Dynamics of Execution Quality

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Abstract

This project aims to evaluate the order execution quality of four major market centers: Citadel Securities LLC, Virtu Americas LLC, Jane Street Capital, and G1 Execution Services LLC. The SEC Rule 605 filings of each market center is used to calculate the Net Price Improvement (NPI) of shares, an important metric of execution quality, over the span of four years. Time Series Analysis has been used to assess the order execution quality of the market centers in question based on two key performance indicators (KPIs): weighted-mean of net price improvement and weighted-median of net price improvement.

Based on results of the time series analysis, we notice that Citadel Securities LLC outperformed the other market centers in terms of weighted-mean of net price improvement until April 2020. Then, we observe a substantial shift, where G1 Execution Services LLC has consistently produced the highest weighted-mean of net price improvement among the other market centers consecutively for 34 months starting from June 2020 to April 2023.

This study considers only the influence of the order type and order size and omits the impact of market conditions such as market volatility and liquidity of the security. Nonetheless, the results can assist traders and investors to make informed decisions and achieve better trade outcomes, brokerage firms to optimize their order routing strategies, regulators to identify potential anomalies, and academic research to develop new insights into market dynamics.

This study only deals with comparison of the order execution quality of market centers based on the net price improvement but provides no recommendations.

Overall, this study helps to understand the order execution quality of major market centers, offering key information and insights to various market participants to optimize their trading strategies.

1. Introduction

The most straightforward approach for any individual investor to buy or sell stocks is to open an online brokerage account with a reputable brokerage firm or online trading platform (for example, Robinhood Securities, Interactive Brokers, etc.). For this project, we will look at Robinhood Securities, LLC. When an individual investor issues a buy or sell order with a brokerage business, it is routed to one of the firm's market centers. When the market center gets the order from the company, it matches it with another participant's corresponding order (Buy is matched with Sell and vice versa) and executes the order. These market centers profit on the bid-ask spread, which is the difference between a security's purchase (bid) and selling (ask) price. They make money by purchasing securities at slightly lower prices than the market and selling them at slightly higher prices.

2. Background

This section elaborates and deals with the background and purpose of SEC Rule 606 and SEC Rule 605, which are the key pre-requisite concepts for this study.

2.1. SEC Rule 606 (formerly Rule 11Ac1-6)

According to SEC Rule 606, also known as the "Disclosure of Order Routing Information," was introduced in the year 2000. This rule mandates brokerage firms to disclose comprehensive information about their order routing practices to their clients. Broker-dealers are also required to inform clients of the venues (market centers) of their specific orders as well as the quality of execution obtained at those venues. Each client is entitled to a free written copy of the report, which will be mailed to them. The main purpose of the SEC Rule 606 filing is to foster transparency in the order routing practices by brokerage firms. By providing investors with details about how their orders are routed and executed, it aims to enable investors to evaluate the efficiency and potential conflicts of interest in their brokers' order routing decisions and empowers them to compare different brokerage firms and make more informed choices when selecting a broker for their trading needs.

Figure 1 depicts Robinhood Securities, LLC's SEC rule 606 filing for S&P 500 equities in April 2023. We can observe that the huge proportion of orders placed with Robinhood have been routed to Virtu Americas LLC (55.27%) and Jane Street Capital (16%), followed by G1 Execution Services LLC (14.21%) and CITADEL Securities LLC (12.15%)

Robinhood Securities, LLC - Held NMS Stocks and Options Order Routing Public Report
Generated on Fri Jul 28 2023 10:52:07 GMT-0400 (Eastern Daylight Time)

2nd Quarter, 2023

April 2023

S&P 500 Stocks

Summary

Non-Directed Orders as % of All Orders	Market Orders as % of Non-Directed Orders	Marketable Limit Orders as % of Non-Directed Orders	Non-Marketable Limit Orders as % of Non-Directed Orders	Other Orders as % of Non-Directed Orders
100.00	24.06	16.33	14.23	45.38

Venues

Venue - Non-directed Order Flow	Non-Directed Orders (%)	Market Orders (%)	Marketable Limit Orders (%)	Non-Marketable Limit Orders (%)	Other Orders (%)	Net Payment Paid/Received for Market Orders(USD)	Net Payment Paid/Received for Market Orders(cents per hundred shares)	Net Payment Paid/Received for Marketable Limit Orders(USD)	Net Payment Paid/Received for Marketable Limit Orders(cents per hundred shares)	Net Payment Paid/Received for Non-Marketable Limit Orders(USD)	Net Payment Paid/Received for Non-Marketable Limit Orders(cents per hundred shares)	Net Payment Paid/Received for Other Orders(USD)	Net Payment Paid/Received for Other Orders(cents per hundred shares)
Virtu Americas, LLC	55.27	39.75	40.32	49.05	70.83	65,834.20	31.7129	44,567.60	30.0190	27,538.26	29.0805	154,668.36	78.2402
Jane Street Capital	16.00	17.84	18.00	17.06	13.97	48,666.93	27.7978	31,590.29	27.3189	14,437.33	27.1554	68,963.21	66.6374
G1 Execution Services, LLC	14.21	28.83	27.35	18.95	0.24	57,719.68	30.6579	34,580.36	29.6456	4,939.19	25.0064	11,416.94	36.7439
CITADEL SECURITIES LLC	12.15	9.22	10.07	12.19	14.45	49,833.78	19.7014	32,414.90	18.3553	21,880.44	17.2510	91,891.35	43.9069

Figure 1. Robinhood Rule 606 filing for April 2023

2.2. SEC Rule 605 (formerly Rule 11Ac1-5)

According to *Financial Industry Regulatory Authority (FINRA)* [1], the *U.S. Securities and Exchange Commission (SEC)* [2] enacted Exchange Act Rule 11Ac1-5 in November 2000. Rule 11Ac1-5's goal is to improve order execution quality disclosure to the public. Market centers that trade securities on the national market system are required by the SEC to file monthly electronic reports in line with Rule 11Ac1-5. These reports include information about the execution quality at each market center on a stock-by-stock basis, such as how market orders of diverse sizes are executed in relation to the open quotes. These reports must include information on effective spreads, or the spreads paid by investors who route their orders to a single market center. Market centers must also report the extent to which they provide investors with executions at prices higher than the public quotes using limit orders. According to the SEC, the Rule directed self-regulatory organizations ('SROs') that trade national market system securities to collaborate and submit to the Commission a new national market system plan (the 'Joint-SRO Plan') establishing procedures for market centers to follow in making their monthly reports public.

