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ALGORITHMIC TRADING: HOW HIGH FREQUENCY ALGORITHMS CAN IMPROVE MARKET EFFICIENCY AND REDUCE ARBITRAGE OPPORTUNITIES

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Preface

This dissertation explains the circumstances that lead to the revolution of the financial industry during the past fifty years. I focus on the evolution of the environment that brought the rise of the new financial industry, based on sophisticated computer, quantitative analysis, big data analysis, high frequency trading algorithms ending with the development of artificial intelligence. The following pages will introduce the automated transacted operations, starting from the first, portfolio balancing quantitative software, passing through the sophisticated calculators that allowed market makers and big dealers to raise liquidity of markets reducing overall costs, and ending with more complex high frequency trading algorithms, used for example to catch arbitrage opportunities and short misalignment in two or more prices in capital markets.

I will comment some episodes of markets failures, from last two decades, caused by computers errors and software bugs that caused the skepticism, in particular toward high frequency trading (HFT) algorithms. Then I will show some solutions for these issues, in order to understand how to avoid future market failure or massive companies-linked errors that, with the developing of more powerful trading system, are getting more and more bigger, riskier and potentially devastating for financial markets.

In the last chapter I will go in depth in the study of the high frequency trading, illustrating mechanism that major markets participant developed, explaining the evolution of strategies from hedging to pure arbitrage and speculation. Concluding, I will show a Code, written in VBA, that simulate the HFT algorithms in presence of arbitrage and I will provide an empirical evidence of market efficiency followed by my personal opinion about the future of automatized transactions. In order to test my personal HFT algorithm I use Rotman Interactive Trader Software, that allows me to simulate a real market condition in presence of inefficiency given by the misalignment of bid-ask prices of the same stock in different markets, for example in regulated and over-the-counter market, or regulated market and dark pool. To respect the privacy of the Luiss Blue

Team, that every year compete in Rotman International Trading Competition in Toronto, I can not publish the algorithmic code that I developed and used to win the Algorithmic case in Toronto last two years. Any case, I will provide a simplified version of it, that works with stocks and ETF, and I will suggest a possible code for arbitrages with options.

Contents

Chapter 1

Historical background and theoretical framework

1.1 THE RISE OF ALGORITHMIC TRADING: THEORETICAL ASPECTS

Nowadays, for most of us, it could result obvious the use of computer, or software and algorithms that transact operations in order to buy and sell currencies, or stocks in markets and stock exchange all around the world. But until fifteen years ago, the 100% of transaction where made by human, using calculators only as support of their methodologies and strategies. It is immediate to imagine what may have been the causes that led to the massive use of computer and algorithms in the financial operations. Obviously, one of the reasons is that developing and use algorithms is cheaper because it has no need of offices, wages, insurances and material needs that an employee must have. But, apart from a budget constrains point of view, what makes the difference between "classical" trading system and the new one? The breakthrough is the fact that modern computer can trade with strategies that humans could never apply, because of the speed of the machines and calculus power. In fact, they can receive, read, analyze, and take decision on information in few milliseconds, but even another important aspect must be considered.

Quoting Richard Feynman, a famous physics and pioneer in quantum computing field, he said "try to imagine, how much harder physics would be, if electrons had feelings". If we consider financial institutions the atoms and financial markets the molecules, actors of market are basically the electrons of this system. The fact that I want to evidence, is that we are reducing the impact of human feeling, whose effects have been the center of many studies in the field of Behavioral Finance, explaining many markets anomalies by human psychological influences and biases. And maybe one day someone will find absurd that economy, and in particular financial markets has been susceptible to human sentiments for a while.

But not everybody is convinced that the spread of automatized transaction will have a positive impact on markets. There have been several different situation when algorithms failed or crashed, and entire stock exchange felt overwhelmed by the massive number of order that some algorithms sent, causing the famous events known as "flash crash" of August 2012, with hundreds of millions dollars lost in few minutes. I will study in deep this aspect in the following chapter; for now we consider only the positive aspects reviewing the major drivers of the emergence and popularity of computer-based automation field.

There is no doubt that algorithmic trading development is strictly related with the great innovation of Information Technology, including hardware, software, infrastructures, that made relatively easier for everybody to write a code than before. This innovation follows the famous Moore's Law, the founder of Intel and pioneer of modern semiconductor industry, a several billion dollars market that is the heart of the modern technology. Moore stated two different laws, the first one says that the number of microprocessors double every year (after '80 the effective time was 18 months). The second law is about the costs, in fact he sustained that the cost of a processor doubles every 4 year (every generation), but this means that the growth rates are not related, and so they are destined to stop. The aspect he didn't considered was the fact that the high entry barriers, the growing demand and the very low production cost for the old generation, made this sector much more profitable than he imagined. Moreover, we can apply Moore's Law to financial system, in fact from 1929 the total market capitalization of US stock doubled every decade, and meanwhile the total trading volume doubled every 7,5 years, accelerating during the last period until 2,9 year. Basically, we can say that both markets are growing at exponential rate.

Another important aspect that we must consider is the increased demand for financial services, caused by the population growth and the economic complexity that lead to a much more complex, interconnected and coordinated financial system. The globalization increased the number of market participants, the variety of financial transactions, with globally interconnected counterparties. All institutions benefit from the financial technology and that is why it becomes indispensable.

From a pure economic point of view, the most important developments that contributed to the rise of the algorithmic trading are five:

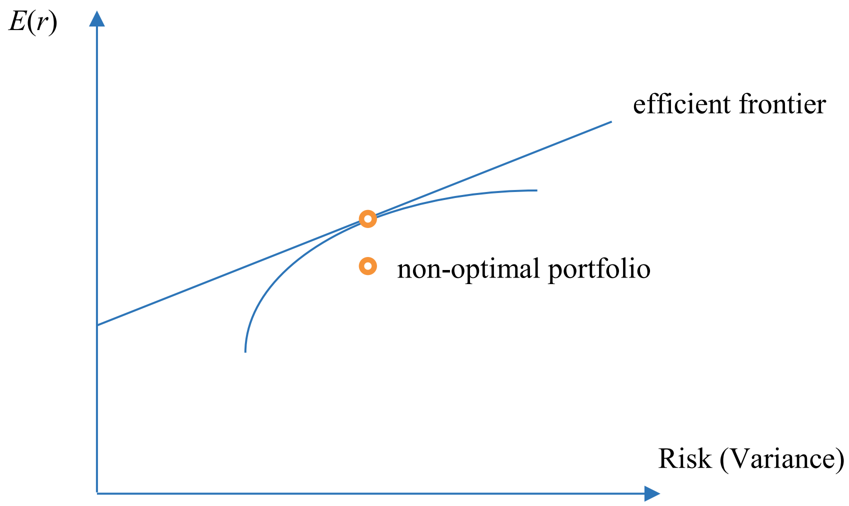

Figure 1.1 Efficient frontier.

1. The first one is the Quantitative Finance breakthrough, thanks to modern portfolio theory pioneers such as Markowitz, Sharpe, Rosenberg and Black Scholes. In 1952, Harry Markowitz published a revolutionary article that become the milestone of Modern Portfolio Theory.[1] He assumed that all investors can express their preferences on different investments basing their decision on expected return and variance. In particular, given the same expected return, all investors will choose the less risky portfolio, made by a given number of different risky assets. Given a mean-variance objective function, investors must maximize their expected value of a quadratic objective function, which means to solve an optimization problem, for example using Lagrange formula. This solution is the first algorithmic trading strategy, given by the difference between the optimal portfolio weights and the current ones. This optimal portfolio belongs to the tangency line connecting the risk-free rate with the optimal portfolios curve, also called the efficient frontier (Figure 1.1).

   Some years later, Sharpe (1964), Lintner (1965) and Mossin (1966) developed the Capital Asset Pricing Model (CAPM). They started by the assumption of portfolio selection theorem and with empirical studies on the Markowitz's theory concluded that all investors hold the same tangency portfolio, that is composed by all assets traded in market, weighted according with their market capitalization. Basi-

[1] Markowitz, H., "Portfolio Selection", *Journal of Finance*, 7(1), 77-99, 1952.

cally, the total market portfolio is the tangency portfolio. This is also known as the evolution of the Two-Fund Separation Theorem.[2]

In 1970 Rosenberg proposed an innovative model in which he isolated a small number of K factors that could explained most of the markets return. Before 1970, to implement a market portfolio algorithm it was necessary to estimate the inverse of covariance matrix of all traded assets. This was a problem mainly because a 5000 × 5000 matrix contains 12’497’500 unique parameters, and moreover this matrix is clearly not invertible. With the Rosenberg’s Linear Multifactor Risk Model, the total number of parameters to be estimate is not $\frac{n(n-1)}{2}$ but $nK + \frac{K(K+1)}{2} + n$ that means that number increase linearly with new assets and not exponentially. Moreover, this new matrix is invertible, that means that can be easily used in Markowitz-type mean-variance optimization algorithms. In fact, in 1975 Rosenberg founded the first truly quantitative investment consulting firm, called Barr Rosenberg Associates (BARRA). His software largely populated algorithmic trading equity market and was used from institutional investors and portfolio managers.

