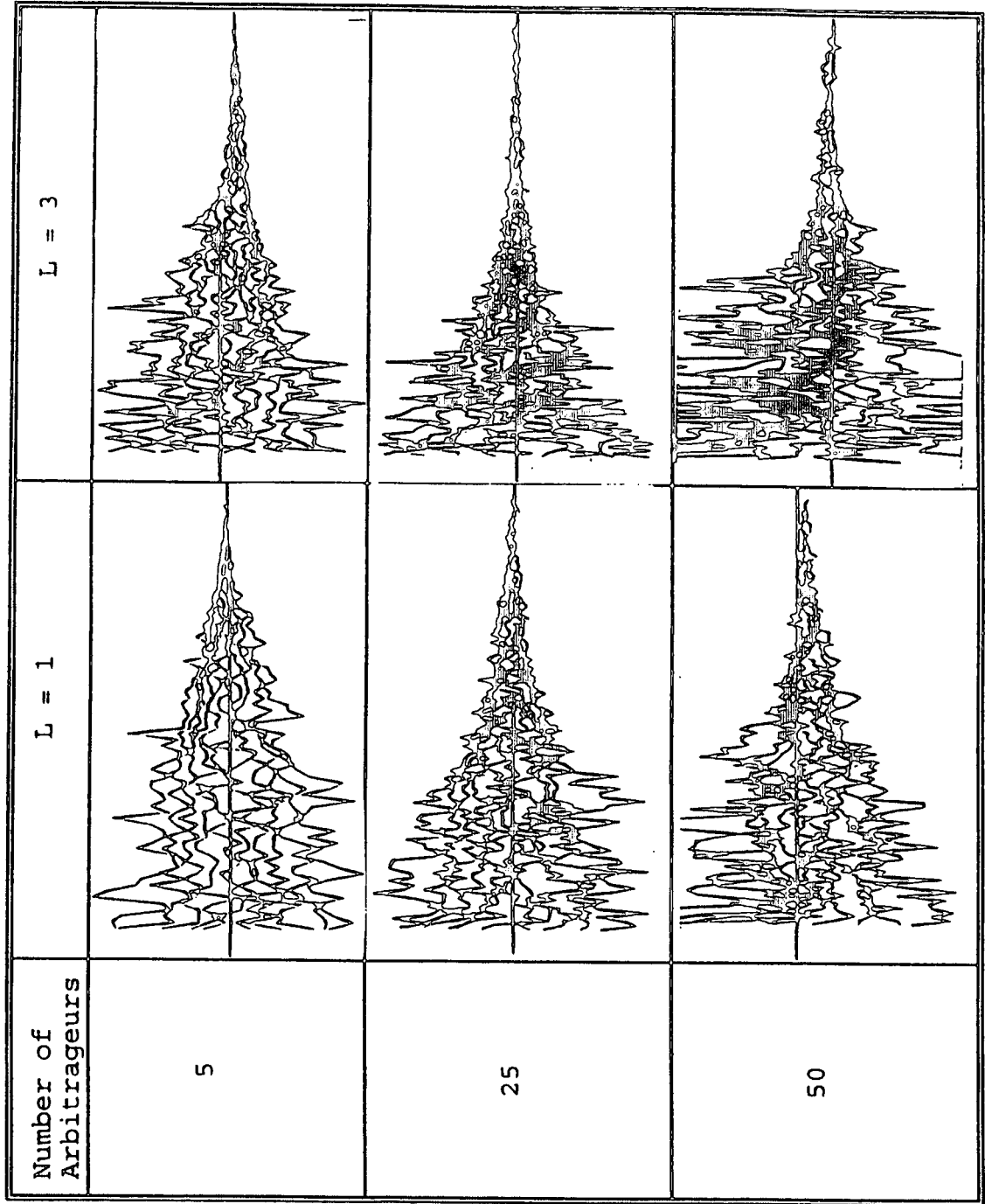


Fig. 7A Average transactions in 10 replications with different inventories
 $\Delta m=10, a=50, L=2$