According to the Joint-SRO Plan, the rule 605 submission contains the following twenty-six fields:

1. **Designated Participant**: An entity that engages in trading activities within a certain market is referred to as a designated participant. It could be a broker-dealer, a market center, or any other organization involved in order execution. The following are the participant identifying codes: Amex is "A"; BSE is "B"; CHX is "M"; CSE is "C"; NASD is "T"; NYSE is "N"; PCX is "P"; and Phlx is "X".

2. **Market Center Code**: A market center is a location or platform where trade occurs. It could be an exchange, an electronic communication network (ECN), or any other type of trade system. A Designated Participant assigns the market center code.

3. **Month and Year**: The term "date" refers to the precise day or time for which the information in Rule 605 filing is being reported. It shows when the trade action occurred. It is shown as a six-digit code in the format "yyyymm" in the report.

4. **Ticker Symbol**: A ticker is a one-of-a-kind symbol or abbreviation used to identify a certain securities or financial instrument. In stock exchanges or financial markets, it is typically used to denote the name of the traded instrument.

5. **Order Type**: The instructions offered by an investor or trader when placing an order to purchase or sell a security are specified by the order type. The following are the order type codes: "11" for market orders, "12" for marketable limit orders, "13" for inside-the-quote limit orders, "14" for at-the-quote limit orders, and "15" for near-the-quote limit orders.

6. **Order Size**: The quantity or volume of shares or contracts mentioned in an order to buy or sell a security is referred to as order size. It tells how many units the investor or dealer wishes to buy or sell.

The following are the order size codes: "21" represents 100-499 shares; "22" represents 500-1999 shares; "23" represents 2000-4999 shares; and "24" represents five thousand or more shares.

7. **Total Covered Orders**: The total number of orders placed by participants during the stated period is represented by total covered orders.

8. **Total Covered Shares**: The total volume or quantity of shares involved in orders placed by participants during the stated period is represented by total shares.

9. **Cancelled Shares**: Cancelled shares are the volume or number of shares that were initially part of an order but were later cancelled by the participant prior to execution.

10. **Market center Executed Shares**: Market center executed shares are the total number of shares of covered orders executed at the receiving market center.

11. **Away Executed Shares**: Away executed shares are the total number of shares of covered orders executed at any other venue.

12. **Shares from 0 to 9 Seconds**: It reflects the total number of shares of covered orders executed from 0 to 9 seconds after order receipt.

13. **Shares from 10 to 29 Seconds**: It represents the total number of shares of covered orders executed from 10 to 29 seconds after order receipt.

14. **Shares from 30 to 59 Seconds**: It represents the total number of shares of covered orders executed from 30 to 59 seconds after order receipt.

15. **Shares from 60 to 299 Seconds**: It reflects the total number of shares of covered orders executed from 60 to 299 seconds after order receipt.

16. **Shares from 5 to 30 Minutes**: It reflects the total number of shares of covered orders executed from 5 to 30 minutes after order receipt.

17. **Average Realized Spread**: The average difference between the execution price of a trade and the midpoint of the National Best Bid and Offer (NBBO) at the time of trade is referred to as the average realized spread. It gives an indicator of the cost or profit of conducting trades. It is given in USD with four decimal points.

18. **Average Effective Spread**: The average effective spread is the difference between a trade's execution price and the prevailing market price at the time of trade. It considers the effect of market liquidity on the transaction's cost. It is given in USD with four decimal points.

19. **Price Improved Shares**: Price improved shares are the volume or quantity of shares that were executed at prices lower than the National Best Bid and Offer (NBBO) midpoint.

20. **Price Improved Avg Amount**: For shares executed with price improvement, this is the share-weighted average amount per share that prices were improved. The sum must be represented in dollars and rounded to four decimal places.

21. **Price Improved Avg Time (Secs)**: For shares executed with price improvement, it is the share-weighted average period from the time of order receipt to the time of order execution. The period must be given in seconds and conducted to one decimal place.

22. **At-the-Quote Shares**: At the quote shares indicate the total number of shares of covered orders executed at the quote.

23. **At-the-quotation Avg Time (Secs)**: For shares executed at the quotation, it is the share-weighted average time from the time of order receipt to the time of order execution. The period must be given in seconds and conducted to one decimal place.

24. **Outside-the-Quote Shares**: Outside the quote shares reflect the total number of shares of covered orders executed outside the quote.

25. **Outside-the-Quote Avg Amount ($)**: The share weighted average amount per share that prices were outside the quote for shares executed outside the quote. The sum must be represented in dollars and rounded to four decimal places.

26. **Outside-the-Quote Avg Time (Secs)**: For shares executed outside the quote, it is the share weighted average time from the time of order receipt to the time of order execution. The period must be given in seconds and conducted to one decimal place.

2.3. Evaluating a market center

There are several things to consider when evaluating a market center's performance. The primary parameters for assessing a market center's transaction execution quality, according to *Fidelity Capital Markets* [3], are listed below:

1. **Price Improvement**: This is calculated as a percentage of shares executed at prices above the current National Best Bid or Offer (NBBO). Specifically, sell orders must be either above the best bid or below the best offer for purchases.

2. **Execution Price**: This factor is calculated as the proportion of shares that are traded at or close to the National Best Bid or Offer (NBBO) for security across all exchanges and/or market centers.

3. **Execution Speed**: This metric measures how quickly market centers typically execute orders after receiving them.

4. **Effective Spread**: This term refers to the average difference between a trade's execution price and the going market price at the time of the trade. This sum reflects how frequently and how much a broker-dealer raises the price of a share.

It is critical to remember that evaluating the performance of market centers can be difficult for individual traders because some performance measures and data may not be easily accessible. In these circumstances, it may be beneficial to rely on industry reports, reviews, and insights from reliable sources to evaluate the performance of the market center. This project primarily deals with analyzing and understanding the dynamics of order execution quality based on the data from rule 605 filings.

3. Methods

This section elaborates and deals with data collection, research design, data analysis techniques, software and tools used for this study, data visualizations, assumptions, and limitations of the study.

3.1. Configuration File

The configuration file (config.yml) serves as a crucial component in our data analysis process, allowing us to customize and select specific parameters for our analysis. This configuration file empowers us to focus on order sizes, order types, tickers, and market center IDs to evaluate the order execution quality across different market centers.

