Time and Pro-rata Matching: Evidence of a change in LIFFE STIR Futures

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Abstract

We examine the impact of the introduction of a time pro-rata matching algorithm on market quality in the NYSE LIFFE Futures market. Using microsecond stamped trade and order data we are able to characterize the trading and quoting behavior of agents in this market which allows us to test a range of theories on optimal allocation methods. We show that removal of the pure pro-rata matching algorithm eliminates the incentives for traders to "drown" the order book with overly large orders. Instead, the introduction of a time element to the priority algorithm encourages traders to submit many very small (single share) orders after their primary order which then serves to increase their time priority, as compared to traders submitting orders subsequently. This conduct appears to have a negative impact on market quality, with the Euribor, Euroswiss and Short Sterling contracts all showing a deterioration in a variety of liquidity measures, including effective spreads, reductions in quoted depth and trading volumes. The staggered introduction of the time pro-rata matching algorithm across the three contracts provides a natural experimental setting to test the impact of this change.

JEL classification: G13, G14

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1. Introduction

A key issue of interest to regulators, exchange operators and market participants is the design of markets to optimise market quality. The choice of order precedence rules in an exchange's order matching engine is perhaps one of the most important of all market design choices. Perhaps for this reason the NYSE LIFFE[1] has utilised several different order precedence rules since 1999. Order precedence rules governs how competing limit orders submitted to an exchange will be executed in comparison to other orders in the book. We use microsecond level trade and order data to examine the staggered introduction of a time pro-rata precedence rule for short term interest rate futures. We test theoretical evidence on optimal trader behaviour in the presence of such execution mechanisms and document the impact this change has on the quality of the LIFFE market, one of the largest futures markets in the world, trading over 941,000,000 contracts worth one million euros each in 2013 alone.[2]

Most equities markets adopt a pure price-time priority order precedence rule. The LIFFE market has had a variety of matching algorithms since 1999, when a priority pro-rata mechanism was introduced. Priority pro-rata gave priority to the first order submitted and then allocated the remaining volume based on an individual orders share of the total quantity demanded at that price step. In 2005 the LIFFE abandoned the priority allocation, moving to a pure pro-rata allocation. This meant that it was no longer important how long an order had resided in the order book, rather the only consideration was the size of the passive order relative to total prevailing depth. Lepone and Yang (2012) provide evidence that this change harmed market quality by reducing depth and increasing quoted spreads. This pro-rata mechanism was adopted until 2007 when market regulators opted to switch to a mixed time pro-rata matching algorithm. This paper focuses on this particular change.

In the context of the ongoing debate around the merits of high frequency trading (HFT), where participants vie for favourable queue position through high frequency order submissions and cancellations, some have proposed "frequent batch auctions" as a market design response (Budish, Cramton, and Shim, 2013) or "minimum resting times" for orders (Stafford 2014). Indeed, the existence of pro-rata allocation may favour HFT participants as the cost to cancel and re-enter orders is lowest for these participants. The removal of time priority also reduces the disincentives that would usually be present with price-time priority.

The remainder of this study is structured as follows: Section 2 documents the institutional settings of the NYSE LIFFE market. Section 3 reviews the existing literature and develops hypotheses' based on this literature. Sections 4 and 5 outline the data and method used in our analysis. Section 6 examines the results of our study, Section 7 tests the robustness of our findings and Section 8 concludes.

2. Institutional setting

In August 2007, NYSE LIFFE introduced a new trade matching algorithm on the three month Sterling (Short Sterling) with the key feature of the system being that it combines price-time priority with pro-rata matching. Up until this point, LIFFE had operated a pro-rata algorithm, introduced in August 2005, where incoming markets orders were allocated among passive limit orders in proportion to the size of the limit order without consideration to when these

[1] The London International Financial Futures and Options Exchange
[2] See NYSE Euronext Global Derivatives Monthly Statistics (www.glovalderivatives.nyx.com)

orders were submitted. In such a system, the larger the limit order in proportion to the prevailing level of depth, the higher the allocation against the incoming market order. Following a successful trial, the matching system was introduced for the three month Euro (Euribor) futures and three month Swiss (Euroswiss) Futures in September 2007.[3]

The mixed time pro-rata system used for LIFFE's Euribor, Short-Sterling, and Euroswiss contracts determines the allocation of volume by considering the size of passive order and well as their relative time of entry into the market. The allocation is specifically determined according to an algorithm presented below:

$$A_n = MIN\left\{v_n\,, \frac{f_n}{\sum_{r=1}^{N} f_r} \times M\right\}$$

$$f_n = \left(\frac{v_n}{\sum_{r=1}^{N} v_r}\right) \times \left(\frac{(N+1)-n}{\sum_{r=1}^{N} r}\right)$$

where; A is the allocation volume for each resting order *n* against incoming market orders of *M* size. N is the total number of resting orwders at the best bid or ask, sorted by time (such that n=1 is the oldest to the newest, N); n is the individual order being considered, r is the ascending time priority sequence 1 to N; A_n is the allocation for resting limit order *n*; v_n is the volume of the resting limit order being considered, *n*; f_n is the "Time Pro-Rata" factor calculated for the resting limit order being considered, *n*; and *M* is the incoming market order volume.[4]

The implementation of such an allocation system in short-term interest rate futures (STIRs) is due fundamentally to characteristics of these contracts. STIRs exhibit low volatility compared to the exchange imposed minimum price increment and furthermore bid and ask prices commonly stay at constant values for substantial periods of time. The use of some variant of pro-rata matching is therefore favourable in this setting since it ensures execution without necessarily requiring traders to cross the spread in order to get ahead in the queue.

3. Literature review and Hypotheses Development

STIR futures contracts provide fund managers, treasuries, and other market participants with the means and flexibility to manage their exposure to unanticipated movements in financial markets.[5] Unlike many security futures products, where the process of trade execution operates on a price-time priority basis, short-term interest futures contracts typically use some

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[3] Prior to the change in August 2005, LIFFE operated a 'Priority Pro-Rata' system. This algorithm operated as a pure-quantity matching system, with the exception of the first order at a given price which would receive 100% fill as long as the order satisfied the minimum volume threshold up to a cap. In 2013, LIFFE moved to adjust the time pro-rata system by increasing the time weighted component of the algorithm. However, after one day of operation, market operators quickly reversed the change following complaints from market participants.

[4] http://www.risk.net/risk-magazine/news/1501573/liffe-launch-pro-rata-algorithm-stir-futures

[5] It also provides participants with the ability to engage in speculative as well as arbitrage activities (either cross-market or cross-product).

variant of pro-rata matching. Contracts such as the Euribor and Short-Sterling which are traded on LIFFE, the Eurodollar which is traded on the CME, and the 2 year Treasury Notes traded on the CBOT, are all examples of contracts that utilise pro-rata trade execution.[6]

An examination of the existing research in this area shows a significant body of work on determinants of order submissions (e.g. Parlour 1998, Foucault 1999, Goettler et al 2005, Foucault et al., 2005, Rosu, 2009) including the response of limit orders to changes in spreads, depth, volatility, and other market conditions. Passive order traders incurs costs due to uncertain time to execution (Lo, MacKinlay and Zhang (2002), Parlour and Seppi (2008) as well as informational asymmetries (Huang and Stoll (1997). Yet despite the focus on optimal trading strategies, there is a distinct lack of literature on how a change to an order submission regime impacts on trader behaviour and market quality. This is perhaps unsurprising when one considers that wholesale regime changes related to trade execution are quite rare.

