Upstairs, Downstairs:
Electronic vs. Open Outcry Exchanges

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Abstract. Computerized trading has made great inroads in equity and derivatives markets, especially in Europe and Asia, but open outcry markets remain dominant in the United States despite predictions of the imminent demise of floor trading. This article identifies three factors that influence the relative liquidity of computerized and open outcry markets: the sizes of upstairs and downstairs liquidity pools, the magnitude of the risk that upstairs traders face in being "picked off" when trading via limit order in an open outcry market, and the quality of information available to floor and upstairs traders. Although liquidity differences certainly influence the choice of trading technology, network effects and coordination costs may allow the less liquid trading method to prevail. In the presence of coordination costs, the existence of mechanisms for coordinating the trading choices of investors and hedgers, agency costs, and the organization and governance structures of exchanges also influence whether open outcry or computerized trading will dominate.

JEL Classification: L11, L12, L31, G10, G20. Key Words: Securities market structure, financial exchanges.

1 Introduction

Computerized trading of financial instruments has made considerable headway since its conception in the 1960s. Virtually all European and Asian securities and derivatives exchanges are currently electronic. Moreover, electronic trading has made some inroads in the United States as well. The International Securities Exchange (ISE) is a completely computerized options exchange, the InterContinental Exchange (ICE) is an electronic energy market, and the major US derivatives exchanges have introduced electronic trading platforms. Nonetheless, despite the integration of computers in various elements in the trading process, the major securities, derivatives, and options exchanges in the US all execute the bulk of their transactions via an open outcry auction on the exchange floor.

There are long-standing arguments about the relative efficiency of computerized and open outcry trading. Floor trading has its committed advocates who assert that floor-based markets are inherently more liquid than electronic ones; for instance, the CEO if LIFFE in 1997, Daniel Hodson, asserted "[n]o electronic trading system will be able to replicate the advantages of open outcry" (quoted in Young and Theys, 1999). Others dispute these arguments (Pirrong, 1996). The empirical record is mixed, although recent evidence suggests that electronic markets can offer as much or more liquidity than floor-based markets (Pirrong, 1996, 2003c; Breedon and Holland, 1997). Nor does the survivor test provide unambiguous answers. Some electronic exchanges have won head-to-head battles against open outcry markets. Over several months in 1997-1998, trading of Bund futures contracts shifted

entirely from the open outcry LIFFE (which had had a 70 percent market share) to the computerized Eurex. Similarly, in 1998, the French derivatives exchange MATIF operated its floor and an electronic system simultaneously; within two weeks of the commencement of the head-to-head battle between the computer and the floor, all volume had migrated to the computerized platform and MATIF closed its floor soon thereafter. But open outcry has had its successes as well. Heretofore the major floor-based US derivatives and securities exchanges have continued to attract the lion's share of order flow in the face of competition from electronic platforms, although the ISE is gaining significant market share.

This mixed record raises the question: what determines whether a computerized or an open outcry exchange prevails? This article addresses this question by adapting a canonical market microstructure model. The model is premised on the insight that there are multiple pools of liquidity, and that the costs of accessing these pools can differ across trading technologies. Moreover, traders in floor-based and computerized markets may have different information. These factors, in turn, imply that liquidity, and hence the cost of trading, can differ across trading technologies.

More specifically, floor ("downstairs") traders can supply liquidity in an open outcry market, but "upstairs" traders can do so as well by submitting limit orders to the floor.[1] Upstairs and downstairs traders have different

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[1]To clarify, in this article I use the term "upstairs trader" to refer to traders not on an exchange floor who supply liquidity on exchanges through limit orders. These are to be distinguished from upstairs traders who participate in off-exchange trading, such as block positioners, third market dealers, and internalizers. Extensive empirical evidence (summarized in Pirrong, 2002 and 2003a) demonstrates that upstairs off-exchange traders typically attempt to screen out the informed and restrict their counterparties to

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information sets, which affect their costs of supplying liquidity. Floor traders may have an information edge due to their "time and space" advantage over upstairs traders. Due to the time lags inherent in trading via limit order, upstairs traders face the risk of having their limit orders "picked off" due to the arrival of information subsequent to order submission; the risk of being picked off is lower for a floor trader whose bid or offer are good "only as long as his breath is warm." Furthermore, floor traders and upstairs traders may have access to different sources of information that affect the quality of their value signals, which in turn affect the risk and cost of supplying liquidity.[2]

Electronic trading abolishes the time and space advantage of the floor trader. All traders on an computerized market face identical risk of being picked off. This reduces the cost upstairs traders incur to supply liquidity. *Ceteris paribus* this makes the computerized market more liquid than its open outcry counterpart. But *ceteris* may not be *paribus.* Floor traders have very specialized skills, and might not be able to supply liquidity as efficiently through a computerized system as on the floor. Moreover, if traders have access to better information on the floor than upstairs (due to factors *other* than the time and space advantage), floor traders incur higher costs to supply liquidity in a computerized system than they do on the floor.

Based on these considerations, the model implies that the relative poten-

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the verifiably uninformed. Pirrong (2002, 2003a) analyzes market structure with "cream skimming" of this sort.

[2]Upstairs traders can give some discretion to floor brokers as a means of reducing the costs of supplying liquidity via limit order. However, as noted by Grossman (1992), floor brokers cannot fully redress the "free option" problem inherent in supplying liquidity via limit order.

tial liquidity of computerized and floor markets depends primarily on three factors: (1) the relative sizes of the upstairs and downstairs liquidity pools, (2) the cost that upstairs traders incur in an open outcry environment due to their time and space disadvantage, and (3) the quality and quantity of information available to upstairs and downstairs traders. In turn, these factors depend on trading technology (in both the computerized and floor systems) and information technology. Variations in these factors over time or across markets can therefore cause temporal and cross sectional variation in trading technology.

If there are no costs of coordination, the trading mechanism (computerized or open outcry) that offers the greatest *potential* liquidity attracts the entire order flow; a system's potential liquidity is realized if all uninformed traders use that system. However, financial trading exhibits network effects (Pirrong, 2002, 2003a-b). Due to these network effects, the liquidity of a market depends on how many investors and hedgers trade there. Hence, an inefficient trading technology can survive if it is costly to coordinate the movement of investors and hedgers to the more efficient system. When such coordination costs exist, the inefficient trading mechanism can survive unless the trading cost differential implied by the potential liquidity differential exceeds the cost of coordinating a movement of investors and hedgers to system with the greater potential liquidity.

The existence of coordination costs implies that there is no guarantee that the most efficient trading platform prevails. In this environment, exchange ownership and governance structures influence trading technology choice. Similarly, the structure of the brokerage industry and the integra-

tion of trading and brokerage activities also influence the choice of trading platform. The number and relative size of brokerage firms that can make order routing decisions can influence coordination costs, and the integration of proprietary and agency trading in upstairs firms can influence the incentives of these firms to support computerized trading.

The remainder of this article is organzied as follows. Section 2 presents a formal model of liquidity in an open outcry market with both upstairs and downstairs traders. Section 3 presents a similar model of liquidity in a computerized market. Section 4 uses these models to identify the factors that determine the relative liquidity of computerized and open outcry exchanges. Section 5 discusses how coordination costs and network effects inherent in liquidity imply that the most liquid trading technology will not necessarily be adopted. It shows further how exchange organization and governance, and the structure of the upstairs trading industry influence the choice of trading technology. Section 6 summarizes the article.