The configuration includes the following mappings for order sizes and order types, which we have used to filter and categorize the relevant data:

- Order Size Mapping:

    o 100-499 shares: 21

    o 500-1999 shares: 22

    o 2000-4999 shares: 23

    o 5000 or more shares: 24

- Order Type Mapping:

    o Market orders: 11

    o Marketable limit orders: 12

    o Inside-the-quote limit orders: 13

    o At-the-quote limit orders: 14

    o Near-the-quote limit orders: 15

Additionally, we have specified the tickers of interest and the market center IDs for our analysis in the configuration file. *Figure 2* shows the contents of the configuration file.

```
 1 ▾ ##########################################################
 2   # This is the configuration file that lets the user to select
 3   # order sizes, order types, ticker list, market center IDs for analysis.
 4   # User can also select the project working directory.
 5   # If multiple ranges or types are desired, use comma to separate values
 6   # If no specific value is desired, use "".
 7   # Automatic SEC Rule 605 file downloads are currently supported
 8   # using download_rule605_filings.R for CDRG, JNST, NITE.
 9   # ------------------
10   # Order Size Mapping
11   # ------------------
12   # 100-499 shares - 21
13   # 500-1999 shares - 22
14   # 2000-4999 shares - 23
15   # 5000 or more shares - 24
16   # ------------------
17   # Order Type Mapping
18   # ------------------
19   # market orders - 11
20   # marketable limit orders - 12
21   # inside-the-quote limit orders - 13
22   # at-the-quote limit orders - 14
23   # near-the-quote limit orders - 15
24   # ------------------
25   ##########################################################
26   # Provide Input Values below:
27
28 ▾ default:
29     order_type: "11"
30     order_size: "21"
31     tickers: "AAPL,AMZN,MSFT,GOOG"
32     market_center_ids: "CDRG,JNST,NITE"
33     |
```

Figure 2. Contents of the configuration file

By utilizing this configuration file, we can selectively focus on specific criteria and filter the data to perform a comprehensive evaluation of order execution quality across the chosen market centers and tickers.

3.2. Data Collection

This subsection emphasizes intricate details of the data collection process such as data source, time frame, data cleaning, data integrity and quality checks, data storage and management, and data format.

3.2.1. Data Source

In accordance with SEC regulations, market centers are obligated to file SEC Rule 605 reports monthly, and these filings are readily accessible on their respective websites. According to <u>FINRA</u> [4],It is noteworthy that several prominent market centers (enumerated below) have designated FINRA as the authorized participant responsible for displaying their identification details along with hyperlinks to their disclosures of SEC-Required Order Execution Information (SEC Rule 605).

Table 1 presents a comprehensive compilation of diverse firms, featuring their unique Market Center IDs (MCID), and alongside, their respective Firm Names as hyperlinks. These Firm Name hyperlinks serve as URLs that redirect to the latest SEC Rule 605 filings available on the individual market centers' official websites.

Table 1. Market Centers and URLs to download Rule 605 files

MCID	Firm Name
ADAM	A.G.P. / ALLIANCE GLOBAL PARTNERS
ALNC	A.G.P. / ALLIANCE GLOBAL PARTNERS
BARD	ROBERT W. BAIRD & CO. INCORPORATED
BBOK	BARCLAYS CAPITAL INC.
BERN	BERNSTEIN SANFORD C & CO. LLC
BMOC	BMO CAPITAL MARKETS
BTIG	BTIG LLC
CANT	CANTOR FITZGERALD & CO.
CDRG	CITADEL SECURITIES LLC
CODA	CODA Markets Inc.
COWN	COWEN AND COMPANY LLC
CSTI	Canaccord Genuity Inc.
DADA	DAVIDSON (D.A.) & CO. INC.
DAWA	DAIWA CAPITAL MARKETS AMERICA INC.
DOWL	DOWLING & PARTNERS SECURITIES LLC
EBXL	LEVEL ATS
EDJO	Edward Jones
ETMM	G1 Execution Services
FBCO	CREDIT SUISSE SECURITIES (USA) LLC
GSCO	GOLDMAN SACHS AND COMPANY
GTSZ	GTS Securities LLC
GUGS	GUGGENHEIM SECURITIES LLC
HRTF	HRT Financial LP
IATS	Interactive Brokers LLC
ICBX	Instinet LLC
INTL	StoneX Financial Inc.
JEFF	Jefferies LLC

MCID	Firm Name
JNST	JANE STREET CAPITAL LLC
JPBX	J.P. Morgan Securities LLC
JPMS	J.P. MORGAN SECURITIES LLC
JPMX	J.P. MORGAN SECURITIES LLC
JSCA	Jane Street Capital LLC
JSJX	JANE STREET CAPITAL LLC
KBWI	KEEFE BRUYETTE & WOODS INC.
KEYB	KEYBANC CAPITAL MARKETS INC.
KING	C. L. KING & ASSOCIATES INC.
LATS	BARCLAYS CAPITAL INC.
LEER	LEERINK Partners LLC
LEHM	BARCLAYS CAPITAL INC.
LQNA	Liquidnet H2O
LQNT	LIQUIDNET
MACQ	MACQUARIE CAPITAL (USA) INC.
MAXM	MAXIM GROUP LLC
MLCO	BofA Securities Inc.
MLIX	Instinct X
MSCO	MORGAN STANLEY & CO. LLC
MZHO	MIZUHO SECURITIES USA INC.
NFSC	NATIONAL FINANCIAL SERVICES LLC
NITE	Virtu Americas LLC
OPCO	OPPENHEIMER & CO. INC.
OTAA	OTA LLC
PAUL	PAULSON INVESTMENT CO. INC.
PIPR	PIPER JAFFRAY & CO.
PPFD	Pershing LLC
RAJA	RAYMOND JAMES & ASSOCIATES INC.
RBCM	RBC CAPITAL MARKETS LLC
RHCO	TRUIST SECURITIES INC.
RILY	B. Riley Securities Inc.
SBSH	CITIGROUP GLOBAL MARKETS INC.
SGAS	SG Americas Securities LLC
SGMT	Goldman Sachs & Co LLC
SOHO	TWO SIGMA SECURITIES LLC
SPHN	STEPHENS INC.
STFL	STIFEL NICOLAUS & COMPANY INC
SUFI	SUSQUEHANNA FINANCIAL GROUP LLP
UBSA	UBS ATS
UBSS	UBS SECURITIES LLC
VERT	THE VERTICAL TRADING GROUP LLC
VIRT	Virtu Americas LLC

MCID	Firm Name
VNDM	Wall Street Access
WABR	WALL STREET ACCESS
WBLR	WILLIAM BLAIR & COMPANY LLC
WBSI	Wedbush Securities Inc.
XTXE	XTX Execution Services LLC

3.2.2. Data Collection Process

The data collection process for this study depends on the market centers chosen. The SEC Rule 605 filings for the market centers in question (Citadel Securities LLC, Virtu Americas LLC, Jane Street Capital, and G1 Execution Services LLC) have been downloaded via internet using the URLs to the corresponding websites (Refer Table 1). As part of this project, the data collection process for SEC Rule 605 filings of Citadel Securities LLC, Virtu Americas LLC, and Jane Street Capital has been automated using R code from the file *download_rule605_filings.R*

The data collection process employed in this study is contingent upon the selection of specific market centers. To obtain the requisite SEC Rule 605 filings for the designated market centers, including Citadel Securities LLC, Virtu Americas LLC, Jane Street Capital, and G1 Execution Services LLC, a systematic approach has been adopted, which involves the utilization of URLs provided on their respective websites (as presented in Table 1) to access and download the relevant SEC Rule 605 filings from the internet.