The last “quantitative revolution” came in 1973 when Black and Scholes with Merton (1973) published one of the most famous articles about the pricing of option and other derivatives. This paper had an incredible success among economic researcher that let them win the Nobel Prize in 1997. Thanks to their studies, the use of derivatives increased a lot, and became a multi-trillion-dollar industry continuously evolving and generating a large quantity of new derivative securities. In order to let the new securities appetizing as possible, there were developed dozens of derivatives, for example swaps, caps, collars, exotic and rainbow options and so on.

2. The second innovation came from the same period and is a consequence of the study we mentioned above, the index funds. In 1969 Wells Fargo Bank was the first one to invests 6 million dollars in an equally weighted portfolio made by 100

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[2] The Two-Fund Separation Theorem implies that a riskless bond and a single mutual fund are the only investment vehicles needed to satisfy the demands of all mean-variance portfolio optimizers

equities of New York Stock Exchange. This new type of investment was revolutionary because allowed institutional investors to trade “passively”, keeping the costs of back-offices, accounting and trade reconciliation at minimum. Remember that in the ‘70s this work was made only by humans, that means a lot of wages to pay, offices to rent etcetera… But even this “passive” investment portfolio needed to be balanced every time that market fluctuations altered the proportion of the index, and so there were developed the modern value weighted portfolio. For example, if in 1969 Wells Fargo had invested 100$ in company A and 100$ in company B, and company A made plus 10% while B decreased of 10%, they should now sell part of A and buy part of B. Instead, with the new equally weighted portfolio, the investment on each equities is proportional to his market capitalization, that means that if shares go up, the value of those shares in my portfolio grows at the equal rate, and so I do not need to rebalance my portfolio. However, over time and thanks to financial engineering’s innovations, this definition of “passive” investment becomes outdated. We now define as “passive” strategy every investment process that does not require discretionary human intervention, despite the active nature of their trading, for example 130/30 strategies, trend-following futures strategies or hedge fund replication. This mainly because algorithms facilitated the automatization, lowering costs of management and simplifying the investment decision process.

3. The third milestone is strictly related with the focus of this thesis. The arbitrage opportunities, and arbitrage traders always existed, in different form from what we imagine today. Probably, the formers markets during Middle Ages moved from a city to another just buying and selling the same products that where worth differently. What I mean is that arbitrages opportunities, defined as the possibility to trade the same good at two different prices, and basically to make a risk-free profit from that, always existed since exists an economy, since the first merchant born. So, the truly innovation during the ‘80s was the use of modern algorithms, in a context of fast computers advanced telecommunications and electronics markets, that can detect, identify and generate profit in a split second, operating contemporary in

all markets around the world. Later failure of arbitrages funds[3] showed that pure arbitrage opportunities can not exist because there is none totally risk-free investment opportunity in the market. An advantage of this strategy is that portfolios are made by long and short positions, that allows to have positive returns in every market condition, and not only in bullish period. Obviously, arbitrages strategies are largely unknown because the major hedge funds managers have no interest in publishing them, causing air of mystery around the strategies. Only few studies tried to explain some simple version of arbitrage strategies, that's why I decided to study arbitrages and give an example in last Chapter of this dissertation.[4] The last important aspect of arbitrage strategies is the liquidity providing function that they assumed, increasing efficiency in illiquid markets, but even reducing mispricing caused by markets anomalies.

4. Another important breakthrough was the application of automatized computer-made quotation to exchange-traded equities, allowing institutions to implement execution strategies in order to reduce the volume impact on prices. For example, because of the downward-sloping demand curve nature, a large institution that needs to rebalance its multibillion-dollars portfolio must expect to execute the transaction at different prices, and not only at the initial market prices. The bigger is the volume traded higher will be the price alteration. That's why most important institutional use to "split" the original transaction in smaller different orders determining timing and sizes with stochastic dynamic software, so that they can minimize the "cost" of such transaction.

   Strictly related with the automated execution of large market orders is market-making.[5] The main role of market-makers is to give liquidity to markets, constantly quoting two prices at which they are willing to buy (Bid price) and sell (Ask price). As you can imagine, this means that the market-maker must buy and sell every time that a counterpart wishes, and this could be very risky in case of large market fluctuations or trends and that's why there is a spread between bid-ask prices that is

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[3] Long-Term Capital Management, the hedge fund managed by Scholes, Merton and Meriwether is a famous example.

[4] Lehmann (1990), Lo and MacKinlay (1990), Khandani and Lo (2007).

[5] In the last chapter, I will give a practical example of a market making algorithm.

the compensation that firms require for taking risk. The activity of algorithms in this case is to submit and cancel limit orders at prices that reflect risk, demand, offer, volumes, fees, arbitrages across different markets or securities and meanwhile being profitable for the market-makers. We must consider the fact that, as humans, even computers can make mistakes, with the difference that in this last case consequences are dramatic. That's why auto-quoting algorithms are extremely complex and require enormous barrier costs to entry in this sector.

5. And, last but not least, the biggest innovation that contributed in large part to the widespread of automated financial markets is the consequence of modern and sophisticated telecommunication systems combined with fasters than ever computers. High Frequency Trading (HFT) can trade million transaction per hour. They have been the truly revolution in financial industry, impacting for 60%-70% of total transaction in US market.[6] Nevertheless, the number of financial institutions that use them is quite small respect to the number of transactions. According with a study of Baron, Brogaard and Kirilenko (2019) we know that those firms earn large, persistent profits while assuming very low risk. The logic of HFT is the opposite of market-makers, basically reducing liquidity of markets instead of providing it, and earning profits from this kind of "speculative" activity.

1.2 THE RISE OF ALGORITHMIC TRADING: PRACTICAL ASPECTS

In the previous section, I analyzed the rise of Algorithms in financial sector from a theoretical point of view. Now I want to describe exactly how and when the automatic calculators become part of the every-day trading in the biggest financial markets in the world.

Automatized transaction systems are well known phenomena by all market participants, but it is not as new as we could imagine. The digitalization of order flow began in the 1976 by the implementation of the "Designated Order Turnaround" system by New York Stock Exchange, that changed drastically the methods of trading. Through electronic workstation called "display book", orders to buy and sell securities were executed electronically.

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[6] Data for 2009-2010. Source www.Investopedia.com

Before 1971, traders were displayed in the famous trading-floors, screaming prices and information across the room or using expensive telephonic communication to communicate each other. In 1971, the National Association of Securities Dealers (NASD) created the first Automated Quotation system (NASDAQ) that became the first electronic stock market, specialized in new economy companies such as high tech corporations, and growing in impressive manner (accounting for the 42% of total stock market volume in 1992) until the technologic bubble of 2000.

In 80' the Securities Exchange Commission imposed to all market makers to quote more than 1'000 of most traded stocks on NASDAQ at a given prices. As expected, SEC increased the liquidity of markets, but there happened something else that they did not expected. The first algorithms were born. They were called SOES (Small Order Execution System) and can be defined as the ancestors of modern HFT. The SOES bandits, the name used to call those traders, were exploiting delays of market makers in the update of bid ask prices to make their profits.

During 70' and 80' NYSE and NASDAQ dominated computerized trading markets, until the SEC authorized the existence of Electronic Communication Network (Regulation Alternative Trading Systems 1992). Duopoly, in fact, was not beneficial for financial markets, and the introduction of this new system was destined to revolutionize the financial market. Those ECNs facilitate negotiation of financial products, in after-hours outside of the traditional stock exchanges and with the use of algorithms to execute orders. In fact, investors sending orders to ECNs were automatically matched with orders from the opposite side, without intermediaries, and if this was not possible because of a lack of offers, transaction were executed on NASDAQ as soon as the bid or ask price was hit. In other words, ECNs assumed functions of brokers, dealers, market-makers and exchanges market. Another important event for financial markets occurred in 2001 when stock exchanges changed their quoting methods from fractions (the minimum tick was 1/16th of a dollar, that is \$0,0625 cents) to decimals (now traders can negotiate in the order of \$0,01). This meant that the minimum bid-ask spread was reduced from 6,25 cents to a single penny, an incredible advantage for algorithmic trading. The last important progress in the history of automatized trading came in 2005 with the Regulation National Market System, a series of implementation for equity markets designed by SEC. The most important laws were two, the Sub-Penny Rule

(Rule 612) that introduced the thousandths of dollar in quoting systems, and the Older Protection Rule (Rule 611) which allowed market orders posted electronically to be immediately executed at the best price nationally (National Best Bid and Offer). The Rule 611 had an exception, that execution of an order was allowed anyway even if the price was not the one suggested by NBBO. This was possible only in the case that the posted price was the best in another market and that the transaction was executed within a second from the last NBBO. This paved the way to more and more complex software and hardware, developed to exploit frequent arbitrage opportunities of markets.

In Europe the MIFiD I of 2007 regulated the existence of Multilateral Trading Facilities, the European version of ECNs and the obligation at Best Execution prices as for NBBO. Effects of the new regulations across different countries was basically the same, pushing up the new phenomena of Algorithmic Trading and his evolution in High Frequency Trading.