2   Liquidity in an Open Outcry Market

Consider a market for a financial instrument. The true value of the instrument is v. Two types of agents desire to trade it. First, there is a large (but finite) number of noise traders. Net noise trader demand for the asset is (a) perfectly inelastic, and (b) a normal random variable with mean 0 and variance S. Individual noise trader demands are uncorrelated, so the variance of the sum of several noise trader's demands is equal to the sum of the variances of their individual demands. Noise trader demand and the value of the asset are orthogonal. There are also K risk neutral informed traders who know

the true value of the asset v. The noise traders and informed traders trade via market order.

This section presents a model of a floor-based, open outcry trading mechanism. This exchange is modeled as in Kyle (1985). Specifically, the financial instrument is traded in a batch auction on the floor of the exchange.

There are two types of traders who can supply liquidity to the market by absorbing any imbalances in market orders submitted to the floor by the informed and noise traders. First, there are F_N traders, $\mathbf{F} = \{F_1, F_2, \ldots, F_N\}$ who can trade on the exchange floor. The F_N floor traders can supply liquidity by shouting out bids and offers on the floor of the exchange. Each such "floor trader" F_i is risk averse, with a constant absolute risk aversion coefficient α_i. Equivalently, the risk tolerance of floor trader F_i is $t_i = 1/\alpha_i$. The total supply of risk bearing capacity (i.e., aggregate risk tolerance) of the floor traders is $T_F = \sum_{F_i \in \mathbf{F}} t_i$.

At the time that they must submit their orders to the auction (where this time is denoted by X_F), each floor trader's information implies that the expected value of the instrument is zero, and the variance of the instrument value is σ^2.

The second group of liquidity suppliers consists of "upstairs" traders. These traders cannot trade on the floor, but can supply liquidity by submitting limit orders to the market. There are U_M such traders, $\mathbf{U} = \{U_1, U_2, \ldots, U_M\}$. Each upstairs trader U_j is risk averse, with a constant absolute risk aversion coefficient μ_j. Equivalently, the risk tolerance of upstairs trader U_j is $\tau_j = 1/\mu_j$. The total supply of risk bearing capacity (i.e., aggregate risk

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tolerance) of the upstairs traders is $\mathcal{T}_{\mathcal{U}} = \sum_{U_j \in \mathbf{U}} \tau_j$.[3]

An upstairs trader has a different information set than the floor trader. This in part reflects the fact that upstairs traders and floor traders have different sources of information. For instance, an upstairs trader typically has access to computerized information resources that the floor trader does not. As another example, upstairs traders for grain merchants receive reports on grain movements, transportation costs, weather, and buying interest from their firms' networks of elevators, loading stations, and processing plants in major consumption and production regions. They use this information when devising their order placement strategies.[4]

Conversely, the floor trader may have access to information that the upstairs trader does not. Miller (1991) and Coval and Shumway (2001) argue that the floor is informationally rich, and that the information available on the floor is not available upstairs. Coval and Shumway summarize this argument nicely:

> [W]e ask whether there exists information which is regularly communicated across an open outcry pit but cannot be easily transmitted over a computer network. Any signals which convey information regarding the emotion of market participants; fear, excitement, uncertainty, eagerness, etc. are likely to be difficult

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[3]The numbers and preferences of floor and upstairs traders are assumed exogenous. This is plausible, especially in the short run. Floor traders have specialized skills. Moreover, traditional open outcry exchanges have fixed numbers of members and are notoriously reluctant to adjust the size of their memberships.

[4]Grossman (1992) also conjectures that upstairs traders may possess some information that floor traders do not.

to transmit across an electronic network. For instance, a trader who tries to unwind a large short position by waving his arms and jumping up and down in an open outcry exchange, might have difficulty communicating such eagerness across a computer screen. Certainly more complex signals, such as fear in his eyes or voice, would be impossible to discern across a network (Cowan and Shumway, p. 4).[5]

Relatedely, Benveniste, Marcus, and Wilhelm (1992) argue that floor trading is informative because (1) it is not completely anonymous, and (2) floor traders interact repeatedly. Due to these factors, floor traders share information on the characteristics of order flow and intrinsic value, thereby reducing information asymmetry and increasing liquidity. In contrast, such features are absent in computerized markets. *Ceteris paribus* this would tend to make them less liquid than open outcry exchanges. Conversely, Pirrong (1996) ar-

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[5]Cowan and Shumway argue that due to these "non-market signals," the floor trading environment is informationally richer than a computerized environment (p. 20). This comparison is somewhat one-sided, however, as Cowan-Shumway do not investigate whether there are different "non-market signals" available upstairs that are absent on the floor; Grossman (1992), for instance, suggests that upstairs traders may possess some information that floor traders lack. It would be interesting to measure noise levels in upstairs trading rooms, for instance. It would also be interesting to see whether volumes of phone, email, or instant messenger traffic involving upstairs traders are correlated with price volatility or lead it. As a result of this one-sidedness, Cowan and Shumway's interesting results do not prove that floor traders have more information than upstairs traders, although they do suggest this possibility. Moreover, their description also focuses on liquidity-related information, rather than value-related information. It may be the case that even if better liquidity-related information is available on the floor, better value-related information is available upstairs (due to, for instance, easier access to electronic information resources). Computer trading system developers are working to use visual and aural displays to communicate information about market activity of the type that is available on the floor (Young and Theys, 1999).

gues that repeated interaction and imperfect anonymity can also sustain collusion among floor traders, which would tend to increase trading costs.

Owing to these considerations, at the time (X_F) that the *floor trader* must submit his order, the upstairs trader's information implies a different distribution for v than possessed by the floor traders. Specifically, each upstairs trader $U_j \in \mathbf{U}$ estimates that the mean of v is zero, and the variance of v is $\theta\sigma^2$, where $\theta <=> 1$. $\theta < 1$ ($\theta > 1$) if the upstairs trader's information is superior (inferior) at any point in time.[6]

It must also be recognized, however, that upstairs traders operate at a disadvantage relative to floor traders even if the two types of traders have identical information at a given point in time. Specifically, a disadvantage arises from time and space considerations. Due to (a) the time required to submit a limit order to the floor, and (b) the time to withdraw or alter a limit order, an upstairs trader must determine his trading strategy before a floor trader. That is, the floor trader's time and space advantage allows him to wait longer than the upstairs trader to decide the price at which he is willing to trade.

If information about the instrument's true is revealed between the time that the upstairs trader must submit his order (where this time is denoted by $X_U < X_F$) and the time that an downstairs trader must submit his, the up-

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[6]The model assumes that information flows affect only the traders' estimate of the variance of the asset value, and do not affect their estimate of the mean. This assumption captures a key effect of information differentials and makes the analysis considerably simpler. The appendix presents a model in which upstairs and downstairs traders observe signals of differing precision that affect traders' estimates of both the mean and variance of asset value. The implications of this more complicated model are identical to those of the model presented in the main body of the text.

stairs trader's time and space disadvantage forces him to condition his order on less information than the floor trader. This makes the upstairs liquidity supplier more vulnerable to being "picked off." Due to this consideration, at the time he must submit his order, the upstairs trader's information implies that the mean value of the instrument is zero, and the variance of this value is $\Delta\theta\sigma^2$, with $\Delta > 1$. That is, the delay in execution increases the risk that the upstairs trader incurs to supply liquidity. Δ is larger, the greater the rate of information flow between X_U and X_F and the greater the amount of time required to submit a limit order.