Perhaps the closest examination of the issues covered in this paper is provided by Lepone and Yang (2012). The authors examine the impact of the change in LIFFE's matching algorithm from a pro-rata priority allocation to a pure quantity pro-rata system of execution. Examining trading in the Euribor futures contract the authors show that the change to a pro-rata matching system leads to a deterioration of market quality. Specifically, the papers two key results are a reduction in prevailing and total order book depth as well as a widening of the bid-ask spread. The authors suggest that the reduction in depth may be related to cost of execution. They argue that if the time to execution associated with associated with a passive trade is significant then traders will switch to market orders which will result in lower levels of depth.

Contrary to the findings in Lepone et al. (2012), Field and Large (2008) theoretically postulate that market participants rationally respond to pro-rata matching by 'over-sizing' their orders. Since allocation is determined by order size, and because orders relative to market depth are too small to allow passive execution of orders, each limit order participant has an incentive to post a much larger quantity than they desire to execute. In other words, over-sizing is required to maximise the probability of a trader's execution. However, the consequence of this rational individual action is that order book depth is driven aggressively upwards as liquidity suppliers attempt to maximise their chances of executing passively. This finding is inconsistent with Lepone et al. (2012). Field et al. (2008) do however concede that liquidity suppliers face the possibility of over-trading risk, which in their model limits traders from engaging in an order size 'arms race'.[7] A secondary consequence of over-offering is that liquidity suppliers may be more inclined to cancel their limit orders once their trading objectives were achieved.

Janecek and Kabrhel (2007) offer some additional insights into the impact of matching regimes on market quality. The authors examine the impact of the mixed time pro-rata algorithm on trade behaviour and suggest that it induces rational trader's to behave in a manner that is inconsistent with general market efficiency. Large passive suppliers are encouraged to split large orders into a series of small orders in order to obtain a greater proportion of any subsequent matching volume. Since a large passive trader is forced to trade

[6] Longer term contracts such as 5-Year and 10-Year Treasury Notes trade on a price-time priority basis.
[7] If such overtrading risk is relatively weak and/or traders are numerous, then over-offering can persist indefinitely.

in a detrimental way, the corollary of this that small passive traders have an advantage as they are already trading in an optimal way.

The mixed findings in the literature on the effects of the matching algorithm on market quality suggest that further work is required to comprehend the effects of these regime changes. To ensure a better understanding of the impact on trade behaviour and market quality of such a regime change the following questions will be empirically addressed in the following sections. They include:

1) *Does the removal of a pure-quantity pro-rata allocation system reduce depth at the BBO?* Field and Large (2008) suggest that pure pro-rate allocation motivates individual traders in low volatility markets to over-size their orders. This finding is disputed by Lepone and Yang (2012) who show that movement to a pro-rata system of matching leads to a reduction in market depth.
2) *Does the removal of a pure-quantity pro-rata allocation system reduce trading volume?* If rational individual traders are over-sizing their orders in a pure pro-rata system, then they also face the possibility of over-execution risk. Copeland and Galai (1983) note that the submission of a passive order grants a free trading option to market participants. As such, as the size of a passive order rises against the desired quantity, the risk of the option increases. We suggest that the removal of a pure pro-rata system reduces the need for over-sizing orders and unintended trades.
3) *Does the change to a mixed time pro-rata allocation system affect trader submission behaviours?* Janecek and Kabrhel (2007) suggest that this system induces rational traders to behave in a manner inconsistent with general market efficiency because large passive suppliers are forced to split their orders into a series of small (single share) in order to obtain maximum execution. As a result one would also expect that as passive orders are filled up to their desired allocation, that any remaining volume be cancelled. This will result in significantly higher rates of order cancellations in a pro-rata regime.
4) *Does the change to a mixed time pro-rata allocation system affect bid-ask spreads?* Lepone and Yang (2012) suggest that the transition from priority-pro rata to a pure pro-rata system should not influence bid-ask spreads significant since they are extremely tight to begin with. Upon empirical inspection, the authors show an increase in quoted spreads.

4. Data

Three instruments traded on the NYSE LIFFE were the subject of the introduction of the mixed time/pro-rata priority matching algorithm. These are three month futures products over the Stirling (Short Stirling), Euro (Euribor) and Swiss (Euroswiss) interest rates. For each trading day in each instrument, we identify the series of currently traded contracts, ranging from the "near" contract to the first three "deferred" contracts. We only consider the quarterly expiry contracts and exclude serials due to the illiquidity concerns. In our primary analysis, the "near" contract is used, with the first deferred contract used for robustness. For example, on the 1st of June 2007 the "near" contract is the June 2007 contract and the first "deferred" contract is the September 2007 contract, since this instrument is trading with a quarterly expiration cycle. Five days prior to the expiration of the near contract, we begin using the first deferred contract, since Frino and McKenzie (2002) identify significant trading volume associated with rollover strategies in futures contracts during this period.

Data on all trades in each of these securities is gathered from the *Thomson Reuters Tick History* provided by the Securities Industry Research Centre of Asia-Pacific (SIRCA). Trades are stamped to the microsecond and identify both the price and quantity traded. We exclude strategy trades that do not impact the book from our analysis.[8] Hasbrouck and Saar (2013) document that if an incoming market or marketable limit order is executed against a number of standing limit orders, a series of trades will be generated equivalent to the number of standing limit orders involved in clearing the trade. We accordingly aggregate all trade reports with the same microsecond timestamp together as the same incoming market order. Figure 1 shows that almost 45% of trade reports are followed by a trade report with an identical timestamp due to market orders executing against many standing limit orders in pro-rata allocation.

<Insert Figure 1 >

Figure 2 excludes trades with identical timestamps and shows that approximately 50% of successive non-zero trade reports occur within 10ms, with a very low frequency occurring past 20ms. This is indicative of the high-frequency nature of the LIFFE market. Figure 3 zooms in on this 10ms period, showing that a large majority of these trade reports occur exactly 1, 2, 3 or 4 milliseconds after the previous trade. The uniform nature of this delay is indicative of a high participation of algorithmic and high frequency traders in our dataset hitting the market on the millisecond boundary.

<Insert Figure 2>

<Insert Figure 3>

Individual quote updates are also provided by SIRCA for each of the instruments of interest. These quotes provide the best 10 price levels at the best bid and ask, as well as the number of contracts available at these levels. This data is also stamped to the microsecond and allows us to identify all changes to the limit order book.

To construct market quality measures we use the regular market hours for the Euroswiss and Short Stirling of 7:30 – 18:00 each day. The Euribor has extended hours to reach the US (until 21:00) and Asian markets (until 1:00). As the majority of trading occurs during the European and US sessions, we compute our metrics from 7:00 – 21:00 each day. For all three instruments we exclude both the first and last 15 minutes of the day to avoid capturing the opening and closing auctions.

5. Method

5.1 Impact of the introduction of time/pro-rata matching

[8] "Strategy trades" are a functionality provided by LIFFE which allows participants to perform "strategies" such as a calendar spread trade. These can occur on a separate "strategy market" to the main limit order book.