Notably, for enhanced efficiency, the data collection process for SEC Rule 605 filings pertaining to Citadel Securities LLC, Virtu Americas LLC, and Jane Street Capital was facilitated through the utilization of R code. Specifically, the process was automated using the "download_rule605_filings.R" script, thereby streamlining the acquisition of essential data required for this project.

3.2.3. Time Frame

The temporal scope of the data utilized for analysis spans four years. Typically, the market centers make available the preceding 48-50 SEC Rule 605 filings on their websites, and in this study, all accessible filings within this time frame have been utilized. Consequently, the data pertaining to the four selected market centers encompasses a total of 160 SEC Rule 605 files, encapsulating the comprehensive data set instrumental to the analysis conducted in this study.

3.2.4. Data Pre-processing

The Joint-SRO Plan mandates that market centers publish their monthly reports in the form of electronic data files, which are standard, pipe-limited ASCII files. These files are typically available in either *.dat* or *.txt* formats. ***Figure 3*** shows a code snippet that prints sample content from SEC Rule 605.

```
file_path <- paste0(project_dir, "/data/f605_data")
file_name <- list.files(file_path, recursive = TRUE)[1]
rule605_file <- file.path(file_path, file_name)
file_content <- readLines(rule605_file, n = 7)

# Add a new line for better readability

rows <- ""
for (line in file_content) {
  if (nchar(line) <= 95) {
    rows <- paste(rows, line, "\n", sep = "\n")
  }
}
cat(rows)
```

Figure 3. Code Snippet to print sample content from SEC Rule 605 file

Figure 4 shows the contents of the selected SEC Rule 605 file.

T|TCDRG|202304|A|13|21|11684|1241226|1216822|24404|0|23495|300|360|249|0|-0.0224|||||||||

T|TCDRG|202304|A|14|21|962|102307|101955|352|0|100|252|0|0|0|-0.0664|||||||||

T|TCDRG|202304|A|15|21|547|58422|57097|1025|0|100|175|0|100|650|0.0849|||||||||

Figure 4. Sample content of SEC Rule 605 file

This snippet represents sample rows of data from the file, containing various attributes separated by the pipe (|) delimiter. These attributes provide essential information related to order execution quality for the respective market center and time frame. Below are the steps involved in the data pre-processing.

1. **Combine the files into a data frame**: In this study, we encounter a considerable number of files (at least 48-50 files) for each market center, as discussed in the Time Frame section. To process this data efficiently, we employ a method where we combine the data from each file into a unified data frame.

To achieve this, we begin by defining the column names and class types for the data frame to ensure proper data representation. Each row from the files is then bound together to form the rule605_all data frame. By utilizing this approach, we successfully convert multiple pipe-limited ASCII files into a single, comprehensive data frame named "rule605_all." This unified data frame will serve as a crucial foundation for our further analysis and investigation of order execution quality across various market centers. ***Figure 5*** shows the code snippet to combine multiple SEC Rule 605 files into a single data frame.

```
rule605_files <- list.files(rule605_path, recursive = TRUE)

rule605_col_names <- c(
  "participant", "market_center", "date",
  "ticker", "order_type", "order_size",
  "total_orders", "total_shrs", "cancelled_shrs",
  "mc_exec_shrs", "away_exec_shrs", "shrs_0to9sec",
  "shrs_10to29sec", "shrs_30to59sec", "shrs_60to299sec",
  "shrs_5to30min", "avg_realzd_spread", "avg_effec_spread",
  "px_improved_shrs", "px_improved_avg_amt", "px_improved_avg_secs",
  "at_quote_shrs", "at_quote_avg_secs", "outside_quote_shrs",
  "outside_quote_avg_amt", "outside_quote_avg_sec"
)

rule605_col_types <- c(
  "character", "character", "character",
  "character", "character", "character",
  "numeric", "numeric", "numeric",
  "numeric", "numeric", "numeric",
  "numeric", "numeric", "numeric",
  "numeric", "numeric", "numeric",
  "numeric", "numeric", "numeric",
  "numeric", "numeric", "integer",
  "numeric", "numeric"
)

rule605_all <- process_rule605_files(rule605_files,
                                     rule605_col_names,
                                     rule605_col_types)
```

Figure 5. Code Snippet to combine all files into a data frame

2. **Add ticker listing information as new columns**: To incorporate the ticker listing information in the data frame, we add five new columns namely - in_sp500, in_r1000, on_nyse, on_nasdaq, on_amex. For each row, based on the corresponding ticker listing, these columns will be marked either "TRUE" or "FALSE." *Figure 6* shows a code snippet that adds ticker listing information to the data frame.

```
constituent_data_dir <- paste0(project_dir, "/data/constituent_data")

setwd(constituent_data_dir)

rule605_all <- add_listing_data(rule605_all, "sp500constituents.csv",
                                "in_sp500")
rule605_all <- add_listing_data(rule605_all, "russell1000_constituents.csv",
                                "in_r1000")
rule605_all <- add_listing_data(rule605_all, "tickers_NYSE.csv",
                                "on_nyse")
rule605_all <- add_listing_data(rule605_all, "tickers_NASDAQ.csv",
                                "on_nasdaq")
rule605_all <- add_listing_data(rule605_all, "tickers_AMEX.csv",
                                "on_amex")
```

Figure 6. Code Snippet to add ticker listing information

3. **Filter the data frame based on user input**: The data frame is filtered based on the order type and order size chosen by the user in configuration file. As per the configuration file, this study considers only order

size 21 which translates to 100-499, and order type 11 which translates to mkt_ordr. ***Figure 7*** shows a code snippet to filter the dataframe based on the user input provided in the configuration file.

```
rule605_df <- rule605_all %>%
  filter(order_type %in% order_type_ip) %>%
  filter(order_size %in% order_size_ip) %>%
  filter(mc_exec_shrs != 0)

rule605_df[is.na(rule605_df)] <- 0
```

Figure 7. Code Snippet to filter the dataframe

4. **Data Cleaning**: We make the below updates to the data frame:

- order type and order size codes are translated to their respective descriptions based on the mapping provided in the configuration file.