Today, in equity markets of US, Europe and Asia High Frequency Algorithms impact for a big part of volumes. In particular, an innovation that led to the increase of trading volumes was the developing of “dark pools”, developed as Alternative Trading Systems, they are anonymous trading pools where counterparties can trade and improve their strategies without need to reveal their identity, an so without giving information to competitors about their strategies.[7]

There are many strategies that HF firms implement the generate their profits, and most of them regard the speed of execution, that allows them to close transactions before others even realize the possibility to make a profit. Usually the strategies used by those companies, i.e. GETCO, are based on micro-gains, in the order of a fraction of a penny on short-term market fluctuations. Because of this reason those strategies require a high turnover in capital and are extremely dependent on market conditions and infrastructure, particularly on calculus power and ultra-low latency, which means that orders are sent at speeds of 1 microsecond, or $1 * e^{-6}$ seconds. For this reason, HFT companies are continuously improving their systems, both in software and hardware components. In order to be profitable those strategies, that have margins of a penny or even less, need to execute a lot of trades in a time so short that the average investors neither

[7] Strategies will be described in Chapter 2

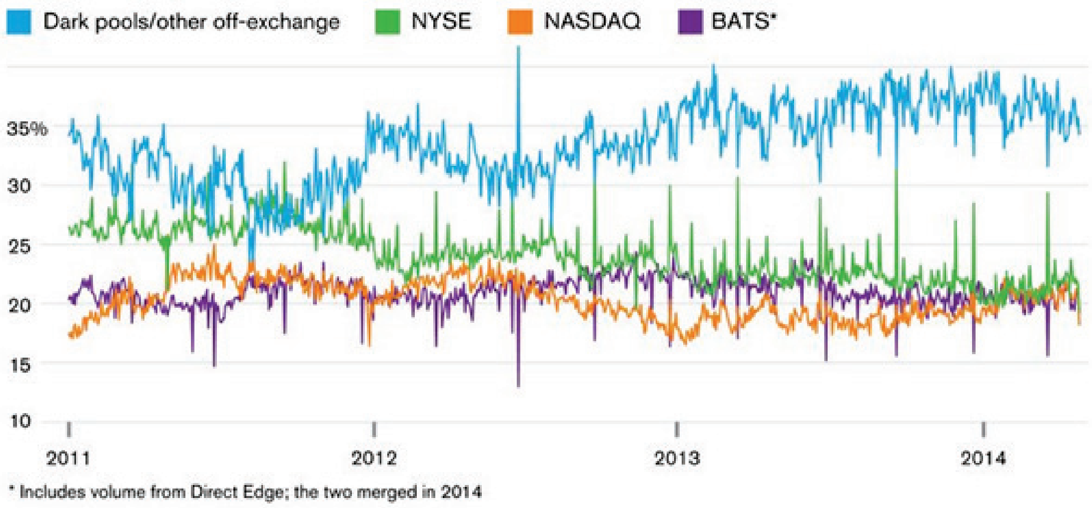

Figure 1.2 Darkness rising: percentage of trading volume, based on daily close.

knows what is going on. In 2019 there are 40 dark pools (source Bloomberg.com) out of 45 ATSs in U.S., accounting for 40% of total equity volume (Figure 1.2).

There exists three different type of dark rooms:

1. The Broker Dealer Owned are set up by large broker dealer such as Credit Suisse's CrossFinder, Goldman Sachs' Sigma X, Citi's Citi Match and Morgan Stanley's MS Pool, for their clients, but even the owners operate with their own algorithms.
2. The Exchange Owned pools play the role of agents. Prices are obtained from exchanges such as NBBO (National Best Bid and Offer) so there is no price discovery. Most famous are NYSE Euronext and BATS Trading. Moreover there are some dark pools that work exactly as the exchange owned but they are Agency Owned like Liquidnet and Istinet.
3. Independent firms like GETCO and Knight developed their own dark pools, and they operate just like the large Broker-Dealer, so with price discovery and with their own strategies.

The main problems of dark pools are the lack of transparency, that could lead to a conflict of interest between traders and owner of platforms and the predatory algorithms. In fact, traders of dark pools are the ideal fodder for predatory algorithms, that take advantage of anonymous orders and latency issues to implement their strategies. Many dark pools owners were fined for several millions dollar for misleading consumers and wrongdoing in their position.

1.3 WE DEPEND ON ALGORITHMS, BUT WE STILL DO NOT REALIZE IT

One of the characteristics that differentiate human from other animals is the capacity of use objects as extension of our body, in order to expand our capacity of do works that would be unrealizable with only our strength. Strictly related with this concept is the definition of the word "technology", from Greek "τέχνη" (techne) which means "art, skill, cunning of hand" and λογία (logia); in the ancient Greek the word was referred to the use of goods and services to the pursue of an objective. We could speculate about the fact that the first technological invention was the club. Thanks to this object, humans, that were too weak to fight big animals with their own hands, became so strong that reached the top of the food chain in few years. Moreover, through the club, we were able to control fire, that allowed us to learn how to shape iron, gold and other materials that become indispensable for our life. We became literally dependent from technology. Over time, conception of technology changed as the world changed, and today when we talk about innovation and technology we immediately think to the last version of smartphone or tablet and so on. But exactly in the same way prehistorian became slave of the same technology that took them out of their animal condition, we are becoming subject of modern machines. Try to think about your everyday without some of the technology, for example your smartphone that wakes you up every morning, or your SatNav that drive you in the place you want, or the website that allows you to buy your dinner without spent one hour at the supermarket. At the same way, financial markets are become dependent on technology, with the only difference that, if for any reason they will stop to work for a while, nobody will know what to do and how to do. We did not realize that algorithms took over not only in financial markets, but they control more and more every aspects of our life. Not only they chose the music you will listen after the current song on YouTube, the film you will watch on Netflix, the sponsored advertisement that you will read on your next Google research, but even the price of you next train ticket and the road you will chose to go to the cinema. Amazon, Google, Tesla and many others non-financial companies use algorithms for many different tasks. For example, Google use them to rank results of research and Tesla use very complex software combined with Artificial Intelligence to drive their no-pilot cars. There was a day when a book on Amazon called "The making of a fly" by the biologist Peter Lawrence was priced 23'698'655,93 $ plus 4 $ shipping. Obviously, this was actually caused by an error in algorithms that rebalanced many times the price without control. In United States, some state adopted software to analyze legal documents, combine them with personal background, e.g. ethnicity, age, education, type of crime, and use them to provide a risk-evaluation to decide the future of a prisoner, i.e. if the prisoner should stay in jail or get release on parole. So the future of men and woman is decided by and algorithm that predict potential criminal conduct on a base of prisoners' profiles. While the millions of results of a research on Google give us the impression of autonomy of choice, the 90% of us do not get past the top ten results. The illusion of choice is only given by the possibility to search something between results that were chosen among billions of results, that the algorithms previously filtered for us, based on our social background, geographic position, and other personal's parameter. Many companies use algorithms to screen CVs of applicants, choosing their future employees between thousands of candidates that are rejected only because they do not satisfy the algorithms' requirements. But if this situation could cause laughs, there are other circumstance where bugs in algorithms can be far worse. Just think about this summer when a Tesla in San Francisco did not stop because there was a pedestrian that was crossing out of the strips and was not recognized as a human by the car, or, if such errors happen in financial markets. What I want to evidence is the fact that in last years, we passed from a world where human where controlling and using technology as a tool, having their own decision and influencing the environment with such decision, to a completely different world. Now, we are taking decision based on what technology is telling us. We buy what algorithms say, at the price they chose, driving the streets they signal or maybe without driving at all. From a pessimistic point of view, we can affirm we inverted the relation we had with them, allowing their decision-making capacity to take over. Basically, we went from a situation where technology was answering to human problems, responding to human needs, to a state in which human are reacting to technological stimuli. Essentially, even if this could seem the plot of a utopian film like Matrix, what I said is just the mechanism of the world around us. But when and how exactly we passed from control the machines to being controlled by them?

Initially, humans were the systems, and technological inventions were the "artefacts" that was serving to support the decision-making process. Later, technology made a big step forward, becoming able to act, explore, invest, evaluate and create in the same way that humans would, basically assisting humans needs, and turning to be more and more essential for different process, entire industries and sectors. In the past, technology was evolving in a continuously evolving environments, developing instruments that shaped the world around us, until technology itself become the environment and we started to evolve ourselves around it. Essentially, we came to be the "artefacts" of an "artefact" and we can not invert this process anymore. In this essay, we are concerned about is the financial sector, that developed one of the highest degrees of dependence from technology. As I said, humans have been replaced for the most of financial job, and decision process are now resulting of complex algorithms analysis, that in few milliseconds or microseconds do what a person takes minutes or hours to do. The more and more high investment in infrastructure, for example the thousands miles of fiber that link New York to Chicago, the millions paid from companies to rent offices as near as possible to exchange, and all the dollars invested in R&D are only few evidence of the reliance of financial system to digital technology. Moreover, because of the complexity and the size of the digitalization phenomena, is impossible both for humans and computers to monitor all exchange and trades that take place in each moment of the day.