The staggered introduction of the time/pro-rata matching algorithm provides a unique natural experiment to examine the impact of such a change on the quality of the futures market. Additionally, the unchanged pro-rata matching of the Long Gilt future provides an additional control for market-wide fluctuations. To assess the impact of this change on market quality, we employ an event-study approach, using a dummy variable to identify stock-days where matching is conducted using the time/pro-rata algorithm. The following regression specification is used to assess the impact on market quality:

$$y_{it} = \alpha_i + \beta_1 Mixed_{it} + \sum_{j=1}^{4} \gamma_j \, Control_{j,it} + \varepsilon_{it} \qquad (1)$$

where y_{it} is a market quality measure for stock i on day t, α_i is a set of date fixed effects, $Mixed_{it}$ is a dummy variable taking a value of 1 for contract-days where the mixed time/pro-rata matching algorithm is used and 0 when pure pro-rata is used. $Control_{j,it}$ is a set of j control variables including $\$Volume_{it}$ (the natural logarithm of traded contract dollar volume); $Volatility_{it}$ (the contract's high-low price range divided by the time-weighted midquote) and $Price_{it}$ (the time-weighted midquote).

5.2 Liquidity measures

Our first metric of liquidity is the time-weighted quoted bid-ask spread. The quoted spread is constructed as the difference between the lowest available ask price and the highest bid price for each contract. The quoted spread is measured in basis points by dividing the nominal spread by the prevailing midquote, $m = (Ask + Bid)/2$:

$$QuotedSpread = [(Ask - Bid)/m]10^4 \,. \qquad (2)$$

The time-weighted quoted spread for each contract-day, $QuotedSpread_{it}$, is calculated by taking the time-weighted average of quoted spreads between the opening and closing times documented in the data section for each market. We also examine effective spreads, which take into consideration the actual prices at which trades execute. Effective spreads reflect the cost of a transaction for the demander of liquidity. For a trade that occurs at time τ we measure its effective spread as:

$$EffectiveSpread = 2q[(p_\tau - m_\tau)/m_\tau]10^4 \qquad (3)$$

where p_τ is the transaction price, m_τ is the midpoint of the NBBO prevailing at the time of the trade, and q indicates the direction of the trade (+1 for buyer-initiated trades and -1 for seller initiated trades). Buyer and seller initiated trades are identified by comparing the prevailing transaction price to the prevailing quotes using the Lee and Ready (1991) algorithm.

Quoted dollar depth is the value available to be traded at the best bid and ask. It represents the immediately available liquidity at the best prices available in the market. This value is constructed by multiplying the price and contract size by the number of contracts available across both the best bid and offer at any point in time, as in Equation 4:

$$Quoted\ Depth_{i,t} = \left(Best\ Ask_{i,t} * Volume_{a,i,t} * Contract\ Size_i + Best\ Bid_{i,t} * Volume_{b,i,t} * Contract\ Size_i\right) \quad (4)$$

where $Best\ Ask_{i,t}$ is the lowest ask price for contract i at time t, $Volume_{a,i,t}$ is the consolidated volume available at that best ask level, $Contract\ Size_i$ is the dollar-value of one contract, $Best\ Bid_{i,t}$ is the highest bid price for contract i at time t and $Volume_{b,i,t}$ is the volume available at that best bid level. The quoted depth metric is constructed by weighting all quoted depth observations for the stock-day by the percentage of the trading day for which that depth level was active.

As these futures are characterised as "one tick" markets – that is they trade at the minimum tick size most of the time – they are likely to have skewed measures of quoted spreads. To address this problem, we also analyse the proportion of the day for which the stock trades at this minimum tick.

$$Constrained_{i,t} = \frac{Time\ Constrained_{it}}{Time\ Traded_{it}} \quad (5)$$

5.3 Trading Characteristics

The change in the matching algorithms is expected to not only affect the quality of the market for traded securities, but it is also expected to alter the behaviour of individual trader order strategies. To assess whether traders adopt the optimal order splitting strategies identified by Janecek and Kabrhel (2007) we compute the number of single-share allocations per day. We also document the size of order entries and cancellations in order to determine if there is a significant shift in the patterns of order entry and cancellation. In order to identify quote updates and cancellations from changes in the depth, we exclude reductions in depth due to trade executions and classify the remaining quote updates into one of the following categories:

1. New limit order: only increases depth,
2. Cancellation: only reduces depth.

From each of these changes we record both the number and the average daily size of entered and cancelled orders per contract. This also allows us to construct the cancel-to-trade ratio for each contract-day.

6. Results

Figure 4 documents the change in quoted BBO depth (combined bid and ask $Depth) around the introduction of the time pro-rata matching algorithm. Panel A shows a significant reduction in quoted depth on the 13th of August, exactly one week prior to the introduction of the time pro-rata matching algorithm. This pre-emptive week is likely driven by brokers need to test their algorithms before going live on the new market. The reduction in BBO Depth is most marked for the Euribor contract, which exhibits prevailing depth levels of up to $12 million combined on the best bid and ask prior to the change, and approximately $500,000 on average in the post period. Similar reductions are observed for the Short Stirling (from $2-6 million pre to less than $500,000 post) and in the less liquid Euroswiss (from $1 million pre to less than $200,000 post). Panel B shows the same period in 2006 to identify if there are any seasonal explanations for our results. The event date (20th August, 2006) does not exhibit any significant change in any of the contracts. If anything, an upward trend is observed through time.

These results provide preliminary evidence that traders "drown" the orderbook in an arms race to capture ever larger sections of the orderbook which is spurred on by the use of a pure pro-rata matching algorithm. These findings are furthermore consistent with the expectations of Field and Large (2008). The introduction of the mixed time pro-rata algorithm increased the importance of time precedence, resulting in far smaller orders being entered to the limit order book. This resulted in a drastic reduction in depth in August 2007, as is visible in Panel A of Figure 4.

<Insert Figure 4 >

Figure 5 is a histogram of order entry and cancellation behavior across all three contracts pre- and post-introduction of the time pro-rata matching algorithm. Prior to the introduction significantly larger orders were entered into the market. In addition the magnitude small orders (approximately 150,000 – 200,000 per month) is dwarfed by the 300,000-500,000 small orders entered or canceled per month in the post period. The increase in these small orders comes at the expense of large orders, which become much less prevalent after the introduction of the time pro-rata matching algorithm. Such behavior is consistent with traders being less concerned about over-submitting volume to receive larger pro-rata orders, and instead being more concerned with maintaining a higher position in the order book, as is predicted by Janecek and Kabrhel (2007).

<Insert Figure 5 >

Our analysis of the impact of the introduction of the time pro-rata matching algorithm utilizes the staggered introduction of the new matching algorithm across the three contracts. Table 1 reports the results of this introduction on a variety of market quality and trading characteristics. Panel A documents the treatment sample, analyzing the introduction of the time pro-rata algorithm, whilst Panel B provides a control specification, with a similar time horizon (a year earlier) in order to account for potential seasonality issues.