As in Brown-Zhang (1997), Glosten (1994), and Hellwig (1980) I assume that both floor traders and upstairs traders submit continuous demand schedules. That is, they indicate the quantity that they are willing to buy or sell at each possible price. As in Brown-Zhang and Glosten, I interpret these schedules as collections of limit orders at different prices. With an infinitesimal tick size, the floor and upstairs traders can submit continuous demand schedules.

The floor auction takes place immediately after the floor traders submit their bids and offers, i.e., at the auction takes place at $X_F + dt$. This captures the fact that floor traders' bids and offers are binding for a very short period of time.

Analysis of the equilibrium in this market proceeds in the usual way by conjecturing a linear equilibrium, and solving for the relevant parameters. Specifically, upon learning v the informed traders conjecture that the price

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on the exchange is a linear function of order flow:

$$P = \lambda_F(\sum_{k=1}^{K} w_k + z) \tag{1}$$

where w_k is the order that the informed trader k submits, z is net noise trader demand, and λ_F is a constant. Given this conjecture, the informed trader l chooses w_l, $i = 1, 2$ to maximize:

$$V = w_l E[v - \lambda_F(w_l + z + \sum_{k \neq l} w_k)] \tag{2}$$

where the expectation is taken over z. Given that v and z are orthogonal, the symmetric solution of the informed traders' maximization problems implies that:

$$w_l = \beta_F v = \frac{v}{(K+1)\lambda_F} \quad \forall \quad l \leq K \tag{3}$$

Conditional on order flow, floor trader F_i chooses his trade y_i to maximize his risk-adjusted profit:

$$E_F \Pi_i = \max_{y_i} \{y_i E_F[v - P|K\beta_F v + z] - \frac{.5\hat{\sigma}_F^2 y_i^2}{t_i}\} \tag{4}$$

where $\hat{\sigma}_F^2$ is the variance of v conditional on $K\beta_F v + z$ and the floor traders' other information, and where P is given by (1). Note that due to the normality of v and z, $E_F[v|K\beta_F v + z]$ is given by the regression of v on $K\beta_F v + z$:[7]

$$E_F[v|K\beta_F v + z] = \frac{K\beta_F \sigma^2}{K^2 \beta_F^2 \sigma^2 + S}(K\beta_F v + z) \tag{5}$$

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[7]The subscript on the expectations operator indicates that this expectation is conditional on the information available to the floor trader at the time he submits his order. Trading by limit order effectively permits conditioning orders on price. Since price is a linear function of order flow, this is equivalent to conditioning trades on order flow: This is true for upstairs traders as well.

Moreover, by (1), $E_F[P|K\beta_F v + z] = \lambda_F(K\beta_F v + z)$, and

$$\hat{\sigma}_F^2 = \frac{S\sigma^2}{K^2\beta_F^2\sigma^2 + S} \tag{6}$$

The first order conditions for a maximum imply:

$$y_i = \frac{t_i[\frac{K\beta_F\sigma^2}{K^2\beta_F^2\sigma^2 + S} - \lambda_F](K\beta_F v + z)}{\hat{\sigma}_F^2} \tag{7}$$

Conditional on order flow upstairs trader U_j chooses his trade x_j to maximize his risk-adjusted profit:

$$E_U\Pi_j = \max_{x_j}\{x_j E_U[v - P|K\beta_F v + z] - \frac{.5\hat{\sigma}_U^2 x_j^2}{\tau_j}\} \tag{8}$$

where $\hat{\sigma}_U^2$ is the variance of v conditional on $K\beta_F v + z$ and the information available to the upstairs trader, and where P is given by (1). Note that due to the normality of v and z, $E_U[v|K\beta_F v + z]$ is:

$$E_U[v|K\beta_F v + z] = \frac{K\beta_F\Delta\theta\sigma^2}{K^2\beta_F^2\Delta\theta\sigma^2 + S}(K\beta_F v + z) \tag{9}$$

Moreover, by (1), $E_U[P|K\beta_F v + z] = \lambda_F(K\beta_F v + z)$, and

$$\hat{\sigma}_U^2 = \frac{S\Delta\theta\sigma^2}{K^2\beta_F^2\Delta\theta\sigma^2 + S} \tag{10}$$

Define $\eta = \Delta\theta$. The first order conditions for a maximum imply:

$$x_j = \frac{\tau_j[\frac{K\beta_F\eta\sigma^2}{K^2\beta_F^2\eta\sigma^2 + S} - \lambda_F](K\beta_F v + z)}{\hat{\sigma}_U^2} \tag{11}$$

Market clearing implies:

$$\sum_{F_i\in\mathbf{F}} y_i + \sum_{U_j\in\mathbf{U}} x_j + K\beta_F v + z = 0. \tag{12}$$

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Substituting the expressions for the y_i and x_j and simplifying implies:

$$\lambda_F = \frac{1}{\frac{T_F}{\hat{\sigma}_F^2} + \frac{\mathcal{T}_\mathcal{U}}{\hat{\sigma}_U^2}}[1 + \frac{K\beta_F(T_F + \mathcal{T}_\mathcal{U})}{S}] \tag{13}$$

Substituting from (6) for $\hat{\sigma}_F^2$, from (10) for $\hat{\sigma}_U^2$ and from (3) for λ_F produces a quadratic equation in β_F:

$$T_F + \frac{\mathcal{T}_\mathcal{U}}{\Delta\theta} = \sigma^2(K+1)\beta_F + \beta_F^2\frac{K(T_F + \mathcal{T}_\mathcal{U})}{S} \tag{14}$$

The positive root of this equation gives the equilibrium β_F, and hence the equilibrium λ_F.

Note that λ_F measures the liquidity of the open outcry exchange. As shown in Pirrong (2002, 2003a-b), noise trader expected trading costs are increasing in λ_F; hence, the market is less liquid, the greater is λ_F. Taking derivatives of the relevant quadratic generates several key results.

1. λ_F is decreasing in T_F. Hence, the market is more liquid, the greater the risk bearing capacity of the floor traders.

2. λ_F is decreasing in $\mathcal{T}_\mathcal{U}$. Hence, the market is more liquid, the greater the risk bearing capacity of the floor traders.

3. λ_F is increasing in η, and hence is increasing in Δ and θ. This implies that the market is less liquid, the greater the time and space advantage of the floor traders. Moreover, the market is less liquid, the less precise the information possessed by upstairs traders at any point in time. All of these factors make supply of liquidity from upstairs traders less elastic.

4. λ_F is decreasing in S, and becomes arbitrarily large as S approaches zero. This result is relevant in evaluating the effect of coordination costs.

It is also possible to show that the risk adjusted profit earned by each floor trader and each upstairs trader depends on these parameters. Of particular importance for the purposes of this analysis is the fact that the risk adjusted profit earned by floor traders is inversely related to $\mathcal{T}_{\mathcal{U}}$ and positively related to Δ and θ. That is, floor trading is more profitable, the lower the aggregate risk tolerance of the upstairs traders, the greater the floor traders' time and space advantage, and the greater their information advantage at any point in time.