We have seen how much our life are affected by the use of algorithms, sometimes in aspects that we neither consider, and how world around us has changed in last centuries, passing from a "human-centric" state to a "technological-centric" system, giving to innovations and machines the opportunity to shape the future in so many different aspects that we could neither imagine. The result of this role swap will create new challenges and open new possibilities for future, and we will make our business to benefit from that.

But is this necessary a bad thing for financial market? Taking into account the Flash Crash of 6 May 2010[8], even if is it true that algorithms have amplified the roller-coaster of prices, this does not necessary mean that they were wrong. The simply worked as they were programmed, they did the job that humans had teach them. Since everybody were selling, stop losses triggered a massive sell wave, they did what was more obvious to do in that situation, to sell, and faster than competitors. But try to think to 1987, when US stock market fell by more than 22 % in few hours and human Wall

[8] Flash crashes will be discussed deeply in next chapter.

Street brokers just did not responded to their phones, in order to avoid the demand of the customers to sell. In your opinion, which one was the worst scenario for a stock-holder? For sure, even if algorithms amplified the crash, they guaranteed the efficiency of markets even in a so unordinary situation. This was exactly the seed that in the years later caused the replacing of people with computers. Going back to the present day, with financial companies that are spending millions in infrastructure and locations to reduce the latency of telecommunications to few milliseconds, and in a market where profits can be available for less than a second, in some cases for an eye-blink, how can people with our massive reaction time compete in this game?

In conclusion of this section, that has little to do with financial markets, but a lot in common with technological development, I want to give food for thought to the reader. Thinking about our always increasing dependence from software and considering how human decisions are replaced by algorithmic ones, we are going into the direction of a technological domination. But without forward us in speculations worthy of Isaac Asimov, I think that is time for people to decide what this means for us as individuals and as a society.

Chapter 2

Algo Trading and Regulation

2.1 ALGORITHMIC TRADING STRATEGIES

Because of the highly technical know-how requirement in informatics and quantitative analysis, the current trend is to search traders with degrees or PhD in Math, Computer Engineering, Data Science, Statistics and even Physics. Innovation is a keyword in this sector, and to stay ahead of the competition algorithms must be updated, changed and adapted to different market condition, sometimes even in few days. Algorithms are used to analyze market dynamical and determine timing, price, quantity in order to impact optimally on markets. An indicator of how much algorithms influenced the transactions over time is the size and value of average orders, that dropped from 1'600 shares in 1995 to 200 shares in 2011 or in terms of value from an average of 19'400$ per order to 6'400$ (Deutsche Bank Research). Another parameter that changed over time is the duration of investment, that in the case of traders' algos do not last more than a few second, and never goes over-night. The average U.S. holding time for stock is 22 seconds.

A diffused practice that is spreading across trading firms is the "co-location" which consist in the purchase of real estate near to the physical exchange buildings. This allows HF firms to be a fraction faster than competitors located in the next city, or even some kilometers down the street, in order to make possible all that strategies that I discuss below. The close location of servers and the high investment in infrastructure between exchange and traders, enables firms to access stock prices some thousandths of seconds before other investors, enough to allow algorithms to implement their strategies and obtain large profits. This delay between the moment an information is sent to the moment the same information is received from another operator is called "latency". In fiber optical cables impulses have a speed that is more or less two third of the speed of light so 200'000 Km/s or 200 Km/ms. This means that an HFT that is 1'000 km far from the exchange will have 10 ms of delay (5 ms to receive and 5 to resend the order). In a context where computers are able to send 5000 orders in a second means a massive delay respect to another firm that is located at 1 km from the exchange. Ultra-low latency direct market access (ULLDMA) is the set of technology used by firms like Goldman Sachs, Credit Suisse and UBS to reduce the speed of execution. Direct Market Access allows algorithms to bypass brokers and dealers and operate directly on markets (no-touch). The average speed of those firms is over 5000 orders in a second with an execution round trip times of 100 microseconds (1 microsecond is a thousandth of millisecond). But how can those traders take advantage of latency and extraordinary calculus power?

The strategies used by traders can be very different each other. I will discuss briefly some of the most popular strategies, describing their mechanism and trying to provide some example about them. The first and easier strategy is the "passive arbitrage". As I said above, if we think to arbitrage as the simple trade of a good, without bearing any risk, arbitrageurs are as old as the first exchange, or even older. But even if it could seem easy to understand, is not so easy to improve. In fact, technically, there are many studies and economic theorists in general tents to consider arbitrages as impossible events, because are anomalies of markets, and in normal state of the world they should not exists. Ultra-low latency system, co-location, super-computer and all the other technological innovation made this strategy very difficult to improve (to average investors) because of the high competition that developed in last decades. A possible arbitrage strategy could be, for example, to buy Ferrari N. V. in Italian Stock Exchange for 157$ and sell the same quantity in NYSE for 157,10$, gaining profit from the difference in prices quotation and taking advantage from the double listing of the group. But even if this strategy is conceptually very easy to understand and to improve, it becomes really hard to apply into real market condition because trading opportunities could last for milliseconds and are basically "invisible" for the average investor that do not dispose of advanced telecommunication instruments and appropriate computational tools. TABB Group, an international research and consulting firm, has valued the aggregate profits of arbitrage strategies about $21 billion dollars in 2010. Thinking about the big steps forward that technology have made in last decades, combined with the increased volume of financial markets trades, is not difficult to think that the number could be doubled.

The second strategy is based on the rebate, that basically are refund of a fraction of penny, that exchange provide to trading firm for adding liquidity to the market. Both exchange and firms have a profit because firms, the *liquidity providers*, can improve strategies offering shares at same prices and collecting this small amount of dollar from each transaction, and on the other side exchange platforms benefits from the presence of this firms because they provide liquidity to their market. Giving a practical example, the High Frequency trader place a sell limit order at $10.00, and a broker-dealer buy the offered shares at the market price, that is $10.00. At the end of the day, the dealer will pay $10 times the number of shares plus a commission or fee that could be around 1 or more cents while the High frequency trader will receive the 10 dollars per share plus a fraction of cents for each share sold. Assuming that High Frequency firm bought the security for the same price at it sold them, the firm made a net profit equal to rebate times number of shares. At the end high frequency traders, thanks to low latency, became able to find out in every moment occasions to make profits from commissions.

Liquidity providers can profit from different sources and not only from commission rebates. As for SOES bandits in the '80s, modern HFT assume the role of market-makers, placing orders on top of book in both bid and ask side and speculating on the difference. Moreover, on contrary of real market-makers they are not obliged to post their bid-ask prices in every moment, and if they do not believe that market prices are optimal for their strategies can simply cancel all orders and wait for more convenient situations. This could result useful especially in the moments preceding important economic data release, that will impact on market prices or volatility. For example, before the election of the new U.S. presidents the HTF stop to quote important U.S. stock, and immediately after the result, before other traders read and analyze results of news place his order obtaining the "temporal-priority".

Before to proceed in to next strategy is important to understand what is the practice called *"front-running"*. Front-running is an illegal practice that consist in take advantage of information that are still not public, to open a position and benefits from the future movement of the security, previously calculated thank to the information itself. It also can happen that a dealer-broker trade shares knowing that one important client will buy or sell a large quantity of that shares in the immediate future. It is an unfair and unethical practice, comparable to insider trading because consists in use private information and speculate with them. But there are cases when front-running is legal. For example if an index is going to rebalance its portfolio, introducing a new company, it will buy a large number of shares and so will do investors. In this case, information was public days before and so the front-running is not considered illegal.

Next strategy used by HFTs is called *flash trading*. Flash trading is based on orders that are sent before information goes public, in the sense that are placed in few milliseconds after information is published, even before it appears on other traders' monitors. It is clear that the low-latency and co-location are the keys for the success of the strategy, in fact very fast computers can use some computational tools to conduct statistical and econometric analysis of the market behavior before the information goes public. After 2010 some financial journal criticized firms such as Goldman Sachs about this practice, accusing them to gain unfair profit at the expense of other traders that could not access to the information at the same time, basically it was a sort of front-running based on latency advantage. Very sophisticated algorithms are now able to read the news, analyze sequence of words as inputs and provide an output in form of buy-sell order in less than a second. The main issue of this strategy is that sometimes news can be turn out to be fake-news, or sometimes the same journal could be victim of hackers that know how those algorithms work and use them to make their own profits. This strategy is quite aggressive, that is why is part of so-called predatory algorithms.

Predatory strategies consist in to post and cancel orders to buy or sell a security, causing small fluctuations in prices and volumes and allowing the trader to collect a profit from this temporary misalignment. A category of predatory algorithms is the SOAS bandits. As we said before, those traders are able to exploit temporary misalignment of prices, in particular the delay of market-makers. In fact, NBBO, the practice introduced with Rule 611, that allow to execute order only at the best price in all markets, admits a loophole. The law says that order can be executed within a fraction of second at a price that is not the NBBO, enough time for algorithms to accept the order an close the position on the other market that offer a better price. ECN make a profit from the fact that receive greater commissions (the transaction was made internally and not in another exchange) and HFT take a long/short position at a price that is better (for the HTF) of the market price.