- A new column total_exec_shrs is added as the sum of mc_exec_shrs and away_exec_shrs.

Table 2 shows sample rows and columns from the updated data frame rule605_df.

Table 2. Sample rows and columns from the dataframe

market_center	date	ticker	order_type	order_size	px_improved_shrs	px_improved_avg_amt
NITE	2022 May	ASET	mkt_ordr	100-499	3533	0.0114
TETMM	2022 Feb	CCMP	mkt_ordr	100-501	4110	0.0689
TETMM	2020 Nov	SMDV	mkt_ordr	100-502	72313	0.029
TJNST	2021 Apr	HNI	mkt_ordr	100-503	927	0.0614

3.3. Research Design

Based on the article The Little Guy Wins! [5], we calculated the *Net Price Improvement (NPI)* per ticker to assess the order execution quality across various market centers. When examining the effectiveness of market centers, brokers, or trading algorithms, net price improvement is a crucial indicator for determining execution quality. It assists investors and traders in assessing the effects of execution choices and locating opportunities to enhance trading strategies and results. The difference between the execution prices obtained and the current market prices at the time of trade is considered when calculating net price improvement (NPI).

Price improvement in the context of trading happens when a trade is conducted at a price better than the going market rate. It can be done by getting execution prices that are better than the National Best Bid and Offer (NBBO) or by getting prices that are better than the NBBO's midpoint. When trades are conducted at prices that are higher than the going rate on the market, the trader benefits from cost savings or greater profits. Negative price improvement, on the other hand, happens when deals are conducted at prices that are lower than the going market rate, resulting in added expenses or losses for the trader. Both positive and negative price improvements are considered by NPI.

It provides a measure of how effectively trades are executed in terms of obtaining better prices compared to the prevailing market conditions. Positive net price improvement indicates that the trader achieved better prices overall, while negative net price improvement suggests that the trader experienced worse prices on average compared to the market.

It offers a gauge for the effectiveness of trade execution in terms of attaining better pricing than the current market conditions. In comparison to the average price that prevails in the market, positive NPI implies that the trader achieved better prices, while negative NPI indicates that the trader encountered poorer prices.

The calculation of net price improvement per ticker involved several key steps:

1. **Price Improvement and Deviation Calculation**: We first identified the shares executed at better prices than the NBBO midpoint and quantified the total value of price improvement by multiplying the number of shares with improved prices by the average amount of price improvement per share. Additionally, we measured the total value of price deviations for shares executed at prices outside the NBBO quote by multiplying the number of such shares by the average amount of price deviation per share. *(px_improved_shrs * px_improved_avg_amt)* is the total value of price improvement and *(outside_quote_shrs * outside_quote_avg_amt)* is the total value of price deviation for the shares executed at prices outside the NBBO quote.

2. **Net Value Improvement**: By subtracting the value of price deviations from the value of price improvements, we obtained the net value improvement, which represents the overall gain or loss resulting from the execution of shares. *((px_improved_shrs * px_improved_avg_amt) - (outside_quote_shrs * outside_quote_avg_amt))*

3. **Conversion to Cents**: To ensure uniformity, we converted the net value improvement from dollars to cents by multiplying it by one hundred, denoted as *'net_pi_numerator'*.

4. **Net Price Improvement per Ticker**: To determine the net price improvement per ticker, we divided the *'net_pi_numerator'* value by the total number of shares executed for each ticker, i.e., *(net_pi_numerator/total_exec_shrs)*. This step allowed us to assess the average price improvement for trades associated with each specific ticker.

Table 3 shows the sample rows from the data frame along with the net_pi column.

Table 3. Sample rows and columns from the dataframe

market_center	date	ticker	order_type	order_size	net_pi_numerator	total_exec_shrs	net_pi
NITE	2021 Oct	WTRU	mkt_ordr	100-499	6736.08	1924	3.501
TCDRG	2020 Apr	IWY	mkt_ordr	100-500	699784.82	248312	2.818
TETMM	2021 Sep	SBT	mkt_ordr	100-501	354	300	1.18
TETMM	2022 Oct	LGLV	mkt_ordr	100-502	50627.28	19177	2.64
TETMM	2022 Mar	BRKL	mkt_ordr	100-503	3649.5	4866	0.75

5. **Weighted Mean and Weighted Median**: To account for variations in the number of executed shares per ticker, we calculated the weighted mean and weighted median of net price improvement using the *'wtd.mean()'* and *'wtd.quantile()'* functions, respectively, with net price improvement values as weights and the total number of executed shares as the data.

The net price improvement values, along with the corresponding weighted mean and weighted median for each market center based on the ticker listing, were utilized to perform a comprehensive time series analysis. The time series analysis aimed to identify any trends or changes in the execution quality of market centers over the analyzed period.

By following this systematic approach, we gained valuable insights into the order execution efficiency and reliability of different market centers, providing a robust foundation for our research analysis.

3.4. Software and Tools

The data analysis for this research project was conducted using the software and tools that facilitated data collection, data manipulation, visualization, and report generation. The main software and tools utilized are as follows:

1. **R Programming Language**: R, a powerful open-source statistical programming language, was used for data analysis, statistical modeling, and visualization. R provides a wide range of packages and libraries that contribute to the efficient processing and analysis of the dataset.

2. **R Markdown**: R Markdown was employed for generating dynamic and reproducible reports that integrated data analysis code, visualizations, and explanatory text. R Markdown allowed for the seamless integration of code and results, making it easier to share findings and insights.

3. **LaTeX**: LaTeX, a typesetting system, was used to format and typeset the final report document. LaTeX provides a prominent level of control over the document layout, ensuring a professional and consistent appearance.

The combination of R, R Markdown, and LaTeX offered a robust and efficient workflow, enabling streamlined data analysis, report generation, and presentation of results.

3.5. Data Visualization

For presenting the results of this data analysis, tables were the primary method of visual representation used. Tables offer a clear and concise way to present numerical data, allowing for easy comparison and reference.

The tables presented in this study were designed to showcase market center name, weighted-mean of net price improvement, and weighted-median of net price improvement.

3.5.1. By Ticker

For tickers AAPL and AMZN, the highest weighted-mean of net price improvement is achieved by Citadel Securities LLC (TCDGRG) and highest weighted-medium of net price improvement is achieved by G1 Execution Services LLC (TETMM). For ticker GOOG, both the highest weighted-mean and weighted-median of net price improvement is achieved by Citadel Securities LLC (TCDGRG). Similarly, for ticker MSFT, both the highest weighted-mean and weighted-median of net price improvement is achieved by G1 Execution Services LLC (TETMM).