3   Liquidity in a Computerized Market

In a computerized market, all traders are upstairs traders; the traders in **F** must trade upstairs to supply liquidity in a computerized market.[8] This

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[8]I assume that holding the precision of information constant, floor traders are equally efficient supplying liquidity in computerized and floor-based markets. That is, the risk tolerance of $F_i \in \mathbf{F}$ equals t_i in both the computerized and floor-based markets. It may be the case that floor traders are less efficient supplying liquidity in the upstairs market than on the floor since the habits learned in trading on the floor may not be well-adapted to trading on a screen. *The Wall Street Journal Europe* reported that many floor traders on LIFFE were not able to make the transition to trading upstairs (Silvia Ascarelli, "Derivatives Traders Struggle to Grasp Meaning of LIFFE–London Dealers Put Down Their Arms as Exchange Adopts Electronic System," *Wall Street Journal Europe,* November 19, 1999). This is consistent with a decline in t_i when a floor trader moves upstairs. However, it is difficult to determine whether the difficulty floor traders have experienced making the transition upstairs is due to reduced risk bearing capacity owing to the mismatch between floor traders' skills and the computerized trading mechanism (holding information constant) or to less information available being available upstairs (i.e., $\theta > 1$) or to greater competition from upstairs traders (due to the elimination of

has two key implications. First, since upstairs traders in a computerized market can monitor conditions in real time and face no delay in submitting or withdrawing limit orders, computerization eliminates the time and space disadvantage of upstairs traders; now both upstairs and former floor traders can submit their orders at time X_F and the market clears at $X_F + dt$.[9] Second, computerization eliminates the information disparities between floor traders and upstairs traders.

These factors affect the variances that determine the risk of trading in the upstairs market. At the time they must submit their demand schedules of limit orders, those traders in **F** who could trade on the floor in a floor-based

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the upstairs traders' time-space disadvantage). If the first alternative is the correct one (i.e., floor traders do worse upstairs because trading on screen lowers their t_i rather than due to the elimination of information or to greater competition) the following analysis overstates the liquidity of the computerized market. This possibility can be incorporated into the analysis readily through the addition of another parameter, but the conclusion is intuitive. A decline in t_i resulting from the move upstairs reduces the liquidity of the computerized market (relative to that derived here) and therefore favors the open outcry market *ceteris paribus.* It should also be noted that some floor traders from LIFFE did make the transition; several computerized trading "arcades" catering to floor traders opened after the closure of LIFFE's floor (Young and Theys, 1999). Moreover, most MATIF locals made the transition to electronic trading; indeed, the number of locals on MATIF rose after the commencement of electronic trading (Young and Theys, 1999).

[9]This presumes that the trading system has sufficient capacity and bandwidth. Some systems (notably Eurex in 1998 when its volume surged) have experienced capacity bottlenecks that have introduced time lags between order submission and execution (Young and Theys, 1999). Such delays increase the risks and costs of supplying liquidity on a computerized system. The adverse effects of bottlenecks can be addressed formally by introducing a parameter $\Delta_C > 1$ analogous to the Δ parameter in the open outcry model. Miller (1991) argues that features inherent in computerized trading force all users to extend free options to the market. This could also create a $\Delta_C > 1$. It should be noted, however, that designers of computerized systems have recognized this problem and have implemented shortcuts to allow users to revise and cancel orders at a keystroke. Such features sharply mitigate the free option problem. Moreover, it almost certainly true that $\Delta_C < \Delta$, i.e., upstairs traders get faster execution in a computerized market.

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exchange estimate that the mean of the instrument is zero and its variance (before conditioning on price) is $\theta\sigma^2$. Since the upstairs traders in **U** no longer face a time and space disadvantage when trading in a computerized market, their estimate of its variance (before conditioning on price) is also $\theta\sigma^2$.

An analysis similar to that performed above implies that:

$$\lambda_C = \frac{\hat{\sigma}_C^2}{T_F + \mathcal{T_U}} + \frac{K\beta_C\hat{\sigma}_C^2}{S} \tag{15}$$

where λ_C is the depth of the computerized exchange, $\beta_C = 1/(K+1)\lambda_C$ gives the intensity of informed trading in the computerized market, and

$$\hat{\sigma}_C^2 = \frac{S\theta\sigma^2}{K^2\beta_C^2\theta\sigma^2 + S} \tag{16}$$

is the variance of the instrument's value conditional on price and the information available at the time of order submission.

Substituting $\lambda_C = 1/\beta_C(K+1)$ and from (16) into (15) implies a quadratic equation in β_C:

$$\frac{T_F + \mathcal{T_U}}{\theta} = \sigma^2(K+1)\beta_C + \beta_C^2\frac{K(T_F + \mathcal{T_U})}{S} \tag{17}$$

The positive root of this quadratic gives the equilibrium intensity of informed trading, and hence liquidity, on the computerized market.

4   A Comparison of the Liquidity of Computerized and Floor Exchanges

Since (a) λ_F and λ_C are each decreasing in the variance of noise trader order flow, and (b) the variance of noise trader order flow is proportional to the

number of noise traders trading on an exchange, liquidity on an exchange is maximized (i.e., its λ is minimized) when all noise traders trade there. Thus, it is efficient to concentrate noise trader activity on the exchange that offers the smallest λ evaluated when noise trader order flow equals S. Therefore, to determine relative potential liquidity, it is appropriate to compare λ_C and λ_F assuming all noise traders congregate at each type of exchange.[10]

Since (a) the positive root β_F increases as the left-hand-side of (14) rises, and (b) the positive root β_C increases as the left-hand-side of (17) rises, $T_F + \frac{\mathcal{T}_\mathcal{U}}{\Delta\theta} \leq \frac{T_F + \mathcal{T}_\mathcal{U}}{\theta} \rightarrow \beta_F \leq \beta_C$. Thus, $T_F + \frac{\mathcal{T}_\mathcal{U}}{\Delta\theta} \leq \frac{T_F + \mathcal{T}_\mathcal{U}}{\theta} \rightarrow \lambda_C \leq \lambda_F$. That is, the computerized market is more liquid than the open outcry exchange if and only if $T_F + \frac{\mathcal{T}_\mathcal{U}}{\Delta\theta} < \frac{T_F + \mathcal{T}_\mathcal{U}}{\theta}$.

Rewriting this expression implies the computerized exchange is more liquid if and only if:

$$\mathcal{T}_\mathcal{U}(1 - \frac{1}{\Delta}) > (\theta - 1)T_F \tag{18}$$

This expression states that the relative liquidity of open outcry and computerized exchanges depends on (a) the relative size of the upstairs and downstairs liquidity pools (as measured by $\mathcal{T}_\mathcal{U}$ and T_F), (b) the upstairs information disadvantage/advantage (as measured by θ), and (c) upstairs traders' time and space disadvantage in an open outcry market (as measured by Δ).[11]

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[10]It is possible to show using an analysis similar to that in Pirrong (2002, 2003a) that total cost, defined as the sum of noise trader execution costs net of risk-adjusted liquidity supplier profits and informed trader profits, is decreasing in λ. Hence, it is efficient to concentrate trading on the exchange with the lowest λ.

[11]This expression is relevant for given K, S, and σ^2, as would be the case if one were comparing the effect of changing trading technology on the liquidity of a particular security

Several results follow from this expression:

Result 1 $\theta > 1$ *is a necessary condition for the open outcry market to be more liquid than the computerized market. That is, the open outcry market is more liquid only if traders on the floor of an exchange have better information (at a point in time) than upstairs traders.*

The intuition behind this result is straightforward. Since (a) upstairs traders are not at a time and space disadvantage in supplying liquidity in the computerized market, but are in the floor-based one, and (b) when $\theta = 1$ both types of traders have equally precise information at the time they submit their orders in a computerized market, upstairs traders face less risk in submitting an order in the computerized exchange than in the open outcry market. Thus, it is cheaper for upstairs traders to supply liquidity in the computerized market, and they take larger positions at any given price in that market than in the open outcry exchange. With $\theta = 1$, traders in **F** incur the same cost to supply liquidity in the computerized and open outcry markets so the change in technology has no effect on their trading strategies. Thus, with $\theta = 1$, liquidity supplied by upstairs traders is greater and liquidity supplied by traders in **F** is the same in the computerized market as compared to the open outcry market. In this case, a computerized market is more liquid than an open outcry exchange.