Book Trader					
Bid			Ask		
Trader	Volume	Price	Price	Volume	Trader
ABC	30'000	10.01	10.02	2'000	xxx
zzz	1'000	10.00	10.05	5'000	zzz
yyy	2'000	9.98	10.06	1'000	yyy
zzz	400	9.97	10.08	300	kkk
xxx	6'000	9.96	10.11	45'000	zzz
zzz	5'000	9.94	10.13	2'000	xxx
kkk	200	9.90	10.14	8'000	zzz

Figure 2.1 Book trader before placing a buy order.

Now, before to explain next strategy, I start from an example to understand it easier because it could be a little more difficult to understand. Let's say that a trader wants to buy 500 Apple shares at 50$, but on the market book the last price is at 50,02$ while only 100 shares are at 50$. So, the algorithm place a sell order of 400 shares at 50$ in the opposite side of his initial intention.

Other market participant will follow this trend, thinking about a possible information they are missing, or an institutional that want to sell, and send for example other orders for a total of 500 shares. Instantaneously, our algorithm cancels the "fake" order and buy 500 shares at 50$.

All this is happening in less than one second, sometimes in milliseconds, so much faster of human trader. This practice is *called spoofing* and is illegal since 2010 with Dodd-Frank Act. In the image below there is a more realistic example that explain exactly how this strategy can be implemented in a real market.

Figure 2.1 shows a "Book Trader" that is the sorted list of limit orders.[9] At the left there is the Bid-side while in the right there is the Ask side. The first row of bid is the maximum price that buyers are willing to pay to buy, and at the left side the lowest price that sellers are willing to receive. Obviously, prices are decreasing in left column and increasing in right, because of the rule of best price execution.

Our trader called ABC want to improve a spoofing strategy. To do this, he places an order to buy 30'000 shares at a price higher than the best bid. Figure 2.2 shows what happens a few instants later.

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[9] Usually blue cells indicate order sent by the trader, while red orders mean order cancelled.

Book Trader					
Bid			Ask		
Trader	Volume	Price	Price	Volume	Trader
xxx	15'000	10.06	10.06	10'000	ABC
zzz	1'000	10.02	10.07	5000	zzz
ABC	20'000	10.1	10.08	1000	zzz
zzz	1'000	10.00	10.10	300	zzz
yyy	2'000	9.98	10.11	45000	zzz
zzz	400	9.97	10.13	2000	zzz
xxx	6'000	9.96	10.14	8000	zzz

Figure 2.2 Book trader after placing a buy order.

Other markets participants will notice the big volume on the top of the bid side and will recalculate their prevision. In fact, most forecasting pricing models are based on volumes and in particular the first rows of the book are the ones that impact more on the future price forecast. For this reason, to anticipate the bullish trend of the market, some traders will post their own order at a price even higher of our initial order. In the meanwhile, we could have bought some shares at our price, in fact, the volume in table two is decreased to 20’000. Few milliseconds later, trader ABC cancel his buy order and transmit a sell order in ask side at 10.06, that is immediately executed because there is already a counterpart that was expecting the bullish trend. What happened was that ABC created the impression of a trend, bought 10’000 at 10.01 and immediately sold them at 10.06 making a profit of 10’000*0.05$=500$ in less than a second.

Strictly related with spoofing is *pinging*. Pinging consist in place different quantities of orders, but without the intention to manipulate prices or make profits from price fluctuations. The only aim of this strategy is to monitor and study the behavior of other traders, in particular other HFT in order to respond to their strategies, basically implementing a kind of “reversal engineering”.

Layering is really similar to spoofing and pinging, with the difference that a large quantity of orders is sent to the market with the hope to influence stock prices. The mechanism used to speculate on the prices fluctuations is the same that we described for the others aggressive HFT strategies. Market manipulation become illegal in 2010 with Dodd-Frank Act but this did not stopped some traders to practice it. In fact, thanks to anonymous dark pools, it is really difficult for regulators to control every single transaction of market participants, and check continuously the order placed and suddenly cancelled could result even more difficult.

Last practice that I touch in this thesis is the *quote stuffing.* With quote stuffing the objective is to slow competitors' capacity to analyze books, and to do that HTF sent an enormous quantity of orders that are cancelled immediately, in a loop cycle that has two effects. The first one in so slow directly the other algorithms that are forced to process, analyze and rebalance their strategy to respond to the variation of markets conditions and so losing a lot of time, and the second effect is to impact to exchange market itself, that could suffer from the massive number of operation that is required to process.

Even if a lot of bad practices such as sniffing, quote stuffing, latency arbitrage are illegal, there are warries about the fact that still much predatory algorithms are currently running on principals financial markets.

In atypical situation like the Flash Crash of 2010, when volatility of markets hits records, there is a real danger of contagion around the world, and the consequence could make the 2010 seem nothing respect to what will happen. Some solutions were implemented around the world, for example the circuits breakers are now indispensable. They simply pause the markets for some seconds, that are enough for traders to recalibrate algorithms, stop panic and fill out the books with adequate orders. In US the Investor Exchange solved the problem of latency imposing 350 microseconds of delay on trades; NASDAQ recently adopted the same mechanism but only for small and mid-sized companies. The Tokyo Stock Exchange in Asia and Italian, French and Finnish ones in EU discourage manipulative orders introducing a fee of 0.02% on order cancellations. Those expedients reduce drastically the risk of flash crashes, but they only concern a small amount of the total of securities that are traded every day in financial markets. Moreover, with restrictive monetary policy, a possible trade war between US and China, a possible war between US and Iran, the UK leaving the Europe, is easy to understand the fear of investors. If we add to all this political-economic and social background the possibility that a big Flash Crash could occur, we understand that market regulators have to do something more to mitigate these risks or there will be serious trouble ahead.

2.2 THE MURPHY'S LAW: WHEN ALGORITHMS FAIL

If, until now we have described how and why automatized transaction raised in the last fifty years, we cannot forget to describe the dark side of this innovation. As I said above, computers have improved efficiency of markets, reduced transaction costs, increased productivity, allowed to implement strategies that where unthinkable to do by humans, thanks to their speed and their insuperable calculus power. But what we forgot is that, exactly like humans, computers can fail, and when they do, consequences are devastating. Traders often fall in what is called "fat-finger error", in fact most stock-exchange implemented different deadline in order to cancel and repair to human error. But what happens if algorithms, for example a High Frequency Algorithm, fails?

Edward Aloysius Murphy Jr., a famous American aerospace engineer, one time said, "anything that can go wrong will go wrong". Obviously, when he stated this epigram no one knew that computers and machines would substitute the humans in a lot of works, and that aircraft that he was projecting would be able to flight without pilot after few decades. But we can try to imagine a possible corollary to its law, applying his statement to the modern interconnected and automatized world and say, "anything that can go wrong, it will faster and bigger than ever".

In this paragraph, I will comment some episode in the last fifty years when algorithms failed, illustrating the causes, describing the consequences and trying to furnish a solution to avoid the possibility of others similar episodes. Moreover, to each event I associate a word that reassume and explain the causes of failure.

The first one can be described with the word "interconnection". On August 10, 2007 the Wall Street Journal reported a series of loss of the most successful hedge funds in the US. Renaissance Technologies Corp. lose the 8.7% of its capital, Highbridge Statistical Opportunities Fund declared losses for the 18%, Tykhe Capital LLC, a quantitative hedge-fund institution suffered losses for the 20% and on August 14, Goldman Sachs Global Equity Opportunities Fund lost the 30% of its capital in a week10. What surprised analyst is that quantitative hedge-funds applying statistical-arbitrages strategies suffers the biggest losses, and that's why this episode has the nickname "Quant Quake" of 2007. The managers of hedge funds refused to comment publicly on the

[10] Kelly, Sender and Zuckerman (2007)

events, but later studies[11] attributed the cause of the fall to the liquidation of one or more large market-neutral hedge fund's portfolios. This massive operation moved down the prices of most stock, triggering a loop where the value of quantitative funds' portfolios dropped, forcing them to reduce leverage selling part of portfolios, pushing the prices down and reducing further the value. The connection between the quantitative fund's strategies, that suffered the biggest depreciation, is the common use of some ratios, for example book-to-market ratios where highly used to build their strategies. Summing up the large prices' fluctuations fueled across markets and institutions, and algorithmic trading where the oil that feed the fire. Moreover, the years 2007 and 2008 were the period of the most serious financial crisis since the Great Depression, and, even if officially no one shift the blame to algorithms, and the ignorance towards the private-owned firm's strategies let impossible to blame algorithm trading, this could be an inspiration for in-depth studies.

The famous "Flash Crash" of May 6, 2010 reflects, in my opinion, the concept of "velocity". At 2:42 PM the Dow Jones Industrial Average, a stock market index representing 30 large companies listed in NYSE and NASDAQ, dropped 600 points, in addition to the previous 300 points daily fall, losing a total of near 1'000 points in a day. However, in twenty minutes he recovered from its one-trillion-dollar value fall, closing at "only" 300 points under its opening price. The causes of the Dow crash, the biggest decline on an intraday period in the index history, are a mystery. Several theories were published, and many studies tried to analyze and to find a responsible, but until now there is no agreement about the cause of this event.