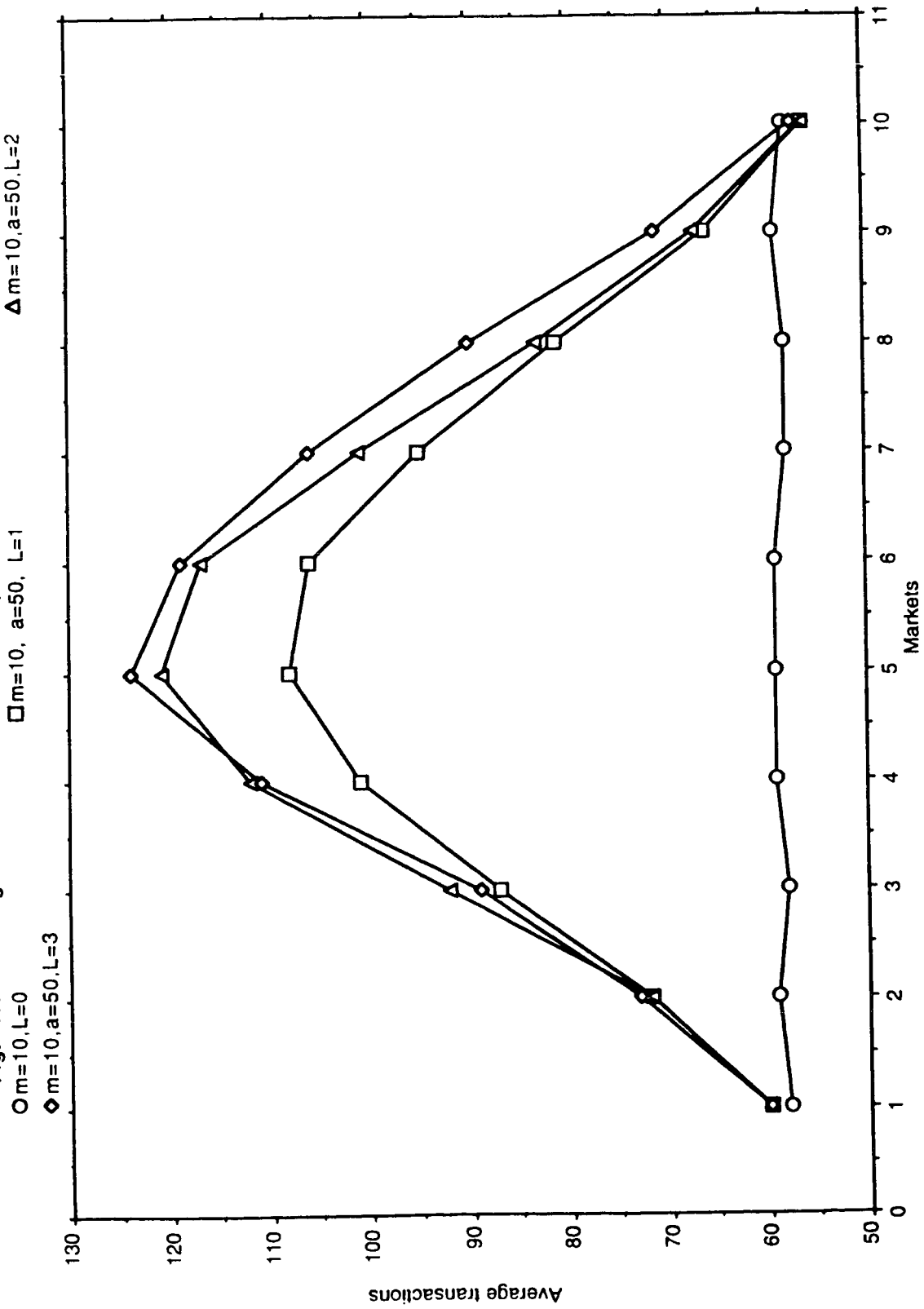


Fig 7B Average transactions in ten replications with different number of arbitrageurs