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or contingent claim. Cross-sectional comparisions (e.g., a comparision of the liquidity of a French stock traded on computer and a US stock traded on the floor) would require controlling for variations in K, S, and σ^2 across instruments. This issue is discussed below.

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Although superior information on the floor is a necessary condition for an open outcry exchange to be more liquid than a computerized one, it is not sufficient. In particular, the floor's information advantage can be offset by a sufficiently large $\mathcal{T}_{\mathcal{U}}$:

Result 2 *Given T_F, θ, and Δ, there is a critical value of $\mathcal{T}_{\mathcal{U}}$, $\mathcal{T}_{\mathcal{U}}^* = T_F(\theta - 1)/(1 - 1/\Delta)$, such that if $\mathcal{T}_{\mathcal{U}} > \mathcal{T}_{\mathcal{U}}^*$ the computerized market is more liquid than the open outcry exchange. $\mathcal{T}_{\mathcal{U}}^*$ is increasing in θ and T_F, and decreasing in Δ.*

Increasing the risk bearing capacity of the upstairs traders increases liquidity in both the open outcry and computerized markets (i.e., $d\lambda_F/d\mathcal{T}_{\mathcal{U}} < 0$ and $d\lambda_F/d\mathcal{T}_{\mathcal{U}} < 0$), but an increase in upstairs risk bearing capacity has a bigger impact on liquidity in the computerized market (i.e., $d\lambda_C/d\mathcal{T}_{\mathcal{U}} < d\lambda_F/d\mathcal{T}_{\mathcal{U}}$). This result obtains because the time-space disadvantage taxes upstairs liquidity supply in the open outcry market; a given increase in $\mathcal{T}_{\mathcal{U}}$ causes a smaller increase in liquidity in the floor-based market than the computerized one because of the effects of this "tax."

Relatedly:

Result 3 *Given $\mathcal{T}_{\mathcal{U}}$, θ, and Δ, there is a critical value of T_F, $T_F^* = \mathcal{T}_{\mathcal{U}}(1 - 1/\Delta)/(\theta - 1)$, such that if $T_F > T_F^*$ the computerized market is less liquid than the open outcry exchange.*

The liquidity of both the open outcry and computerized markets is greater, the greater the risk bearing capacity of the floor traders. However, *ceteris paribus* an increase in the risk bearing capacity of the floor traders has a

smaller proportionate impact on the liquidity of the computerized market because upstairs liquidity supply is greater there.

Result 4 *Given θ, T_F, and $\mathcal{T_U}$, there is a critical of Δ, $\Delta^* = 1/(1+(1-\theta)\frac{T_F}{\mathcal{T_U}})$ such that the computerized market is more liquid if $\Delta > \Delta^*$.*

The greater the time-space tax, the greater the increase in liquidity supply that results from adoption of computerized trading.

The foregoing implies that changes that affect upstairs and floor risk bearing capacities, information disparities, and the time-space tax affect the relative liquidity of floor-based and computerized markets. This analysis permits an appraisal of the effect of several recent (and some not-so-recent) innovations on the relative liquidity of floor-based and computerized markets.

For instance, increases in the capital of institutional traders (e.g., hedge funds) increases upstairs risk bearing capacity. The model implies that *ceteris paribus* this increases the liquidity of the computerized market relative to the open outcry exchange.

Conversely, improvements in floor-based exchange order routing and handling systems increase the liquidity of open outcry markets relative to computerized ones. The model implies that innovations such as SuperDot and computerized specialist posts on the NYSE, or portable electronic broker terminals on the CBOE, increase floor liquidity because they increase the speed with which limit orders can be entered (and cancelled) from upstairs. This reduces Δ, which increases floor liquidity relative to computerized liquidity.

The model suggests that the development of ECNs and online trading has ambiguous effects. On the one hand, these innovations increase the supply

of upstairs risk bearing capacity; with them anyone with a computer and cash can supply liquidity by trading via limit order. Holding Δ constant, this increases the liquidity of the computerized market relative to that of the open outcry exchange. But these innovations also affect Δ. In particular, they reduce Δ because they make it easier for individuals to monitor an open outcry market and also allow them to submit (and cancel) more quickly limit orders directed to the exchange floor. Thus, online trading and ECNs has countervailing effects on the relative liquidity of computerized and open outcry markets, and consequently the net effect is ambiguous.

Finally, information technology affects the relative liquidity of computerized and floor-based markets. Improvements in information technology plausibly reduce θ. Upstairs traders can access electronic information sources more readily than floor traders. As another example, upstairs traders may have access to better analytics for pricing options. Improvements in information technology that improve the quality and quantity of information available via electronic means, and which enhance the functionality and ease of use of these means, increase the relative liquidity of the computerized market. Moreover, Young and Theys (1999) suggest some enhancements to computerized systems that would generate information that mimics the kinds of "soft" information available on the floor.[12] Specifically, they advocate enhanced visual (e.g., color graphics) and aural displays that communicate information

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[12]Some early electronic system designs actually attempted to do this. The NYSE-IBM Joint Study of automation of the floor process (completed in 1968) revealed the identity of the participants in the computerized auction for any stock. Similarly, LIFFE's APT and the CBOT's Aurora (which was never used for actual trading) revealed the identities of bidders and offerors.

about order flow and the number of participants currently active in a particular instrument to provide traders on a computerized system with some of the types of information available on the floor. Some upstairs traders have already developed such software. Thus, even if Cowan and Shumway are correct in opining that the floor currently offers richer information than existing computerized systems, this gap is likely to narrow over time.

This analysis has implications for cross-sectional comparisons of liquidity and trading costs on electronic and floor-based exchanges, such as Venkataraman's (2001) comparison of the electronic Paris Bourse and the NYSE. Venkataraman compares liquidity across exchanges trading different securities by controlling for observable differences that may be associated with the severity of adverse selection problems, the number of noise traders, and the variability in stock prices; his variables are plausible proxies for K, S, and σ^2.

However, liquidity can differ across trading venues even if one controls for differences in the characteristics of securities that may be related to the number of informed traders, noise trading activity, and uncertainty. In particular, risk bearing capacity may vary across markets. If it does, the model implies that liquidity will vary across markets as well even once differences related to variables such as K, S, and σ^2 are controlled for as done by Venkataraman and others. Existing cross-sectional studies do not control for possible differences in risk bearing capacities across markets, and hence cannot be used to determine whether changing trading technology in a *given* market (e.g., a switch to electronic trading on the NYSE) would cause liquidity to rise or fall in that market. Thus, although one may be tempted to interpret lower

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trading costs in a floor market in a cross-sectional study as indicating that the floor is "special" in some way–as would be the case if $\theta > 1$, for instance–such an interpretation is highly problematic if inter-market differences in risk bearing capacity are not controlled for.