Quoted spreads are not found to differ significantly in the post period in either our treatment or control samples. Effective spreads increase significantly after the introduction of the time pro-rata matching algorithm. In our control specification, effective spreads decrease significantly, implying that our results are not driven by the seasonality of the data. The depth at the best bid and offer is found to decrease significantly in the treatment sample, whilst not changing in the control sample. Such a decrease in depth could result in larger orders executing against multiple levels of the limit orderbook more frequently and further explain the increase in effective spreads. The proportion of the day for which spreads are constrained to the minimum tick increases significantly by 2.6% in our treatment sample and is insignificantly different in the control sample. This could be due to traders seeking to acquire time priority more frequently by improving the best bid and offer. However, this improvement is not large enough to result in lowered effective or quoted spreads.

<Insert Table 1>

Turning to the measures of trading activity, there is a significant reduction in traded volume after the introduction of the time pro-rata matching algorithm. There is, however, no significant change in the corresponding control period. Furthermore, no significant change is observed in either the treatment period or control period for the number of trades. The size of trades, however, reduces significantly in the treatment period whilst increasing significantly in the control period. Taken together, these results imply that there are a similar number of trades in both periods, but that the introduction of the time pro-rata matching algorithm leads to a reduction in the average trade size which reduces the total traded volume. This is consistent with traders ceasing to “drown” the order book with larger orders seeking executions. Instead, traders seek time priority with smaller orders, resulting in lower depth at the BBO and less opportunity for liquidity demanders to “overfill” the inflated orders at the BBO. Lastly, there is no significant change in single share orders, whilst the control period sees a decrease in these orders.

Overall it appears that the introduction of the pro-rata matching algorithm has resulted in traders posting less depth on the limit order book. Whilst the orders being posted may represent more “accessible” liquidity, the move to time pro-rata seems to have resulted in a deterioration of all constructed measures of market quality.

Table 2 provides results for each of the contracts individually. While these specifications do not exploit the variation in the staggered introduction of the time pro-rata matching algorithm, they identify within which contracts we see the largest changes in market quality.

<Insert Table 2 >

Panels A, B, and C present the results for the Euribor, the Short Sterling and the Euroswiss, respectively. Quoted spreads do not appear to change significantly on the Euribor or on the Short Sterling. A statistically significant reduction of 0.04 basis points is observed on the Euroswiss. These results are consistent with spreads being constrained for the majority of the day. Effective spreads, however, increase significantly across all three contracts. The increase in spread ranges from 0.04 basis points on the Euribor to 0.08 basis points on the Euroswiss. Consistent with an increase in trading costs, we find that there is a significant reduction in BBO Volume across all three contracts. Lower depth at the best bid and offer could result in larger market orders hitting more levels of the orderbook more frequently, resulting in the higher observed effective spreads. Interestingly, the frequency with which the contracts are constrained to the minimum tick increases. This is indicative of the introduction of time priority encouraging traders to improve the quotes more frequently so as to acquire the first position in the queue, increasing the fraction of time for which the spreads are constrained. This results in the markets being constrained between 2-8% more frequently.

Turning to measures of trading activity, all three contracts see significant reductions in trading activity with the introduction of time pro-rata matching. This reflects the reduced probability of overfilling, which occurs when traders over-size their orders to receive higher fractions of the incoming market orders. Such a strategy opens these traders to the potential to trade more than their optimal size. The introduction of time pro-rata matching emphasizes the importance of submission time, reducing the need to overfill. This is reflected in the reduced volume available at the BBO. As fewer shares are over-quoted at the BBO there is less risk of over filling an order, which results in the reduction of traded volume. We also observe a reduction in the overall number of trades, however this is only significant on the Short Sterling contract. Significant reductions are observed in the average trade size for both the Euribor and Euroswiss. Interestingly the Short Sterling exhibits an increase in average trade size. A significant reduction is also observed in the number of single share trades for the Short Sterling.

7. Robustness

Futures contracts exhibit seasonality in their trading activity. Such seasonality can also impact measures of spreads depending on the months in which they are measured. If seasonality is present in our data, the time-varying nature of our regression analysis may pick up a spurious trend, rather than the specific impact of the change in matching algorithm. To check the robustness of our results to this seasonality, we conduct an analysis identical to that in our main results, using data exactly one year earlier, in 2006. The pre-post dummy is implemented at exactly the same date for each of the contracts analyzed.

Table 3 provides an identical analysis to that of Table 2 exactly one year earlier. No significant change is found for quoted spreads. Unlike our treatment period of 2007, effective spreads decline significantly in the post period in 2006. Similarly, the volume available at the best bid and offer increases significantly in 2006, whilst it decreases significantly in the treatment period. The level of constraint reduces during the control period and is significant at the 10% level. This compares to a significant increase during the treatment period.

<Insert Table 3 >

The measures of trading also demonstrate dissimilar results compared to the treatment period. Volume increases significantly for both the Euribor and Euroswiss contracts during the control period. The number of trades exhibits mixed results, increasing significantly on the Euroswiss whilst reducing significantly on the Euribor and Short Sterling. Trade size increases significantly across all contracts in the post period, whilst decreasing significantly during the treatment period on both the Euribor and Euroswiss. The number of single share orders decreases significantly on both the Euribor and Short Sterling.

Taken together, the contradictory nature of the results during the control period as compared to the treatment period indicates that the changes observed are not a result of the seasonality inherent in futures contracts. Rather, it appears that traders have altered their trading behavior as a result of the implementation of the time pro-rata matching algorithm.

8. Conclusion

This study examines the impact of the introduction of time priority ("time pro-rata matching") across all orders on STIR Futures contracts on NYSE LIFFE on market quality and order submission strategies. Results indicate a significant deterioration in liquidity, measured as the total value at the best bid or offer, across all instruments. Results also show an increase in effective spreads, and an increase in the percentage of time the market is at the minimum spread. There is also a significant reduction in traded volume after the introduction of time pro-rata matching, which is independent of seasonal effects. Analysis of order submission strategies reveals a significant increase in the number of small order entry and cancellations following the change, and the inverse for large orders. This occurs despite no measured change in the number of trades.

These results can be interpreted as resulting from a reduction in liquidity available on the market, which results in liquidity demanders experiencing higher transaction costs, measured through effective spreads, as they are forced to execute against more price levels. The increase in the measured time at the minimum spread size can be explained by the reinstatement of the "priority order rule" which assigns significant benefits to the first order to be submitted at a given price point. Small order submissions, and a decrease in large trades, are expected as an optimal submission strategy under time priority to attain favourable queue position in the order book.

The implications for the exchange and policy-makers are that the current matching algorithm implemented by NYSE LIFFE is possibly not ideal for market participants relative to the previous system. Perhaps the implementation of the model can be optimized to the preferences of liquidity demanders or providers more effectively. Or perhaps a new model is needed. NYSE LIFFE has attempted to make improvements in 2013, but these were quickly reversed, which suggests that the optimal model is currently elusive.

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Table 1
Impact of Time Pro-Rata Allocation Mechanism on Market Quality

This table reports changes in time weighted quoted and effective spreads, depths, percentage of time quoted spreads are constrained at minimum tick, traded volume, number of trades, size of trades and number of single share orders using a dummy variable "Time pro-rata" for the introduction period. Each liquidty measure is regressed with controls for the price of the contract, traded volume and volatility (measured as the daily (high-low)/average price). Panel A presents results for the introduction of time pro-rata matching in 2007 whilst Panel B reports control results for the same period in 2006. The observation period spans 20th of May to the 24th of December in each year. ***, **, * represents significance at the 1%, 5% and 10% level, respectively.