Table 4 shows the overall weighted mean and weighted median of net price improvement for each market center.

Table 4. W-Mean and W-Median of Net Price Improvement by Ticker

market_center	ticker	net_pi_wmean	net_pi_wmed
NITE	AAPL	0.675	0.467
NITE	AMZN	10.851	0.526
NITE	GOOG	16.706	0.474
NITE	MSFT	0.973	0.968
TCDRG	AAPL	0.809	0.546
TCDRG	AMZN	14.194	0.613
TCDRG	GOOG	17.534	0.604
TCDRG	MSFT	1.094	0.939
TETMM	AAPL	0.759	0.573

market_center	ticker	net_pi_wmean	net_pi_wmed
TETMM	AMZN	9.765	0.653
TETMM	GOOG	15.58	0.583
TETMM	MSFT	1.239	1.236
TJNST	AAPL	0.573	0.523
TJNST	AMZN	6.499	0.603
TJNST	GOOG	9.072	0.523
TJNST	MSFT	1.203	1.169
TVIRT	AAPL	-0.02	0
TVIRT	AMZN	-3.566	0
TVIRT	GOOG	0	0
TVIRT	MSFT	-0.64	0
VIRT	AAPL	0	0
VIRT	AMZN	0	0
VIRT	GOOG	0	0
VIRT	MSFT	-0.333	-0.25

3.5.2. By Order Type and Order Size

For chosen order type and order size, we can notice that both the highest weighted-mean and weighted-median of net price improvement is produced by G1 Execution Services LLC (TETMM).

Table 5 shows the weighted mean and weighted median of net price improvement for each market center, grouped by order size and order type. *Table 5* shows the weighted-mean and weighted-median of NPI by order type and order size.

Table 5. W-Mean and W-Median of Net Price Improvement by Order Type and Order Size

market_center	order_type	order_size	net_pi_wmean	net_pi_wmed
NITE	mkt_ordr	100-499	1.914	0.594
TCDRG	mkt_ordr	100-499	2.041	0.644
TETMM	mkt_ordr	100-499	2.337	0.745
TJNST	mkt_ordr	100-499	1.902	0.579
TVIRT	mkt_ordr	100-499	-0.153	0
VIRT	mkt_ordr	100-499	-0.005	0

3.5.3. By S&P 500 listing

For tickers listed in S&P, the highest weighted-mean of net price improvement is produced by G1 Execution Services LLC (TETMM). In contrast, for the tickets not listed in S&P, the highest weighted-mean of net price improvement is achieved by Citadel Securities LLC (TCDGRG). In contrast to the weighted-mean,

the highest weighted-median of net price improvement is achieved by G1 Execution Services LLC (TETMM) irrespective of ticker listing.

Table 6 shows the weighted mean and weighted median of net price improvement for various market centers based on the ticker listing in S&P 500.

Table 6. W-Mean and W-Median of Net Price Improvement by S&P 500 Listing

market_center	in_sp500	net_pi_wmean	net_pi_wmed
NITE	FALSE	1.666	0.533
NITE	TRUE	2.553	0.808
TCDRG	FALSE	1.778	0.583
TCDRG	TRUE	2.732	0.858
TETMM	FALSE	2.022	0.66
TETMM	TRUE	3.104	1.039
TJNST	FALSE	1.61	0.498
TJNST	TRUE	2.682	0.9
TVIRT	FALSE	-0.118	0
TVIRT	TRUE	-0.483	0
VIRT	FALSE	-0.003	0
VIRT	TRUE	-0.018	0

3.5.4. By Russell 1000 listing

The highest weighted-mean and weighted-median of net price improvement is achieved by G1 Execution Services LLC (TETMM) irrespective of ticker listing.

Table 7 shows the weighted mean and weighted median of net price improvement for various market centers based on the ticker listing in Russell 1000.

Table 7. W-Mean and W-Median of Net Price Improvement by Russell 1000 Listing

market_center	in_r1000	net_pi_wmean	net_pi_wmed
NITE	FALSE	1.441	0.489
NITE	TRUE	2.682	0.845
TCDRG	FALSE	1.531	0.561
TCDRG	TRUE	2.899	0.878
TETMM	FALSE	1.727	0.608
TETMM	TRUE	3.267	1.062
TJNST	FALSE	1.391	0.469
TJNST	TRUE	2.749	0.901
TVIRT	FALSE	-0.091	0
TVIRT	TRUE	-0.386	0
VIRT	FALSE	-0.008	0

market_center	in_r1000	net_pi_wmean	net_pi_wmed
VIRT	TRUE	0.008	0

3.5.5. By New York Stock Exchange listing

The orders routed to G1 Execution Services LLC (TETMM) have shown the highest weighted-mean and weighted-median of net price improvement irrespective of the ticker listing in New York Stock Exchange.

Table 8 shows the weighted mean and weighted median of net price improvement for various market centers based on the ticker listing on New York Stock Exchange.

Table 8. W-Mean and W-Median of Net Price Improvement by NYSE Listing

market_center	on_nyse	net_pi_wmean	net_pi_wmed
NITE	FALSE	1.959	0.585
NITE	TRUE	1.808	0.615
TCDRG	FALSE	2.07	0.625
TCDRG	TRUE	1.978	0.679
TETMM	FALSE	2.396	0.729
TETMM	TRUE	2.199	0.77
TJNST	FALSE	1.89	0.567
TJNST	TRUE	1.933	0.615
TVIRT	FALSE	-0.174	0
TVIRT	TRUE	-0.119	0
VIRT	FALSE	-0.006	0
VIRT	TRUE	0.001	0

3.5.6. By NASDAQ listing

The highest weighted-mean and weighted-median of net price improvement is achieved by G1 Execution Services LLC (TETMM) irrespective of ticker listing on NASDAQ.

Table 9 shows the weighted mean and weighted median of net price improvement for various market centers based on the ticker listing on NASDAQ.

Table 9. W-Mean and W-Median of Net Price Improvement by NASDAQ Listing

market_center	on_nasdaq	net_pi_wmean	net_pi_wmed
NITE	FALSE	1.44	0.493
NITE	TRUE	2.685	0.865
TCDRG	FALSE	1.578	0.573
TCDRG	TRUE	2.883	0.87
TETMM	FALSE	1.721	0.607
TETMM	TRUE	3.364	1.081
TJNST	FALSE	1.452	0.486

market_center	on_nasdaq	net_pi_wmean	net_pi_wmed
TJNST	TRUE	2.651	0.829
TVIRT	FALSE	-0.098	0
TVIRT	TRUE	-0.256	0
VIRT	FALSE	-0.002	0
VIRT	TRUE	-0.008	0

3.6. Time Series of Weighted Mean of NPI

In this data analysis, we sought to analyze and evaluate the order execution quality and net price improvement of various market makers over time. To achieve this, we utilized a time series approach and plotted the weighted mean of net price improvement for each market maker.