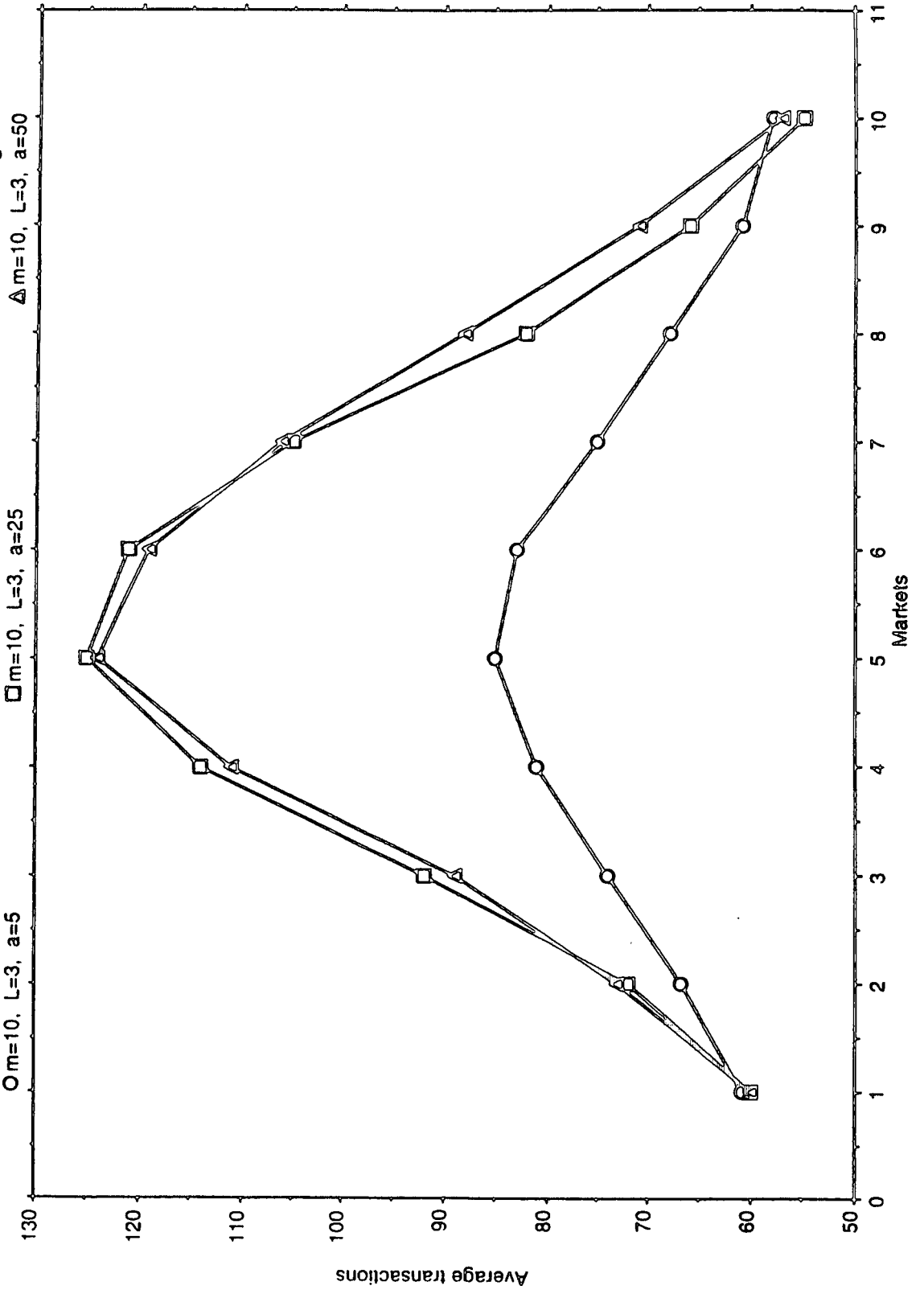