Panel A: 2007 Treatment

	Quoted Spread (bps)	Effective Spread (bps)	BBO $Volume	%Constrained	Volume	Trades	Trade Size (contracts)	Single Share Trades
Time Pro-Rata	-0.001	0.040***	-1.137***	0.026**	-0.234***	-0.049	-0.231***	-0.033
	(-0.858)	(5.953)	(-14.517)	(2.290)	(-5.278)	(-1.246)	(-6.113)	(-0.769)
Price	-0.012***	-0.099***	-0.618**	-0.122***	-0.578***	0.052	-0.645***	0.539***
	(-3.827)	(-4.306)	(-2.171)	(-3.642)	(-4.286)	(0.414)	(-4.729)	(4.078)
Volume	-0.004*	0.024**	0.301***	0.026*				
	(-1.951)	(2.527)	(3.029)	(1.804)				
Volatility	0.055**	0.099***	-1.402***	-0.020	1.089***	0.837***	0.109	0.564***
	(2.638)	(3.620)	(-6.269)	(-1.304)	(21.272)	(12.698)	(1.761)	(10.657)
Intercept	1.794**	6.043**	27.557	4.153*	31.907**	14.510	22.169*	0.175
	(2.467)	(3.155)	(0.886)	(1.924)	(3.039)	(1.384)	(1.963)	(0.010)
Observations	1,398	1,398	1,398	1,398	1,398	1,398	1,398	1,398
Adjusted $\bar{R}^2$	0.709	0.534	0.519	0.302	0.454	0.381	0.250	0.326

Panel B: 2006 Control

	Quoted Spread (bps)	Effective Spread (bps)	BBO $Volume	%Constrained	Volume	Trades	Trade Size (contracts)	Single Share Trades
Time Pro-Rata	-0.001	-0.035*	0.130	-0.017	0.132	-0.023	0.117**	-0.113*
	(-0.089)	(-2.039)	(1.783)	(-1.238)	(1.623)	(-0.390)	(3.187)	(-2.008)
Price	-0.022	-0.095**	-0.066	-0.019	0.227	-0.220	0.324***	-0.458
	(-0.821)	(-2.379)	(-0.444)	(-0.519)	(0.988)	(-0.921)	(3.512)	(-1.671)
Volume	-0.034**	0.019	0.209	0.034***				
	(-3.314)	(1.673)	(1.791)	(5.356)				
Volatility	0.059**	0.264***	-0.529**	0.069	2.017***	1.238***	0.401***	0.988***
	(2.910)	(3.472)	(-2.338)	(1.704)	(9.880)	(7.820)	(7.240)	(7.462)
Intercept	3.629	9.894**	8.170	2.254	-13.838	26.275	-27.757**	48.419
	(1.374)	(2.521)	(0.580)	(0.628)	(-0.614)	(1.120)	(-3.067)	(1.802)
Observations	1,389	1,389	1,389	1,389	1,389	1,389	1,389	1,389
Adjusted $\bar{R}^2$	0.726	0.508	0.171	0.298	0.332	0.370	0.047	0.201

Table 2
Individual Contract Regressions – Treatment 2007

This table reports changes in time weighted quoted and effective spreads, depths, percentage of time quoted spreads are constrained at minimum tick, traded volume, number of trades, size of trades and number of single share orders using a dummy variable "Time pro-rata" for the introduction period. Each liquidty measure is regressed with controls for the price of the contract, traded volume and volatility (measured as the daily (high-low)/average price). Panel A presents results for the introduction of time pro-rata matching in 2007 on the Euribor, Panel B for the Short Sterling and Panel C the Euroswiss. The observation period spans 20th of May to the 24th of December in 2007. ***, **, * represents significance at the 1%, 5% and 10% level, respectively.

Panel A: Euribor

	Quoted Spread (bps)	Effective Spread (bps)	BBO $Volume	%Constrained	Volume	Trades	Trade Size (contracts)	Single Share Trades
Time Pro-Rata	-0.001	0.040***	-1.137***	0.026**	-0.234***	-0.049	-0.231***	-0.033
	(-0.858)	(5.953)	(-14.517)	(2.290)	(-5.278)	(-1.246)	(-6.113)	(-0.769)
Price	-0.012***	-0.099***	-0.618**	-0.122***	-0.578***	0.052	-0.645***	0.539***
	(-3.827)	(-4.306)	(-2.171)	(-3.642)	(-4.286)	(0.414)	(-4.729)	(4.078)
Volume	-0.004*	0.024**	0.301***	0.026*				
	(-1.951)	(2.527)	(3.029)	(1.804)				
Volatility	0.012***	0.080***	-2.044***	0.037*	0.932***	1.042***	-0.261***	0.806***
	(6.026)	(6.069)	(-9.497)	(1.747)	(12.469)	(10.225)	(-3.686)	(8.778)
Intercept	1.704***	9.669***	58.327**	12.240***	66.454***	2.102	66.145***	-45.619***
	(5.575)	(4.395)	(2.143)	(3.787)	(5.162)	(0.176)	(5.076)	(-3.616)
Observations	468	468	468	468	468	468	468	468
$Adjusted\ \bar{R}^2$	0.118	0.273	0.559	0.058	0.330	0.423	0.188	0.319

Panel B: Short Sterling

	Quoted Spread (bps)	Effective Spread (bps)	BBO $Volume	%Constrained	Volume	Trades	Trade Size (contracts)	Single Share Trades
Time Pro-Rata	0.003	0.050***	-1.792***	0.021**	-0.134***	-0.251***	0.098**	-0.558***
	(1.563)	(4.437)	(-23.611)	(1.973)	(-2.802)	(-4.853)	(2.124)	(-8.843)
Price	-0.012***	-0.011	-0.105	0.006	-0.374***	0.289***	-0.710***	0.539***
	(-5.335)	(-0.858)	(-1.381)	(0.605)	(-4.267)	(3.669)	(-13.090)	(5.735)
Volume	-0.003**	0.033***	0.094	0.011				
	(-1.977)	(3.259)	(1.339)	(1.196)				
Volatility	0.009***	0.071***	-0.671***	0.026**	1.021***	0.900***	0.009	0.734***

	(3.834)	(5.663)	(-5.884)	(2.504)	(13.903)	(11.283)	(0.216)	(7.825)
Intercept	2.220***	1.619	12.194*	0.199	45.510***	-20.856***	71.012***	-45.290***
	(10.565)	(1.311)	(1.659)	(0.188)	(5.538)	(-2.824)	(13.976)	(-5.149)
Observations	462	462	462	462	462	462	462	462
Adjusted $\bar{R}^2$	0.067	0.247	0.759	0.054	0.465	0.416	0.218	0.305