It is not immediately obvious how one could control for differences in risk bearing capacity across markets. Specialist capital on the NYSE would be one measure of the capacity of a subset of liquidity suppliers in the US stock market, but since specialists make markets in several stocks there are obvious difficulties in using this data. Moreover, some floor brokers on the NYSE effectively supply liquidity when trading on behalf of institutions. The capital and risk preferences of these institutions influence NYSE risk bearing capacity, but are difficult to measure. Similar difficulties arise in attempting to determine risk bearing capacity in electronic markets. In futures markets the capitalization and risk preferences of locals who supply liquidity on the floor, and upstairs traders who supply liquidity by trading via limit order have not been measured heretofore. Unless risk bearing capacity can be measured and controlled for, cross sectional comparisons of liquidity across floor and electronic markets are of limited utility in determining whether the floor is indeed special–i.e., if $\theta > 1$.

5   Coordination Costs, Competition, and Exchange Ownership

The foregoing analysis is sufficient to demonstrate what factors determine whether a computerized exchange is more or less liquid than an open outcry market. However, equilibrium trading technology choices are not ordained

to maximize liquidity and efficiency, but result from economic processes. Explicit analysis of these processes is required to understand how liquidity differentials affect whether a particular instrument will be traded by open outcry or on computer.

Computerized trading may come to dominate because a computerized exchange prevails in competition with an open outcry market; the shift of trading in Bund futures contracts from the open outcry LIFFE to the computerized Eurex in 1998 is an example. Computerized trading may be adopted because an existing open outcry exchange decides to replace floor trading with a computerized market, á la the Sydney Futures Exchange's and LIFFE's shifts to computers in 1999. As numerous examples attest, an exchange beginning trading in a new instrument may adopt computerized trading from the outset. Conversely, open outcry markets may prevail in competition with a computerized rival, existing open outcry markets may decline to shift to computerized trading (e.g., the IPE), or new products may be traded on open outcry exchanges. Moreover, open outcry and computerized exchanges may compete directly and both survive for some time, as is the case in the U.S. options markets (although the following analysis suggests that this is unlikely to remain the case in the longer term).

The foregoing list of alternatives suggests two key factors *in addition to liquidity differences* likely influence equilibrium trading technology–the nature of competition between exchanges and exchange ownership and governance structures. The nature of competition influences how liquidity differences affect which exchange that noise traders choose to patronize. Absent perfect competition between exchanges, the less liquid trading technology

can survive. Morever, since (as will be seen) trading technology choice has distributive as well as efficiency effects, absent perfect competition the choice of trading technology may depend on who owns and controls an exchange.

Imperfect competition is a very real possibility given the network aspects of liquidity. As in other microstructure models (Pirrong, 2002, 2003a; Madhavan, 2000), both the computerized and open outcry exchanges in the present model exhibit increasing returns to scale. That is, liquidity of both the computerized and open outcry exchange is increasing with the number of noise traders who trade on them because λ_C and λ_F are both decreasing in noise trader volatility S. This has important implications for the nature of competition between an open outcry market and a computerized exchange.

In particular, the increasing returns to scale for both the electronic and open outcry markets implies that competition between exchanges exhibits "tippiness"; if a computerized and open outcry exchange compete, the only stable equilibria involve all noise traders (and all liquidity suppliers) choosing to patronize a single exchange. Any intermediate equilibrium in which some noise traders patronize the computerized market and the remainder trade in the floor-based exchange is not stable; starting at any such equilibrium point, any movement of noise traders from one exchange from to the other tends to "tip" the remaining noise traders towards to that exchange.[13]

There is evidence of "tippiness" in derivatives markets. In 1997-1998, the market share of Eurex in the Bund market grew from about 30 percent to 100 percent within a period of months. Similarly, when MATIF operated

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[13]See Pirrong (2002b) for a proof.

electronic and floor market simultaneously, volume tipped completely to the computerized system within weeks of its activation. Moreover, the fact that all trading in a single instrument tends to congregate on a single exchange (as documented by Pirrong, 1999) is consistent with the existence of network effects.[14]

If noise traders can coordinate costlessly, they will select the exchange that maximizes liquidity and thereby minimizes total trading cost. Similarly, as shown in Farrell and Saloner (1985), if noise traders choose the exchange they patronize sequentially with perfect and complete information, a dynamic selection process tips the market to the more efficient system.

However, with costly coordination or imperfect or incomplete information, it is possible that the less liquid exchange (the exchange with the larger minimum potential λ) can attract the entire order flow. That is, with costly coordination, liquidity differences alone do not determine the market to which volume "tips."[15] The less liquid, higher cost trading technology may survive in competition with a more liquid, lower cost technology. Given this possibility, it is likely that an incumbent technology–open outcry trading in most cases–has an important competitive advantage because to prevail, a computerized entrant must arrange a coordinated defection of noise traders from the

[14]Most cases of market fragmentation–the trading of a given instrument in multiple venues–are attributable to "cream skimming" not considered herein. That is, most "satellite markets" survive only by restricting trading to the verifiably uninformed. See Pirrong (2002, 2003a) for a formal analysis predicting this result and a discussion of the substantial empirical evidence supporting this prediction. The model of this article can be extended to address the possibility of cream skimming competition for a main exchange.

[15]Hereafter, I will use the term "coordination costs" to encompass imperfect and incomplete information.

open outcry incumbent (Pirrong, 1995).

This implies that coordination costs might have a decisive influence on the timing of the adoption of computerized trading. This further suggests that control of order flow might influence the timing of computerization. For instance, if brokerage firms have discretion over routing of the order flow investors and hedgers direct to them, they can affect which exchange prevails in the "winner take all" competition. A small number of large brokerage firms controlling a substantial portion of order flow may be able to coordinate more effectively than diffuse and dispersed individual investors or a set of small brokers. If so, they can exert a potentially decisive impact on trading technology choice. If further they act as perfect agents for their customers (and thereby coordinate their choices to minimize customers' trading costs), such coordination facilitates the tipping of the market to the more efficient technology. For example, Pirrong (2003c) argues that the patronage of large German banks that (a) owned Eurex, and (b) controlled large order flows, was essential to Eurex's capture of the Bund market.

The issues of agency costs and imperfect competition (due to coordination costs and network effects) motivate discussion of another issue–the distributive effects of trading technology and the resulting importance of the organization and control of exchanges. Trading technology choice has distributive implications; for some parameter values computerization benefits upstairs traders and harms floor traders.[16] The longstanding support of

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[16]This is true for reasons over and above those considered in the formal model. The formal model treats floor traders as liquidity suppliers. In fact, some floor traders supply brokerage services which are superfluous in an electronic environment. In general, there is no consistent relation between the effect of parameter changes and technology choice on

upstairs firms such as Morgan Stanley, Goldman Sachs, and Merrill Lynch (sometimes referred to as "MGM") for the adoption of a computerized central limit order book for stocks in lieu of the NYSE floor, and the fierce resistance of the floor community of the NYSE to such proposals illustrates the importance of these distributive effects.