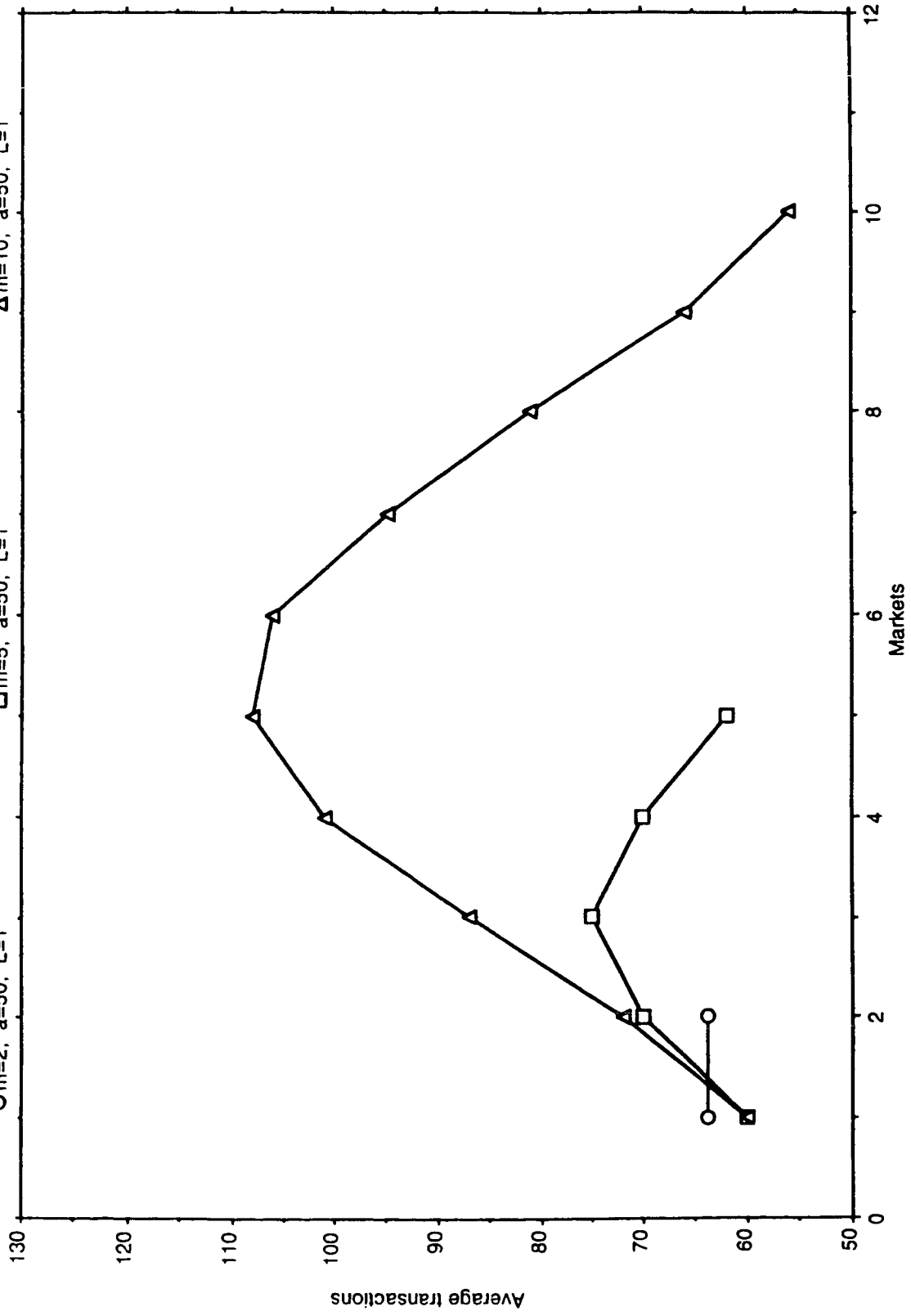