Panel C: Euroswiss

	Quoted Spread (bps)	Effective Spread (bps)	BBO $Volume	%Constrained	Volume	Trades	Trade Size (contracts)	Single Share Trades
Time Pro-Rata	-0.041***	0.084***	-0.801***	0.068***	-0.680***	-0.060	-0.656***	-0.020
	(-2.930)	(3.646)	(-7.844)	(4.169)	(-9.012)	(-1.192)	(-12.823)	(-0.280)
Price	0.044	-0.131**	-0.908***	-0.104***	0.651***	0.047	0.494***	-0.022
	(1.403)	(-2.256)	(-3.651)	(-2.667)	(3.028)	(0.353)	(3.738)	(-0.136)
Volume	-0.061***	0.015	0.454***	0.073***				
	(-4.465)	(0.677)	(6.130)	(6.487)				
Volatility	0.136***	0.327***	-1.925***	-0.028	0.804***	1.253***	-0.669***	1.047***
	(8.838)	(9.781)	(-13.917)	(-0.969)	(5.838)	(14.005)	(-7.509)	(9.247)
Intercept	-2.605	13.391**	87.598***	10.193***	-54.543***	0.149	-43.621***	5.640
	(-0.878)	(2.407)	(3.685)	(2.712)	(-2.614)	(0.012)	(-3.405)	(0.358)
Observations	468	468	468	468	468	468	468	468
Adjusted $\bar{R}^2$	0.203	0.216	0.560	0.115	0.219	0.324	0.318	0.137

Table 3
Individual Contract Regressions – Robustness 2006

This table reports changes in time weighted quoted and effective spreads, depths, percentage of time quoted spreads are constrained at minimum tick, traded volume, number of trades, size of trades and number of single share orders using a dummy variable "Time pro-rata" situated identically to the 2007 introduction period. Each liquidty measure is regressed with controls for the price of the contract, traded volume and volatility (measured as the daily (high-low)/average price). Panel A presents results for the introduction of time pro-rata matching in 2006 on the Euribor, Panel B for the Short Sterling and Panel C the Euroswiss. The observation period spans 20th of May to the 24th of December in 2006. ***, **, * represents significance at the 1%, 5% and 10% level, respectively.

Panel A: Euribor

	Quoted Spread (bps)	Effective Spread (bps)	BBO $Volume	%Constrained	Volume	Trades	Trade Size (contracts)	Single Share Trades
Time Pro-Rata	0.000	-0.030***	0.475***	-0.025*	0.191***	-0.211***	0.352***	-0.255***
	(0.371)	(-3.329)	(6.866)	(-1.911)	(4.204)	(-6.226)	(10.379)	(-6.944)
Price	-0.004	-0.094***	0.971***	-0.070**	0.385***	-0.742***	0.981***	-0.841***
	(-1.018)	(-4.069)	(5.764)	(-2.334)	(3.643)	(-9.691)	(12.014)	(-9.390)
Volume	-0.002*	0.006	0.266**	0.001				
	(-1.904)	(0.584)	(2.525)	(0.093)				
Volatility	0.005**	0.179***	-2.150***	0.158***	2.145***	1.956***	-0.241***	1.611***
	(2.163)	(6.271)	(-8.696)	(4.019)	(20.841)	(21.063)	(-2.814)	(16.605)
Intercept	0.931**	9.423***	-93.812***	7.640***	-26.290**	78.382***	-89.239***	87.912***
	(2.546)	(4.275)	(-5.957)	(2.685)	(-2.579)	(10.611)	(-11.319)	(10.174)
Observations	465	465	465	465	465	465	465	465
$Adjusted\ \bar{R}^2$	0.027	0.235	0.314	0.082	0.486	0.648	0.319	0.548

Panel B: Short Sterling

	Quoted Spread (bps)	Effective Spread (bps)	BBO $Volume	%Constrained	Volume	Trades	Trade Size (contracts)	Single Share Trades
Time Pro-Rata	-0.008	-0.068***	0.496***	-0.026	0.057	-0.222***	0.237***	-0.216***
	(-1.355)	(-3.134)	(4.974)	(-1.361)	(0.789)	(-4.226)	(3.909)	(-3.816)
Price	-0.050**	-0.223***	1.154***	-0.045	0.316	-0.624***	0.906***	-0.704***
	(-2.514)	(-3.649)	(4.586)	(-0.879)	(1.618)	(-4.204)	(6.504)	(-4.401)
Volume	-0.011	0.059***	0.241***	0.035**				
	(-1.196)	(3.387)	(3.534)	(2.236)				
Volatility	0.009	0.260***	-0.850***	0.091**	1.521***	1.265***	-0.039	1.024***
	(0.749)	(5.215)	(-4.402)	(2.496)	(9.564)	(6.958)	(-0.377)	(5.863)
Intercept	5.977***	21.401***	-108.871***	4.803	-20.039	65.337***	-81.849***	71.878***

	(3.009)	(3.730)	(-4.573)	(0.988)	(-1.078)	(4.628)	(-6.174)	(4.721)
Observations	459	459	459	459	459	459	459	459
Adjusted $\bar{R}^2$	0.056	0.256	0.140	0.074	0.354	0.465	0.089	0.361

Panel C: Euroswiss

	Quoted Spread (bps)	Effective Spread (bps)	BBO $Volume	%Constrained	Volume	Trades	Trade Size (contracts)	Single Share Trades
Time Pro-Rata	0.002	-0.070***	0.138	-0.035*	0.377***	0.111**	0.248***	-0.035
	(0.134)	(-3.174)	(1.619)	(-1.690)	(4.849)	(2.378)	(5.187)	(-0.612)
Price	-0.024	-0.319***	0.010	-0.103*	1.334***	0.030	1.081***	-0.263
	(-0.629)	(-5.034)	(0.046)	(-1.779)	(6.497)	(0.192)	(8.147)	(-1.345)
Volume	-0.058***	0.004	0.190***	0.051***				
	(-7.433)	(0.367)	(3.870)	(4.323)				
Volatility	0.115***	0.518***	-0.528**	0.097*	2.037***	1.228***	0.276*	0.986***
	(3.526)	(7.436)	(-2.469)	(1.740)	(8.752)	(9.326)	(1.920)	(6.076)
Intercept	4.049	31.973***	0.805	10.414*	-122.462***	1.698	-102.035***	29.284
	(1.073)	(5.177)	(0.037)	(1.840)	(-6.080)	(0.113)	(-7.843)	(1.528)
Observations	465	465	465	465	465	465	465	465
Adjusted $\bar{R}^2$	0.122	0.279	0.043	0.065	0.172	0.153	0.130	0.084