The firsts reports explained facts of 6 May as the fat-finger error consequences, suddenly denied by Chicago Mercantile Exchange that would avoid this error with "anti-fat-finger-trade" systems. In July 2011 a report of International Organization of Securities Commissions affirmed that High Frequency Traders shorted aggressively in order to liquidate their position and withdrew from the markets to avoid uncertainty. Even in this case, Nanex, a high-frequency data analysis firm, pointed out some inconsistency of the study, including the fact that the majority of the HFT sell orders were never executed because of the lack of liquidity.

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[11] Khandani and Lo (2007)

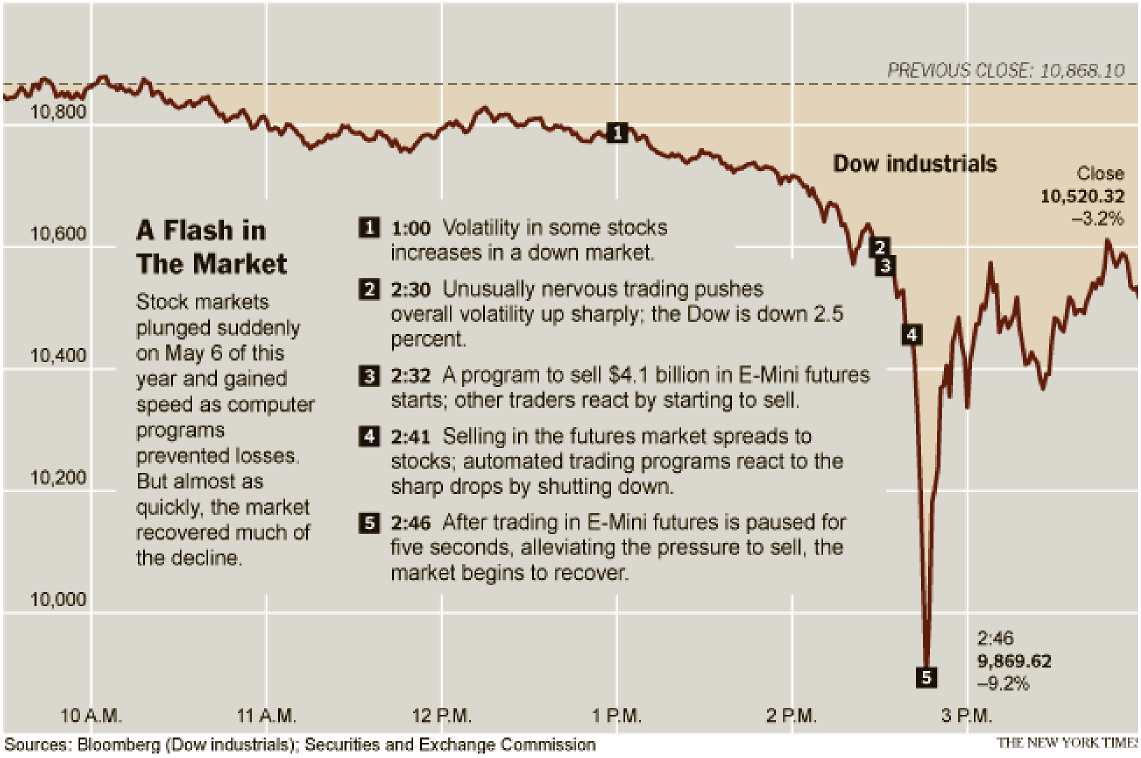

Figure 2.3 “Flash Crash” of May 6, 2010.

The third theory is based on a large E-Mini S&P 500 sell, attributed to Waddell & Reed for 75’000 contracts valued around 4 billion dollars. Lastly, there were reported some technical glitches that affected NYSE and various Alternative Trading Systems, that created some problems on the Consolidated Quotations System for example latency and errors in prices of some stocks.

On September 2010 U.S. Securities and Exchange Commission and the Commodity Futures Trading Commission published a joint report about the Flash Crash and arguing that a large fund (Waddell & Reed Financial Inc.) started a hedging strategies, selling E-Mini S&P contracts for a value of 4.1 billion dollars, drying up liquidity, in particular buy-side, and triggering computer algorithms that had just bought this massive volume, generating the so called “hot-potato” effect (Figure 2.3).

Because of insufficient demand from fundamental buyers and institutions, HFT started to negotiate contracts to each other. But when algorithms reached the threshold price, they stopped trading and abandoned the markets altogether. In those minutes over 1 trillion dollars in market value vanished and meanwhile something of even more extraordinary happened. Stocks of some of the major companies in S&P 500, for example Accenture and Exelon, started to be quoted at 0.01$ while others, such as Sotheby’s, Apple Inc. and Hewlett-Packard, raised to 100'000$. When trading on E-Mini was paused for five seconds, the sell-sides of order books were partially repopulated, and when finally trading resumed, prices recovered most of their consensus values. Some critics were moved against SEC and CFTC report, for example the fact that they took five months to analyze five minutes of market data, or the fact that the Waddell & Reed short sale correspond to the 5% of the total volume of market trades. Again, Nanex12 analyzing W&R orders showed that none of the 6'438 orders were posted in the Ask side, that means that they were executed only when a buyer hit that ask price, and not lowering the bid price. On 2015 the US Department of Justice arrested Navinder Sarao for 22 criminal counts including market manipulation and fraud13. He was a professor and trader operating from his house in London, that through spoofing algorithms sent orders for 200 million dollars, modifying and replacing them 19'000 times before they were cancelled. Whit his strategy he was guilty of pushing down market prices, cancelling orders and buying during the fall, generating a profit of 40 million dollars in few minutes. However, someone claims that blaming a single trader for a trillion-dollar stock market crash is "a little bit like blaming lightning for starting a fire". Concluding, even if we can not blame a single firm, or a single factor that caused the Flash Crash on May 2010, we must highlight the impact of algorithms involved in that trades. During that twenty minutes, over 85% of the transactions has been from HTF to HTF seeking to take advantage of temporarily profitable market condition and blowing the crash out of proportion.

According with Fortune.com, Facebook Initial Public Offering was the fifth biggest IPO in the history, with over 16 billion dollars raised in one single day. The May 18th, 2012 the attention to the big social network IPO was so high that caused some trouble at NASDAQ, the favorite market of technology firms. In fact, NASDAQ's IPO Cross software recorded an unexpected traffic and a huge quantity of orders submitted even before the opening trade, and that caused the "race condition". Basically, orders that were received didn't had the time to be processed, and so other orders were placed "in

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[12] NANEX "Criticism of the CFTC report on the Flash Crash", http://www.nanex.net/FlashCrashFinal/FlashCrashAnalysis_WR_Update.html.

[13] Brush, S., Schoenberg, T., and Ring, S., "How a Mystery Trader with an Algorithm May Have Caused the Flash Crash", *Bloomberg News*, April 22 2015.

queue" causing the computers to recalculate the opening trade, during which time other orders arrived and causing a delay of half an hour. When system was reset, transactions restarted but they were running near 20 minutes behind real time, causing a lot of unfilled orders and cancelled orders but the worst part is that many traders seen their orders being filled at prices higher than the ones that they asked. The total cost for traders of this IPO was calculated around $100 million, and an agreement for NASDAQ to pay $62 million to firms hurt by IPO. For all this reason, the word I associate to Facebook IPO is "latency".

Another firm that has been unprepared in front of technology innovation and software bug was named Knight Capital Group Inc. The nickname that best fits this episode is "glitch" because was a glitch the root of the company's decline. The August 2, 2012 NYSE Retail Liquidity Program were implemented by the exchange because as SEC sustained the over-the-counter market makers whit their practice of internalization outlasted the competition. Internalization was a practice that allowed broker-dealers to post limit orders at a dime of penny difference above or below the exchange bid-ask prices. This means that retail brokers, based on price priority, could buy and sell directly from dealers without including organized exchange that lose a lot of profit. That's why SEC authorized the Retail Liquidity Program that allowed exchange such as NYSE to execute retail orders at sub penny prices and promoting competition. The same day that RLP was put into operations, Knight Capital Group, a big high-frequency trading dealer that owned about the 17% of market share both in NASDAQ and NYSE, started to buy and sell more than 150 securities in NYSE exchange, causing significant fluctuations and a loss of 400 million dollars for the firm. In this case, at the base of the bug there was a human error. In fact, developers had just one month to program the new high frequency trading algorithms and to install on the eight SMARS high speed orders rooters. And even thought they were able to complete the work in time, someone forget to install properly the new Retail Liquidity Program in the eighth SMARS, that ran the old twelve years old legacy code. After twenty minutes, developers decided to roll back to the last good state code, but this led to the contemporary deploying of the legacy code on all 8 servers that had to be shutdown as fast as possible. The group lose the 75% of its capitalization and even after 400-million-dollar fundraising from investors, Knight Capital Group were sold to KCG Holding in 2013.