By employing a time series analysis, we aimed to identify market makers that have consistently demonstrated superior order execution quality and net price improvement compared to others. The weighted mean of net price improvement for each market center was represented as a time series, allowing us to track their performance over the analyzed period.

This time series visualization offered valuable insights into the trends and patterns of each market center's net price improvement. By observing their performance over time, we could determine which market center(s) consistently outperformed others in terms of executing orders at more favorable prices, thereby providing valuable information for traders and investors seeking to make informed decisions.

The time series plot provided a clear and dynamic representation of the order execution quality of different market makers, facilitating a comprehensive evaluation of their performance and highlighting potential opportunities for optimizing trading strategies based on net price improvement. *Figure 8* shows a code snippet and the time series plot that shows the weighted-mean of NPI across the years.

```
# Use the net pi per month for each market center

net_pi_monthly_wmean$date <- as.Date(paste0(
  substr(net_pi_monthly_wmean$date, 1, 4), "-",
  substr(net_pi_monthly_wmean$date, 5, 6), "-01"
))
net_pi_monthly_wmean <- net_pi_monthly_wmean %>%
  distinct() %>%
  mutate(date = yearmonth(date))

net_pi_monthly_wmean <- net_pi_monthly_wmean %>%
  as_tsibble(key = market_center, index = date)

# Plot the data

autoplot(net_pi_monthly_wmean) + labs(x = "Month-Year", y = "Weighted Mean")
```

Figure 8. Code Snippet to plot time series plot of W-mean of NPI

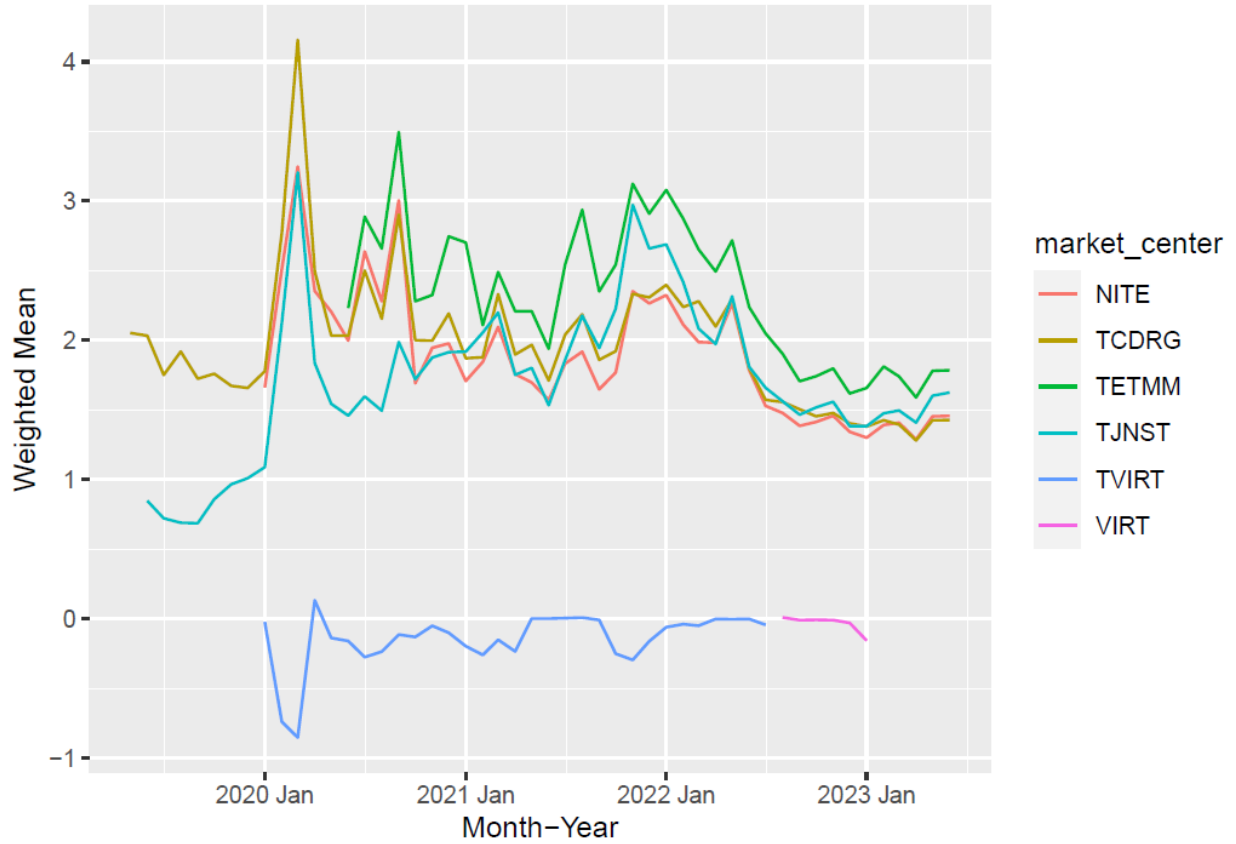Using the code snippet from *Figure 8*, we get the time series plot, shown in *Figure 9.*

Figure 9. Time Series plot showing W-Mean of NPI

Table 10 shows which market maker has achieved the highest weighted mean of net price improvement for each month. We can observe that up until April 2020, Citadel Securities LLC produced the highest weighted-mean of net price improvement. Then, we observe that G1 Execution Services LLC has consistently achieved the highest weighted-mean of net price improvement among the other market centers consecutively for 34 months starting from June 2020 till the end of time frame considered for this study.