Figure 1

Millisecond remainder between trades to 200ms including identical timestamps

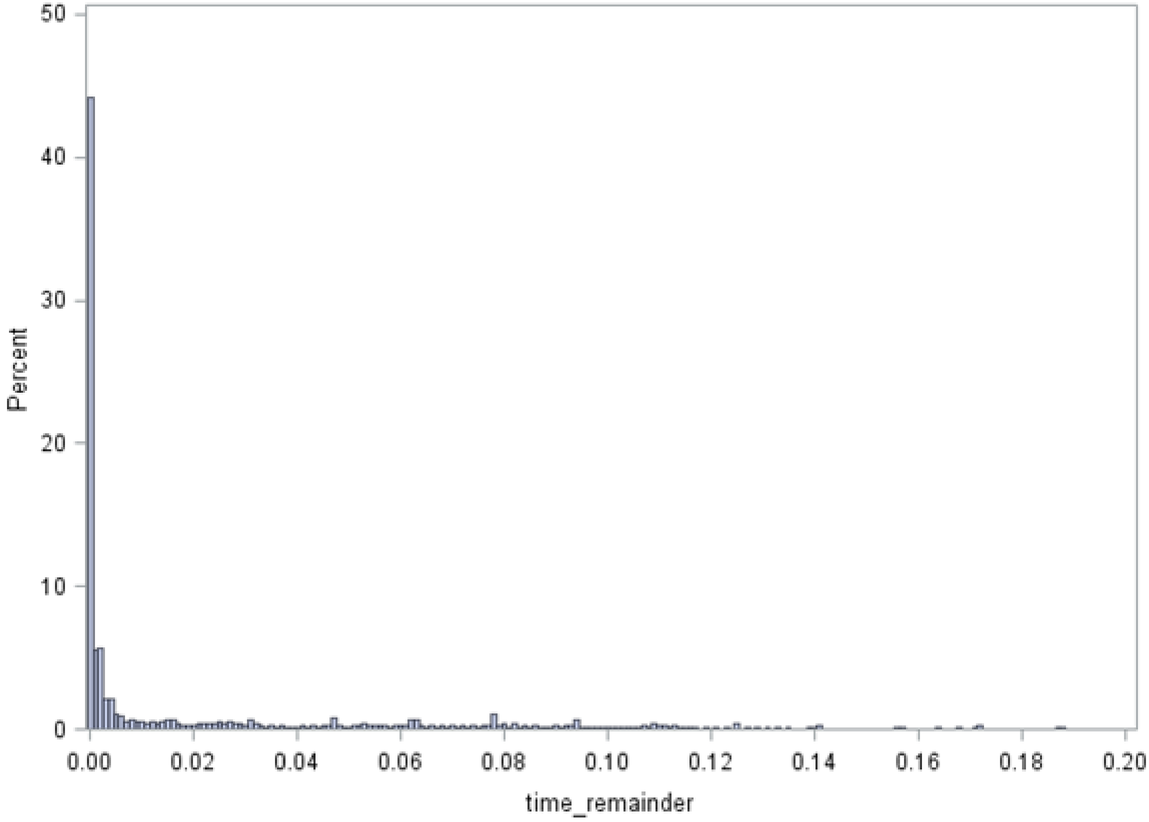


Figure 2

Millisecond remainder between trades to 200ms excluding identical timestamps

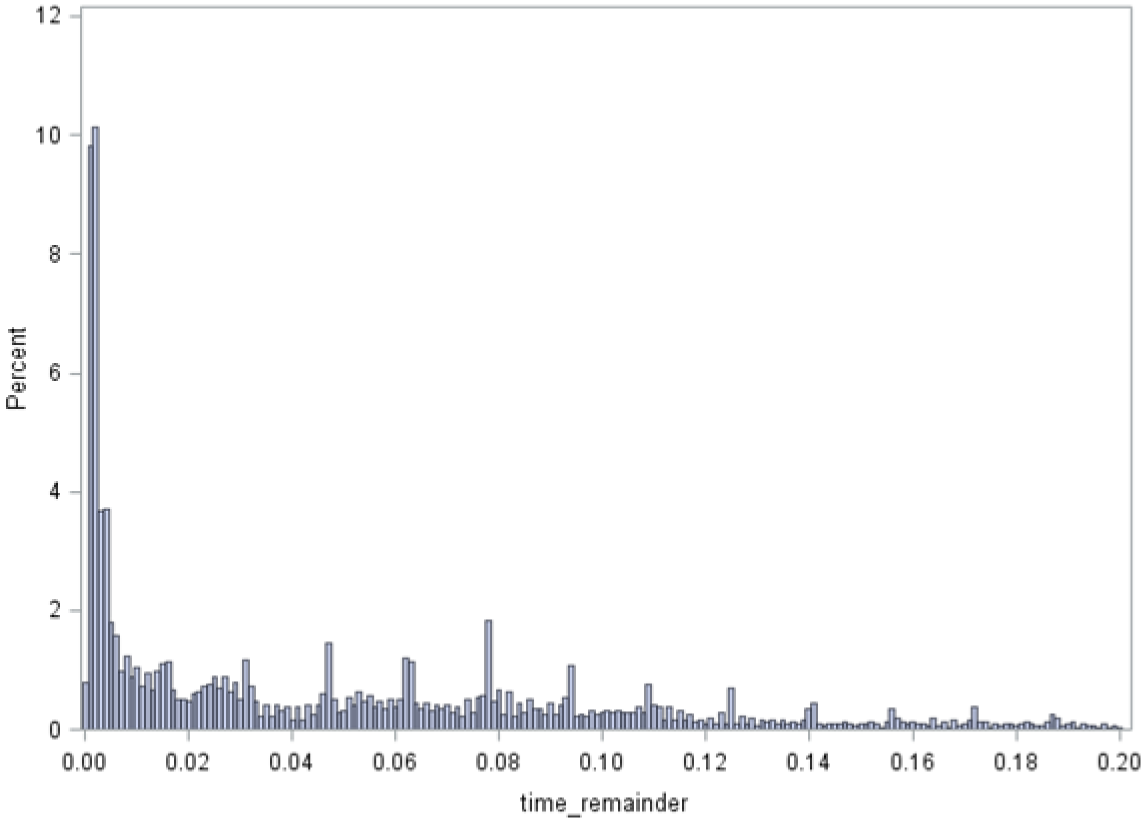


Figure 3

Millisecond remainder between trades to 10ms excluding identical timestamps