"Manipulation" is what happened on September 25, 2012 when Hold Brothers On-Line Investment Services received a cease and desist order from SEC. The electronic dealer used offshore algorithmic trading accounts to manipulate market using "spoofing" and "layering" strategies14. Analyzing the report issued by Securities Exchange Commission in 2012, emerges the following: at 11:08:55:152 AM one of the High Frequency Trading Algorithm shorted 1'000 W. W. Grainger shares at 101.34 dollars per share. Before that moment, bid price was 101.27 dollars, eight cents lower, and the ask was 101.37 $. After the order, ask lowered to 101.34 $ and after 170 milliseconds, at 11:08:55.323 AM the trader sent a buy order of 2'600 shares at 101.33 $ increasing bid of six cents. After 10 milliseconds, at 11:08:55.333 AM the sell orders were filled at 101.34 $ and at 11:08:55.932 AM buy orders were cancelled, reverting bid and ask respectively to 101.27 $ and 101.37 $. The most incredible fact about the events of September 25 is that all of the Machiavellian activity lasted less than 90 cents of second. The company was fined for 5.9 million $ and permanently banned from financial markets. However, this is just one case that emerged from investigation, and surely not isolated. It is probable that there were much more algo-frauds especially in first years of diffusion, when regulatory framework was outdated, and surveillance practices were underdeveloped.

2.3 PROS AND CONS

The benefits of High Frequency Trading are different, and there were many researchers that studied the effects of HFT in particular on the stock market. They showed the great role of algorithms in different aspects of financial markets. The increase in liquidity of the markets (Boehmer, Fong and Wu 2015) due to the higher interest and competition that grew around this new sector made the execution of transaction easier and faster than ever. The decrease of the bid ask spread (Conrad, Wahal and Xiang 2015) was observed both in US and Japan markets, is strictly related with the reduction of transaction costs, result of the increased level of transaction and the greater number of exchanges. Speeding up the velocity of execution of orders improved the price efficiency of markets giving an higher level of information about present and future prices (*price discov-*

[14] I will discuss deeply HFT strategy in Chapter 2.

ery was the subject of the study of Brogaard Hendershott and Riordan of 2014). Information are immediately absorbed by high frequency traders and prices immediately reflect the new data reducing possibility of shock in the markets. Basically, price efficiency across different financial markets improved thanks to the growing of inter-markets connections derived from strategies such as passive arbitrage. Moreover, respect to the past liquidity providers, with HFT the conflict of interest of this practice is reduced. The reduced spread between buy side and sell side cut trading costs for fund investors. Increasing competition among HF traders helps prices to be more stable, and spreads to be narrow, and so not only high-tech firms benefits from those practices, but also all investors such as pension funds and individual can take advantage of best conditions. There are many studies that confirm what I said, e.g. Hendershott and Riordan (2009), Menkveld and Jovanovic (2010) underlined how market making algorithms and arbitrage strategies have a positive impact on price discovery, adding liquidity and detecting anomalies in market prices and eventually fixing them. And finally, Brogaard in 2011 published a study where highlighted the positive correlation between the presence of high frequency traders and intraday volatility. In fact, he showed how the presence and the absence of high frequency traders in stock market lead respectively to lower and higher level of volatility in US.

On the other hand, many studies tried to explain negative aspect of algorithmic trading, analyzing different effects. Van Kervel in 2012 showed that the increase in liquidity on most exchange is only an illusion (*ghost liquidity*). The behavior of HFT lead to overestimate the market liquidity because many orders are sent only to improve strategies such as spoofing or layering, or in other cases when one order is executed in one exchange all other “twin” orders disappear from all other platforms. Other studies demonstrated how the presence of high frequency traders, in particular circumstances such as uncertainty, could have the opposite effect that we said above diminishing liquidity in markets and increasing intraday liquidity. The same prices that we said should be more efficient could result affected by aggressive and predatory strategies, causing the effect of the distortion in the price discovery. The increasing use of dark pools, that are non-transparent platform means that more and more trader prefer to stay anonymous, which allows them to set up unethical practices such as the ones that I described above with negative effect for markets efficiency. Moreover, others argue that they push “classical” investors to dark pools to avoid the issues of HFT on “normal” regulated markets, like the very small size. In fact, the average volume of a single order decreased from 19’400$ per order in 1995 to 6’400$ in 2011 (according with Deutsche Bank Research). If initially the electronification of financial system led to a sort of “democratization” of the business, allowing all investors to trade without the physical presence, or lowering transaction costs, the evolution of more complex, expensive and sophisticated technologies is exacerbating the conflict between the average investor and who can benefits from those innovation, giving an advantage to high-tech big firms. Another trouble is that HTF, in contrast to the classical regulated broker-dealer, are not obliged to provide liquidity in case of bad market condition, just like 6 May 2010. As we said before, what could happen in this situation is that high frequency trading, when detect some anomalies in the markets try to speculate as faster as possible. In a case when a large order was sent, and was executed in a small amount of time, the bid side of the book was emptied by the large sell order. HFT immediately noticed the bearish trend of DOW JONES Index price and started to sell frenetically their positions, contributing to the price drop and realizing al the limits buy orders. When non-algorithms traders had no more orders in the books, algorithms stopped and contemporary all the liquidity of the market disappeared, causing the flash crash. Furthermore, their practice of sub-penny rebate arbitrage is often criticized because does not take any advantage to the retail or long-term investor.

In summary, the debate about the benefits and problems of HFT will continue for a long time. It is still unclear whether HTF is an advantage or a disadvantage for market structure. For example, many “home investors” could be contrary about some practices that make it impossible for them to make profits from arbitrage, but on the other side long-run investors are beneficing so much from HTF. With the increasing velocity at which technology is evolving, with new techniques and instruments that are emerging, for example Quantum Computers, Artificial Intelligence, Machine Learning, the debate will find no answer for a while. But is certain that governments, agencies and regulators must take in consideration what is happening around the world and in particular in the financial system, responding with adequate rules to stay updated with technologies. We have already seen what happened in a context of lack of regulation, and we know from history that every time that something could bring benefit for somebody at the expense of others there is always someone that want to take advantage ruthless. Concluding, we must be able to understand all innovations and the possibility that technology is developing for future. It is literally shaping financial markets, ruling where human used to do, and becoming the protagonist of an environment where we are constantly pushed ad margins, and where computers are substituting the human decisional process that has gone long for millennia.

2.4 REGULATORY FRAMEWORK

Goldman Sachs was in the spotlight when in 2009 a Russian hacker named Sergey Aleynikov stole an Algorithmic Trading Code for stock and commodities from the firm's servers. According with FBI Aleynikov robbed top secret mathematical formulas and algorithms that Goldman was using to gain huge profits. When mass media and journal started talking about this fact, the public opinion was scared about the fact that these stolen algorithms, combined with the recession that was hitting U.S. financial system could lead to a collapse of the entire economy. Moreover, media speculated about this fact, describing Aleynikov as a sort of "terrorist" who was able to destroy our society or let banks fail pushing a button.

However, criticism and attention about the use of HFT shifted quickly from the "world disaster risk" to a "control of strategy" itself. On September 17, 2009 Security Exchange Commission proposed a ban for flash orders because they did not "[…] serve the interest of long-term investor and could affect the efficiency of markets […]" (Rule 602 of Reg. NMS under the Securities Act of 1934.88).

High Frequency Traders are continuously challenging against the new regulation, because even if regulators are continuously enacting new laws and rules about this sector, the practice of HFT is incessantly evolving and increasing its volume and its complexity. Furthermore, many institutions keep their algorithms secrets, and they are so cutting edge that only a few mathematicians and computer engineer able to understand them. If we add the fact that conceptually is possible to use algorithms to manipulate markets, obtain unfair advantage and specially to cause a huge financial crisis we understand why in this specific case regulators are subjected to efforts and hard work to keep up with innovation. The fact is that, thanks to dark pools, this form of trading is really difficult to check, and combined with flash orders practices and manipulative strategies, the illegal activity of traders becomes object of suspicious. Predatory trading also cause price fluctuations without a real reason could be really dangerous for markets.

Both in US and EU, massive pieces of legislation were published in the years preceding the financial crisis of 2007-2008. The European Union law, named Markets in Financial Instruments Directive or MiFID I, valid from November 2007, is the foundation stone of the securities market's regulation. Its equivalent in US is the Regulation National Market System (RegNMS) of 2005. It regards the competition between individual markets and traders, and its objective is to encourage cost-effective and fair prices formation in securities markets. Simultaneously, the technological revolution pushed the markets participants to an arms race for the development of the most advanced IT systems.