The distributive impact is especially important when considering whether an incumbent open outcry exchange will adopt computerized trading. As noted earlier, the existence of coordination costs and network effects (with the concommitant imperfections in competition) might allow an exchange to choose the less liquid trading technology and survive. If so, a dominant coalition of exchange member-owners can induce the exchange to adopt the trading technology that benefits them even though this technology is inefficient. Thus, if upstairs firms dominate an exchange's membership and computerized trading enhances their profits, they could force adoption of a putatively less liquid computerized trading system. Conversely, if the floor community dominates the membership (as is the case at most U.S. derivatives and equity exchanges), the protective umbrella provided by coordination costs and

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liquidity and profitability. The move to computerized trading actually reduces upstairs traders' profits under certain parameter values. Although upstairs traders' share of trading activity is larger with computerized trading, the concommitant decline in their variance estimates exerts downward pressure on their risk-adjusted profits because competition between upstairs traders becomes more intense when Δ falls. If $\mathcal{T}_\mathcal{U}$ is large relative to T_F this increased competition between upstairs traders can result in lower profits in a computerized market. This can occur even if the computerized market is more liquid–indeed, it occurs in part because the computerized market is more liquid. Thus, upstairs traders may not support computerization even if it is more efficient. In the presence of coordination costs, in such circumstances upstairs and downstairs traders may agree to perpetuate floor trading even if this is inefficient. Whatever the exact effect, the general point holds; trading technology changes have distributive effects.

network effects might allow floor members to perpetuate open outcry rather than adopt a putatively more liquid computerized system.[17]

This analysis implies that ownership and governance structures of exchanges affect the timing of the adoption of computerized trading. Ownership and governance structures affect the ability of exchange factions to negotiate arrangements that increase the *joint* wealth of the parties (Pirrong, 2000). Since real world ownership and governance structures do not support all wealth-enhancing "Coasean bargains" among exchange members, frictions inherent in such structures can permit the adoption of a less liquid trading technology.

Integration between trading and brokerage functions in upstairs firms may impact both coordination costs and ownership/governance effects. Some upstairs firms can supply both liquidity and brokerage; their brokerage function gives them influence over the routing of order flow. Their liquidity supply function may give them an incentive to support electronic trading. This incentive is strengthened if (a) computerized markets are more liquid, and (b) these firms internalize the interests of their brokerage customers. Their ability to influence the direction of order flow may also affect their bargaining power in negotiations with members of an incumbent open outcry exchange.

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[17]It is a stylized fact that individuals who trade on the floor dominate the governance of US exchanges, but that corporations (notably banks and brokerage firms) exert far more influence in non-US exchanges than their US counterparts (Young and Theyss, 1999). The pattern of trading technology adoption–with computerized trading making far more headway outside the United States than within it–is consistent with the hypothesis that the interests of dominant membership coalitions influence technology choice. It should also be noted, however, that the large population of skilled floor traders on US exchanges (relative to their European counterparts) implies a large T_F, which would lead to the same result.

If large brokers can coordinate more cheaply than dispersed investors and hedgers, they can more credibly threaten to support a computerized exchange that competes with an incumbent open outcry exchange; indeed, such firms may have an incentive to create such an exchange. The more credible this threat, the greater the power of these integrated firms in negotiations regarding adoption of computerized trading with other members of an incumbent open outcry exchange.[18]

In sum, due to the nature of liquidity, competition in financial markets is likely imperfect, thereby allowing the survival of a less-liquid trading technology. Since liquidity considerations create network effects, trading technology choice is not necessarily determined solely by the relative liquidity of computerized and open outcry markets; liquidity exerts a centripetal force that tends to attract all trading activity to a single exchange. Relative liquidity determines the winning technology if the costs of coordinating movement of noise traders (i.e., investors and hedgers) is sufficiently small. However, an inefficient trading technology may prevail if such costs are high. Thus, factors that influence coordination costs also influence the choice of trading technology. Moreover, since technology choice has distributive effects as

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[18]Of course, there may be a conflict between the interests of the integrated firm and its customers. The trading desks of these firms could prefer adoption of an electronic system even when the computerized market is less liquid (and thereby imposes higher trading costs on the firms' customers). Agency costs between the brokerage firms and their customers could lead the firms to support electronic trading even when this is less efficient. Use of an inefficient trading technology creates a deadweight loss and reduces consumer and producer surplus (i.e., the profits of brokerage firms). Pirrong (1995) demonstrates that the decline in brokerage firms' surplus resulting from an inefficient technology depends on the elasticity of supply of brokerage services. If brokerage supply is very elastic (inelastic), brokers will have a small (large) stake in seeing that the efficient technology is adopted.

well as efficiency ramifications, exchange organization, ownership, and governance can also affect technology choice in the presence of coordination costs. Most notably, an incumbent exchange's technology choice is affected by (a) the relative power of upstairs and floor traders in exchange decision making, and (b) the ability of the exchange governance structure to support Coasean bargains between upstairs and downstairs traders (Pirrong, 2000). Thus, ownership of the exchange (e.g., do floor members or upstairs firms represent a majority?) and the nature of exchange governance affect technology choice.

Although owing to the competitive imperfections resulting from network effects and coordination costs there is no guarantee that the technology adopted is the efficient one, it is clear that the liquidity gap cannot become arbitrarily large. A sufficiently large liquidity difference between two trading technologies can overcome the competitive impediments posed by coordination costs. Moreover, a large liquidity difference creates large gains from trade; a sufficiently large difference creates gains of trade that are large enough to overcome the frictions that impede the consummation of some Coasean bargains among exchange members.

6   Summary and Conclusions

The idea of computerized trading dates back decades, but only in recent years has it acquired an aura of inevitability. Despite this aura, open outcry endures, at least in the United States. The rapid movement towards automation overseas and the continued dominance of floor trading in the US raises questions about the costs and benefits of alternative trading mechanisms, and the determinants of trading technology adoption.

Debates among academics and practitioners over which is the best trading technology have centered on which offers the greatest potential liquidity. The most staunch advocates of open outcry maintain that this trading method is inherently more liquid, but empirical evidence casts doubt on such claims.

To address these controversies, this article presents a microstructural model of computerized and open outcry exchanges. It implies that no single trading mechanism is inherently more liquid. Instead, the relative liquidity of computerized and open outcry markets depends on upstairs and downstairs risk bearing capacity, the magnitude of the risks attributable to their time and space disadvantage that upstairs traders incur to supply liquidity to the floor via limit order, and the quantity and quality of information available to upstairs and downstairs traders.

Computerized markets allow upstairs traders to supply liquidity more efficiently than is possible in an open outcry market; upstairs traders face a greater risk of being "picked off" when they submit limit orders to an exchange floor than if they can enter their orders directly on a computer system. If the pool of upstairs liquidity or the cost associated with the risk of being picked off are sufficiently large, the computerized market will be more liquid than a floor-based market. Moreover, upstairs traders and floor traders may possess different information. If (as some believe) the floor is informationally richer than upstairs dealing rooms, an open outcry exchange may be more liquid than a computerized one, but this is not necessarily so.

Recent institutional and technological changes have affected these factors. For instance, technology investments by open outcry exchanges have reduced the costs that upstairs traders incur to access the floor and thereby boosted

the liquidity of these exchanges. The growth of institutional trading has enhanced the upstairs liquidity pool, thereby increasing the relative liquidity of computerized trading systems. Some developments (such as online trading) likely have had ambiguous effects on the relative potential liquidity of open outcry and computerized exchanges.

Although the relative liquidity of computerized and open outcry markets certainly is an important determinant of trading technology choice, it is not the only factor. Owing to the network aspects of trading, coordination costs can permit an inefficient (i.e., less liquid) trading system to survive. Financial trading markets are "tippy" because investors prefer to trade where others do. If it is costly to coordinate the movement of investors to the more liquid market–as is almost certainly the case–the less liquid one may garner all of the trading volume. This implies that factors that influence coordination costs, which include the structure of the brokerage industry and the ownership and governance structures of exchanges, also influence trading technology choice.