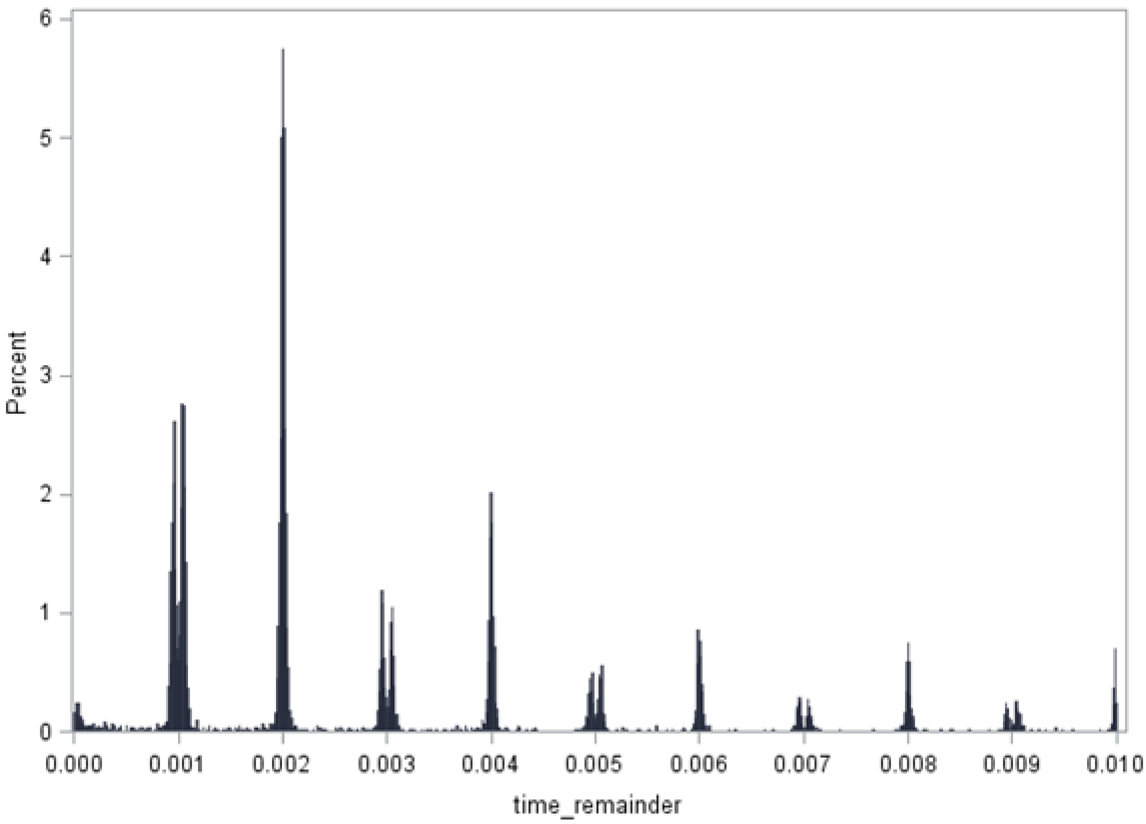
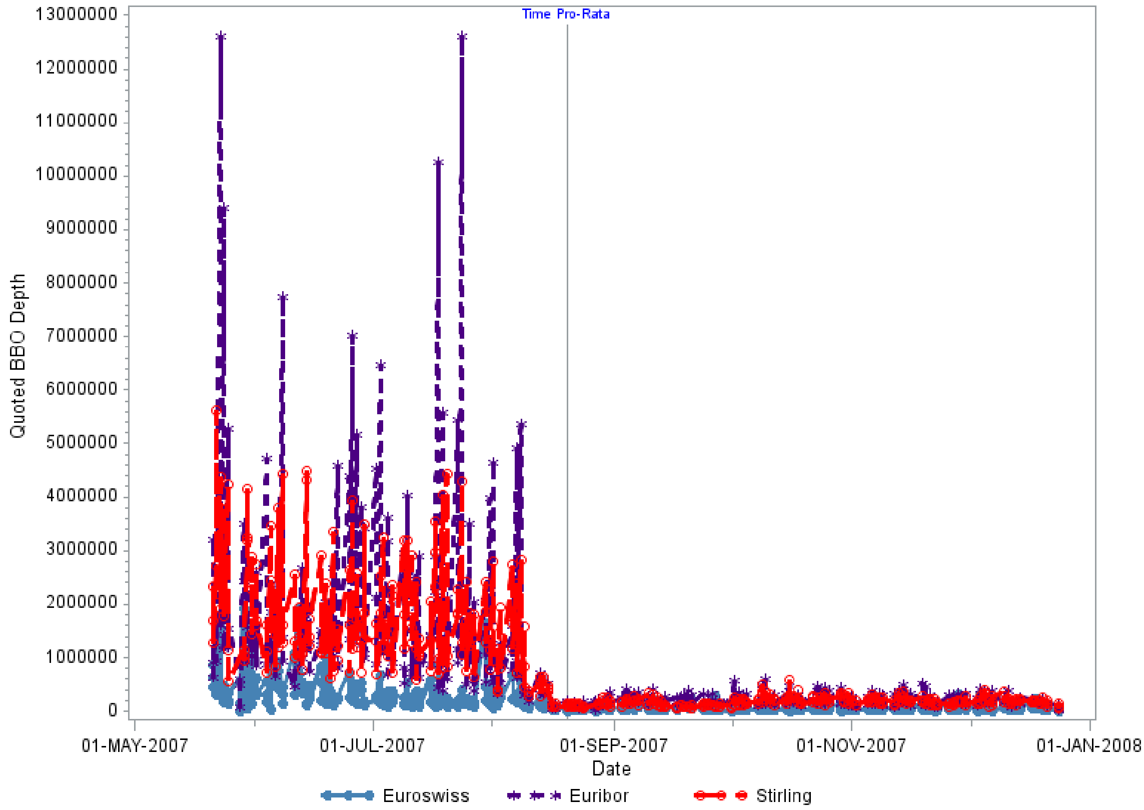


Figure 4

Dollar Depth at the Best Bid and Offer

Panel A: Dollar Depth at the Best Bid and Offer in 2007



Panel B: Dollar Depth at the Best Bid and Offer in 2006

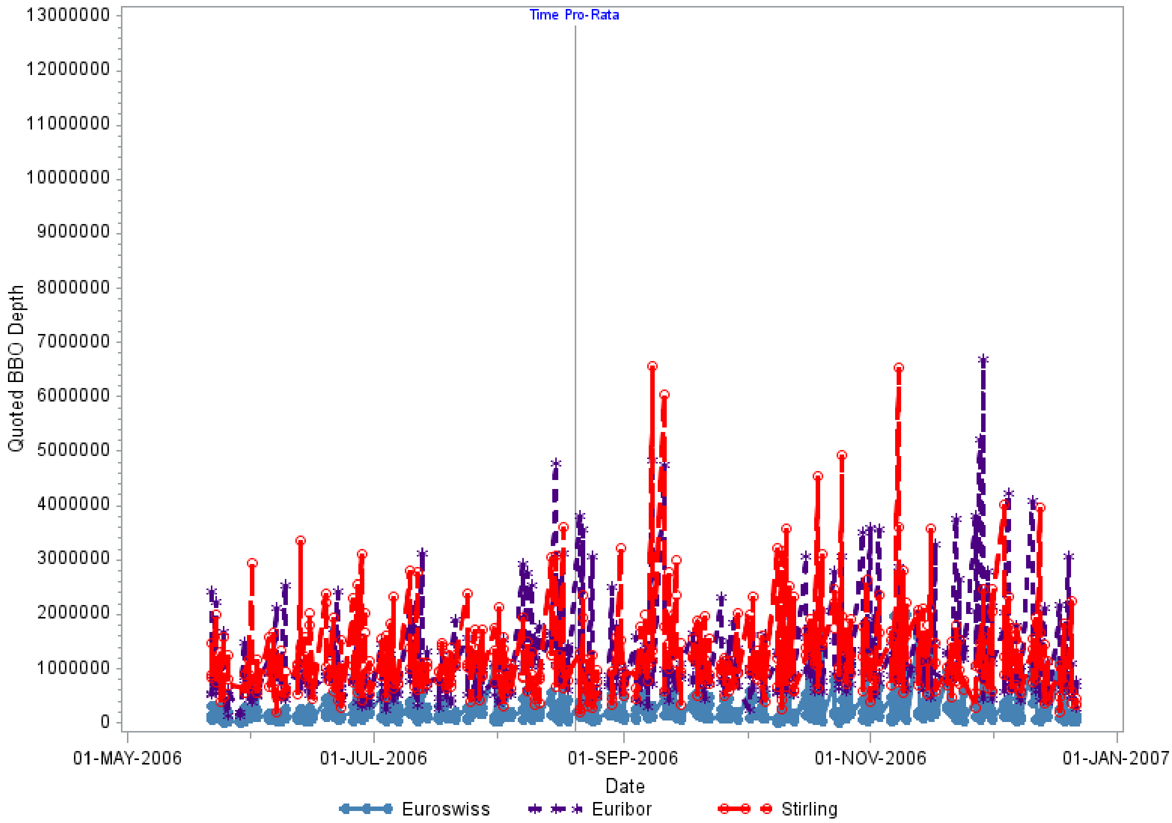


Figure 5

Changes in the size of entered and cancelled orders (contracts)