Table 10. Highest W-mean of Net PI per month

date	market_center	mc_wmean
2019 May	TCDRG	2.05
2019 Jun	TCDRG	2.03
2019 Jul	TCDRG	1.75
2019 Aug	TCDRG	1.92
2019 Sep	TCDRG	1.72
2019 Oct	TCDRG	1.76
2019 Nov	TCDRG	1.67
2019 Dec	TCDRG	1.66
2020 Jan	TCDRG	1.78
2020 Feb	TCDRG	2.77

date	market_center	mc_wmean
2020 Mar	TCDRG	4.16
2020 Apr	TCDRG	2.49
2020 May	NITE	2.2
2020 Jun	TETMM	2.23
2020 Jul	TETMM	2.89
2020 Aug	TETMM	2.66
2020 Sep	TETMM	3.49
2020 Oct	TETMM	2.28
2020 Nov	TETMM	2.32
2020 Dec	TETMM	2.75
2021 Jan	TETMM	2.7
2021 Feb	TETMM	2.11
2021 Mar	TETMM	2.49
2021 Apr	TETMM	2.21
2021 May	TETMM	2.21
2021 Jun	TETMM	1.94
2021 Jul	TETMM	2.54
2021 Aug	TETMM	2.94
2021 Sep	TETMM	2.35
2021 Oct	TETMM	2.54
2021 Nov	TETMM	3.12
2021 Dec	TETMM	2.91
2022 Jan	TETMM	3.08
2022 Feb	TETMM	2.87
2022 Mar	TETMM	2.65
2022 Apr	TETMM	2.49
2022 May	TETMM	2.72
2022 Jun	TETMM	2.24
2022 Jul	TETMM	2.05
2022 Aug	TETMM	1.9
2022 Sep	TETMM	1.7
2022 Oct	TETMM	1.74
2022 Nov	TETMM	1.8
2022 Dec	TETMM	1.62

date	market_center	mc_wmean
2023 Jan	TETMM	1.66
2023 Feb	TETMM	1.81
2023 Mar	TETMM	1.74
2023 Apr	TETMM	1.59
2023 May	TETMM	1.78
2023 Jun	TETMM	1.78

3.7. Assumptions and Limitations

1. **Data Source and Availability**: As discussed in the data collection section, the SEC Rule 605 files have been sourced from corresponding market center websites for the required time frame of the study. Since these files are submitted to the government, they are dependable and are robust to reporting errors, missing mandatory values, or any other issues that could impact the reliability of the analysis. One limitation could be the availability of reports filed before five years, as they might not be readily available on the market center website.

2. **Order Execution Metrics**: As discussed in the Evaluating market center section, there are diverse ways and metrics to consider while assessing the order execution quality of a market center and net price improvement is only one of the metrics. For this study, we did not consider other metrics such as Execution Speed, Execution Price, and Effective Spread.

3. **Market Conditions**: For this study, we assumed negligible influence of market conditions such as market volatility and liquidity of the security on the order execution quality.

4. **Scope of the Study**: This study only analyses the order execution quality of various market centers based on the weighted-mean of net price improvement and does not provide any specific recommendations or suggestions to improve trading strategies.

4. Results and Discussion

For this study, we consider two key performance indicators namely weighted-mean and weighted-median of net price improvement.

Looking at the KPIs, based on the tickers selected by the user in the configuration file, we see that Citadel Securities LLC has achieved highest weighted-mean of net price improvement for AAPL, AMZN, and GOOG, while G1 Execution Services LLC achieved highest weighted-mean of net price improvement for MSFT. Considering the weighted-median metric, G1 Execution Services LLC has achieved the highest KPI for AAPL, AMZN, and MSFT, while Citadel Securities LLC has produced the highest weighted-median of net price improvement for MSFT.

Looking at the KPIs considering the order size and order type chosen by the user, G1 Execution Services LLC has emerged as the top performing market center.

Ticker listing also plays a key role in evaluating the order execution quality of a market center. Considering tickers listed under S&P 500, G1 Execution Services LLC has the highest weighted-mean and weighted-median of NPI. Also, G1 Execution Services LLC emerged as the top performing market center for tickers irrespective of their listing under Russell 1000, New York Stock Exchange, and NASDAQ.

By conducting the time series analysis of the weighted-mean of NPI for all the market centers involved for the entire data collected, we notice that G1 Execution Services LLC is the best performing market center.

5. Conclusion and Outlook

Based on the results obtained from the study, we can draw the following conclusions:

1. **Weighted-Mean and Weighted-Median KPIs**: The study considered two key performance indicators, namely the weighted-mean and weighted-median of net price improvement (NPI), to assess the order execution quality of various market centers.

2. **Impact of Order Size and Type**: Considering the order size and order type selected by the user, G1 Execution Services LLC emerged as the top-performing market center.

3. **Influence of Ticker Listing**: For tickers listed under S&P 500, G1 Execution Services LLC exhibited the highest weighted-mean and weighted-median of NPI. Additionally, G1 Execution Services LLC emerged as the top-performing market center for tickers irrespective of their listing under Russell 1000, New York Stock Exchange, and NASDAQ.

4. **Overall Best Performing Market Center**: The time series analysis of the weighted-mean of NPI for all market centers over the entire data collection period revealed that G1 Execution Services LLC outperformed other market centers, establishing itself as the best performing market center throughout the study.

While this study provides valuable insights into the order execution quality of different market centers based on the weighted-mean and weighted-median of NPI, there are several areas for further research and improvement. The following points outline potential areas of future investigation:

1. **Consideration of Additional Metrics**: To gain a comprehensive understanding of market center performance, future studies could explore the impact of additional order execution metrics, such as execution speed, execution price, and effective spread.

2. **Analysis of Market Conditions**: The study assumed a negligible influence of market conditions on order execution quality. Future research could delve deeper into how market volatility and liquidity affect the performance of market centers.

3. **Recommendations and Strategies**: Future research could focus on providing specific recommendations and strategies for traders and investors to improve their trade outcomes based on market center performance.

Overall, this study lays the groundwork for understanding the order execution quality of major market centers. Further research in the mentioned areas could enhance our understanding of market dynamics and offer valuable insights for optimizing trading strategies and achieving better trade outcomes.

Word Count: 5696

References

[1] "SEC Rule 605 | FINRA.org." https://www.finra.org/rules-guidance/guidance/sec-rule-605#:~:text=Rule%2011Ac1%2D5%20is%20aimed,to%20make%20monthly%20electronic%20reports.

[2] "Market Regulation: Staff Legal Bulletin No. 12 revised (FAQ about Rule 11AC1-5)." https://www.sec.gov/interps/legal/slbim12a.htm#P30_1565.

[3] "Trade Execution quality," capitalmarkets.fidelity.com. https://capitalmarkets.fidelity.com/trade-execution-quality.

[4] "Market centers | FINRA.org." https://www.finra.org/filing-reporting/regulation-nms/market-centers.

[5] B. Alpert, "The little guy wins!" www.barrons.com, www.barrons.com, 2015. Accessed: Aug. 03, 2023. [Online]. Available: https://www.fidelity.com/bin-public/060_www_fidelity_com/documents/barrons-reprint.pdf