It should also be noted that other factors, not explicitly modeled, influence the relative merits of computerized and open outcry markets. In particular, the costs of market operation (including capital costs, real estate and facilities costs, labor costs, and error costs) will also exert an influence on technology choice.[19] The same caveat just mentioned still applies, however;

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[19]See Young and Theys (1999) for a discussion of the comparative costs of open outcry and electronic exchanges. They argue that computerized markets are substantially cheaper to build and operate. Although it is widely believed that computerized systems are less vulnerable to errors than floors, Young and Theys identify some sources of trading errors (e.g., "fat finger problems," spilled coffee, swinging elbows hitting function keys) that are unique to computerized systems and are potentially quite costly. Pirrong (2003c) presents evidence that liquidity differences between LIFFE and Eurex were extremely small, and

given the network and coordination aspects of financial trading, the cheapest technology (including both liquidity and operational costs) may not prevail.

The analysis presented in this article suggests that it is hazardous indeed to attempt to predict (a) which trading technology will prevail and (b) the timing of a switch in trading technology. Myriad technological, financial, and institutional factors affect the costs and benefits of computerized and open outcry markets. Moreover, network effects, the frictions created by coordination costs, and the distributive effects of technology choice imply that shifts in trading technology in a given market will be abrupt, complete, and only partially driven by liquidity and operating cost considerations. Given these conditions, surprising shifts in the dominant technology (e.g., the movement of Bund futures trading from LIFFE to Eurex) and the unexpected longevity of an existing technology (e.g., the tenacious persistence of open outcry in the US) should not be so startling after all.

A   An Alternative Model

The model in the text assumes that upstairs' and floor traders' information affects their estimate of the variance of v, but not their estimates of the mean of v. This simplifies the analysis considerably, but this appendix demonstrates that a similar model in which agents receive signals that affect both the mean and variance of their estimates of v leads to similar results.

Specifically, consider an adaptation the model of Hellwig (1980) that

that Eurex's operational cost advantage was decisive in tipping the Bund market in its favor.

Brown-Zhang (1997) use to characterize equilibrium in a competitive limit order market. In the model of the open outcry exchange, at the time he must submit an order to the exchange, floor trader $F_i \in \mathbf{F}$ observes a signal of value $v + \epsilon_i$ and upstairs trader $U_j \in \mathbf{U}$ observes a signal $v + \delta_j + \phi_j$ where: $E(v^2) = \Sigma_v$, $E(\delta_j) = 0$, $E(\delta_j^2) = \Sigma_\delta$, $E(\phi_j) = 0$, $E(\phi_j^2) = \Sigma_\phi$, and $E(\epsilon_j) = 0$, $E(\epsilon_j^2) = \Sigma_\epsilon$.[20] The fact that upstairs traders have an additional source of noise in their signal (the δ_j) reflects their time and space disadvantage. Moreover, if Σ_ϕ differs from Σ_ϵ, the precision of floor traders' and upstairs traders' signals differ even absent a time and space effect. Floor traders have an information advantage if $\Sigma_\epsilon < \Sigma_\phi$; upstairs traders have an information advantage (at any given time) if the reverse holds. Noise traders submit market orders to trade; there are no perfectly informed, market-order traders in this model. The variance of noise trader order flow is S.

As the number of upstairs and floor traders becomes arbitrarily large, Hellwig proves that the liquidity parameter converges to:

$$\lambda_F = \frac{\Sigma_v S + \Sigma_v A_F B_F}{S A_F + \Sigma_v S B_F + \Sigma_v A_F B_F^2} \tag{19}$$

where

$$A_F = \int_{F_i \in \mathbf{F}} t_i dQ_{\mathbf{F}} + \int_{U_j \in \mathbf{U}} \tau_j dQ_{\mathbf{U}}. \tag{20}$$

and

$$B_F = \int_{F_i \in \mathbf{F}} \frac{t_i}{\Sigma_\epsilon} dQ_{\mathbf{F}} + \int_{U_j \in \mathbf{U}} \frac{\tau_j}{\Sigma_\delta + \Sigma_\phi} dQ_{\mathbf{U}}. \tag{21}$$

In these expressions, $Q_{\mathbf{F}}$ ($Q_{\mathbf{U}}$) is the measure of the set of floor (upstairs) traders.

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[20]The analysis can be extended to allow for individualized signal precisions.

In the computerized market, each trader in $\mathbf{U}$ and each trader in $\mathbf{F}$ observes a signal $v + \phi_i$, where as before $E(\phi_i^2) = \Sigma_\phi$. Here:

$$\lambda_C = \frac{\Sigma_v S + \Sigma_v A_C B_C}{S A_C + \Sigma_v S B_C + \Sigma_v A_C B_C^2} \tag{22}$$

where

$$A_C = \int_{F_i \in \mathbf{F}} t_i dQ_{\mathbf{F}} + \int_{U_j \in \mathbf{U}} \tau_j dQ_{\mathbf{U}}. \tag{23}$$

and

$$B_C = \int_{F_i \in \mathbf{F}} \frac{t_i}{\Sigma_\phi} dQ_{\mathbf{F}} + \int_{U_j \in \mathbf{U}} \frac{\tau_j}{\Sigma_\phi} dQ_{\mathbf{U}}. \tag{24}$$

The expression for B_C takes this form because in the computerized market (a) upstairs traders face no time and space disadvantage, and thus have a more precise signal with error variance Σ_ϕ rather than $\Sigma_\delta + \Sigma_\phi$, and (b) the traders in $\mathbf{F}$ now see the same information as the upstairs traders, and hence receive a signal with variance Σ_ϕ rather than Σ_ϵ

Taking the derivatives of (21) and (24) implies that $d\lambda_F/dB_F < 0$, and $d\lambda_C/dB_C < 0$ unless traders' signals are very noisy.[21] Moreover, B_F and B_C are greater, the more precise the signals traders receive. Owing to these comparative statics, the effects of trading technology are identical between this model and that in the main text if traders' signals are not too noisy.

First, by increasing the precision of their information, the move to a computerized market reduces the risk upstairs traders incur to supply liquidity,

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[21] This is easiest to see in the computerized market. In this case, the derivative is negative as long as $\Sigma_\phi \leq \Sigma_v [A_C^4 + 2A_C^2]/[A_C^2 - \Sigma_v S]$. Thus, as long as the traders' signals are not too noisy, the derivative is negative; for instance, the derivative is negative if $\Sigma_\phi \leq 2\Sigma_v$. A similar (but messier) result obtains for the floor trading case. The critical degree of noisiness depends on total risk tolerance, the variance of noise trader order flow, and the unconditional variance of v.

which in turn increases liquidity through its effect on B_C (again assuming that the signals are not too noisy). If the risk bearing capacity of the upstairs traders is large enough, and/or the reduction in risk is great enough, the computerized market may be more liquid than the open outcry exchange.

Second, liquidity is greater in a computerized market if $\Sigma_\phi < \Sigma_\epsilon$, but liquidity may be greater in the open outcry market if the reverse is true.

Third, relative liquidity depends on the risk bearing capacities on the floor and upstairs. Holding risk bearing capacity of floor traders ($\int t_i dQ_{\mathbf{F}}$) constant, an increase in the risk bearing capacity of the upstairs market ($\int \tau_j dQ_{\mathbf{U}}$) increases the liquidity of the computerized market relative to the liquidity of the open outcry market. Similarly, an increase in the risk bearing capacity of the floor traders (holding that of the upstairs traders constant) increases the liquidity of the open outcry market relative to the computerized exchange.

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