Fig 7C Average transactions in ten replications with different number of markets
 $\Delta m=10, a=50, L=1$
 $\square m=5, a=50, L=1$
 $\circ m=2, a=50, L=1$



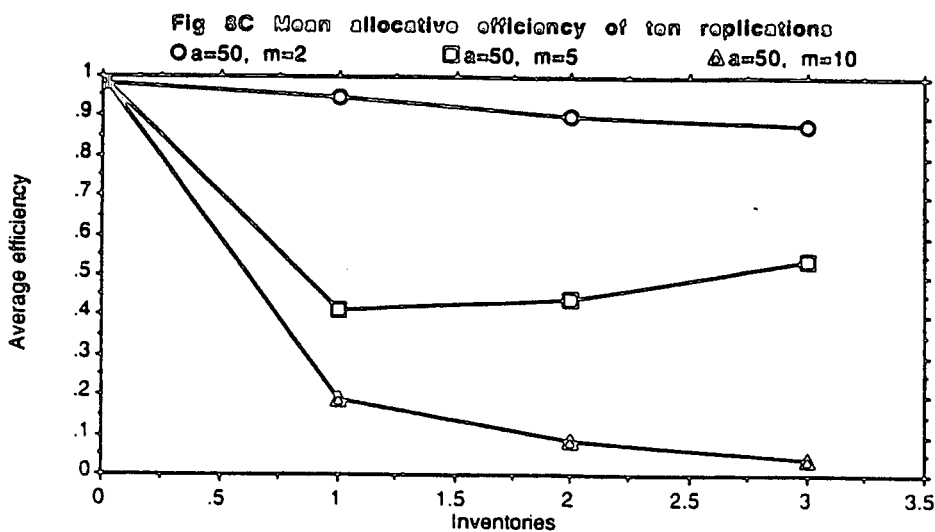
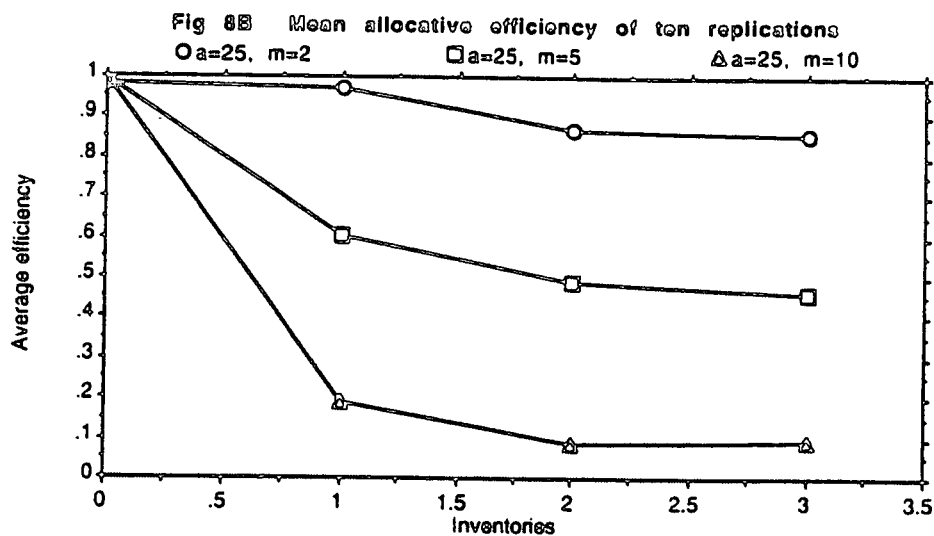
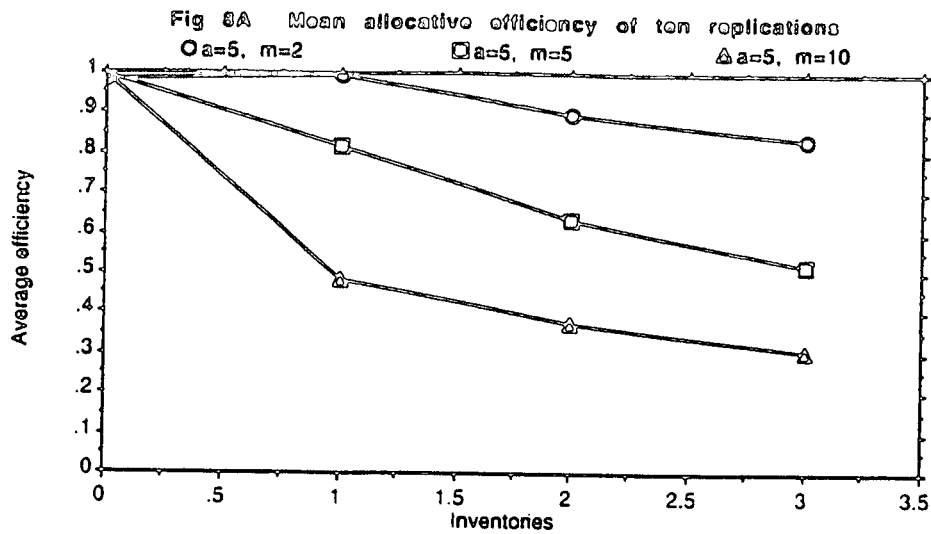


Table 2. Experimental design for a sequence of experiments with varying inventory

		INVENTORY CONSTRAINT OF ARBITRAGEURS			
		L = 1	L = 2	L = 3	L = 4
2 Markets	Number Of Arbitrageurs	10	10	10	10
		10 replications	10 replications	10 replications	10 replications
		10 replications	10 replications	10 replications	10 replications
5 Markets	Number Of Arbitrageurs	5	5	5	5
		25 replications	25 replications	25 replications	25 replications
		50 replications	50 replications	50 replications	50 replications
10 Markets	Number Of Arbitrageurs	5	5	5	5
		25 replications	25 replications	25 replications	25 replications
		50 replications	50 replications	50 replications	50 replications

Table 1. Experimental Design for a sequence of experiments

Number of Markets	L = 0
2 Markets	10 Replications
5 Markets	10 Replications
10 Markets	10 Replications

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