Proposal for measures in automatized transaction sector can be grouped in two main categories that are transparency and market structure. The first is focused on the disclosure of important information by traders to the Supervisory Authority, in order to increase transparency of transactions, while the second regards the effective mechanism that regulate the exchange platform such as dark pools. If from a point of view disclosure could seems the solution of most of the issues that emerged with the rise of HFT, on the other hand the continuous exchange of information would increase the costs for regulators and for traders. Some of the proposals witch regulators are discussing are about authorization an organizational prerequisite regarding risk management obligations, capital requirements and the mandatory notify of algorithms to authority. This could result even more difficult than the disclosure of transactions because algorithms are constantly updated, are protected by the confidential secret and could result really difficult to understand and to report the large quantity of orders that are posted and cancelled each second. Others are concerned about the continue supply of liquidity by HTF even in adverse market condition, still others would introduce a minimum period of time in which orders cannot be cancelled. Both measures could counter the ghost liquidity effect, increasing market stability and encouraging trades to avoid bad market practices such as spoofing, layering and pinging. Other suggestions regard the co-location, in fact, according with European Commission they should be offered to anyone would like to access, without a discriminatory condition and in order to guarantee fair market condition and competitive neutrality. In an article of 2015, Shindler sustained that instead of increase the regulation, that as we said could be dangerous both for trading firms and regulators, an efficient solution would be to focus on lowering information asymmetries among traders and investors, in order to give to everyone the same opportunity to profits from markets. I think that this solution is more utopic than beneficial to markets, in fact one of the foundations of financial markets is the assumption of competition among different participants. If there is a reduction in the autonomy of members there could emerge problem of moral hazard and adverse selections, a reduction in the investments by firms to improve their trading strategies and substantially a shrinking in the profit's opportunities.

There were many cases of violations of the regulation. In March 2012 GETCO LLC was fined for $450'000[15] because Octeg LLC, a high frequency trading platform of Getco failed in control its stock activities and supervision the orders of the HFT. In October 2013 Knight Capital had to pay 12 million dollars to SEC for the malfunction of one of his servers that I described in the second paragraph of this chapter. Knight lost more than 460 million dollars that day and the next year merged with Getco to form KCG Holdings. Some high frequency firms were fined for using the aggressive strategies that I mentioned before. For example Panther Energy Trading LLC during 2013 had to pay 4.5 million dollars to regulators for manipulation of commodity markets through spoofing and layering activities. In June 2014 Citadel LLC was fined for less than a million for several violations included quote stuffing. According with NASDAQ report Citadel sent orders for 19 million shares two or three times per day for a while. Another penalty paid to SEC was in September 2014 when the HFT firm Latour Trading LLC, controlled by Tower Research Capital LLC, agreed to pay 16 million dollars because it underestimated the quantity of risk bearing with its high frequency activities for more than two years. Basically, the company that was accounting for the 9% of U.S. algo trading,[16] used to do its trading without holding enough capital to cover the eventuality of accidents. Other market manipulations were made in October by Athena Capital Research LLC, that used its algorithms to manipulate closing prices of thousands of stocks, implementing "rapid-fire trades" few seconds before markets were closing. Not

[15] Source: The Wall Street Journal

[16] Source: Bloomberg

only trading firms were fined for improper use of HFT but exchange markets too. On January 12 of 2015, Direct Edge, a subsidiary of BATS Global Markets (exchange market founded by HF traders) was fined for 14 million dollars[17] because they did not disclose some order types on its two exchanges, preferring to inform only few of their customers including some HFT firms that took advantage of the asymmetry of information. In the same month UBS paid 14.4 million dollars for the same reason of Direct Edge, keeping secret a new type of order that allowed high frequency traders to obtain the priority respect to other participants of their dark pool.[18]

2.5 MIFID II

Starting from January 3, 2018 in Europe MiFID II[19] and MiFIR[20] has revolutionized financial markets regulation and HFT as well. The article 4(1)(39) identifies algorithmic traders as those traders whose computer algorithm autonomously decide parameters of orders as the size, the timing and prices managing order after its submission with limited or total absent human intervention. The objective of those traders is not necessarily to maximize profits but rather to obtain lower costs and contain market risk. Only the commission sector associated with algorithmic trading is calculated about half billion dollars per year. High Frequency Traders are identified as a particular category of algorithmic traders that is characterized by infrastructure on purpose to minimize latencies (we already talked about colocation, but there are other practices for example proximity hosting and high-speed direct electronic access), autonomous system determination of order generation and execution and high message intraday rates. The risk deriving from HFT traders could be of various types: the systemic risk is the risk generated when a possible crash in one or more single institutions could spread across markets and affect the whole system, causing a catastrophic event. This could derive from a situation called "Too Big To Fail" so referring to all that institutions that are considered too important or too "big" that it is impossible that fail. As we have seen in the past (financial crisis of

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[17] Source: SEC report

[18] Source: SEC report

19 Markets in Financial Instruments Directive (2014/65/EU)

20 Markets in financial instruments regulation (EU regulation n. 600/2014)

2007/2008), that is not true in fact in this situation moral hazard and bad decision could cause a devastating chain of events that impact on financial markets for decades. The strong interconnection that HFT created, united with the opacity of new markets such as dark pools improve exponentially this risk, so regulation evolved to contrast it. More or less we already talked about market stability. Events (flash crash) that could compromise market stability are strictly related with bad market manipulations strategies, that obviously are the main enemy of regulators. Computer errors and bugs are another important risk that we must not undervalue. This is the equivalent of the old “fat finger” error, with algorithms instead of telephone. Is more or less what happened at Knight Capital LLC and we have seen the consequence of algorithms error both for firm and for exchange markets. And last but not least we already seen the market quality and integrity that could be affected by those traders. Even if there are more different opinions about costs and benefits for markets, there is no doubt about the fact that in certain situation, HFT might increase volatility, reduce liquidity, cause issues with price discovery and be the protagonists of unethical strategies such as predatory trading and front running practices. For those reasons, traders are now required to have special authorization and are subjected to additional requirements and controls. They can not send incorrect orders during operations, contribute to manipulate market prices and violate trading venues rules. Furthermore, they are required to store the sequence of detailed transactions for a minimum of 5 years, with an increased duty of notification and transparency for all their operation. Moreover, HFT firms must communicate any time the person in charge of the algorithm, a description of each transaction made and a report of compliance and risk controls. In particular we read from MiFID II text that high frequency firms must dispose of an appropriate system and risk control to guarantee the resilience of trading systems, the respect of the thresholds and limits to prevent inaccurate orders hat could cause uncontrollable market conditions and those systems can not be used must respect the rules of a trading location to which is connected (Italy in 2013 became the first country to introduce a tax on HFT, charging a fee of the 0.02% on transactions that has a duration of less than half second and exceed a threshold). Firms must ensure that their algorithms must work properly, and in case of a failure the systems must be monitored and controlled. If for any reason happen that a trader starts to create market fluctuation or disorder the firms must be able to manage it and correct the errors. Regulation include limits to the number of orders that remain unexecuted, a slow down order flow and adequate minimum tick sizes. Firms must be able to identify orders generated by different algorithms and initiating by different persons. To avoid the problem that we evidenced in Section 2.3, MiFiD II requires that algorithmic traders must follow a precise market strategy with the purpose of operate continuously during the entire trading day (with the exception of extraordinary circumstances), enter in a explicit agreement with the trading venue, which there are states all market-making obligations and requirements, and implement an effective system that guarantee that it accomplishes all the responsibility under the agreement.

Then the EU Directive describe the different form of traders, that we have shortly mentioned before. Market-Making strategies consist in continuously quoting a stock (or a derivative) in both bid and ask side on a single trading venue or simultaneously on different trading venues, ensuring sufficient volumes and competitive prices.

DEA and SA or Direct Electronic Access firms must follow precise procedures to ensure accurate evaluation and review of the correctness of clients using the service, including the control of pre-set trading and credit thresholds. Moreover, DEA have to monitor their clients using the service and develop appropriate risk controls for trading firms that could create or contribute to create disorderly markets. Without such controls the Direct electronic access is prohibited, and the DEA firms must ensure that clients using their access respect MiFID II, Member State competent authority and trading venue rules as well. Notification obligations regards both HFT firms and DEA, that are required to notify to the opportune Member State competent authority the details of systems and controls of the algorithmic strategy and a detailed description of its nature. In particular, the authority must receive the identity of the algorithms (and a person) in the case an investment decision was taken from the algo.

Systems, process and arrangements are mandatory for trading venues to control peak order and volumes, and to ensure that firms are trading properly, respecting agreements and the pre-set volume and price thresholds are not exceeded. Moreover, specific constraint related to tick sizes and management of clocks are explicitly written in the text. Trading venues must be able to recognize erroneous orders and algorithms error, managing those mistakes cancelling or correcting those transactions. Order books[21] must be available for Member State competent authority upon request, to monitor trading and high frequency firms. Rules on co-location and fee structures must be transparent and non-discriminatory, to guarantee fairness for every market participant and prevent manipulation and unfair market strategies.

Other requirements regard the organisational obligation that traders must adopt before to trade on the exchange markets. Algorithms must be tested in a closed non-live controlled environment and on an continuing periodic basis. Tested algorithms must be issued in live conditions in a cautions manner. Investment firms must control continuously process and find out any negative impacts that algorithms could have, developing a “kill button” able to cancel all outstanding orders contemporary and instantly in case of bad conditions. Those firms must adopt an IT environment in line with the standards of the community and with the business. IT must ensure the security of the whole system and meet the legal and regulatory needs of the firm. Finally, “pre-trade” risk limits such as price collars, maximum/minimum order value, outbound message rates and stop-loss limits have to be available to the traders.

[21] “Order books” will be described in detail in Chapter 3

Chapter 3

Empirical evidence of price efficiency

3.1 ROTMAN INTERACTIVE TRADER (RIT)

To show empirically the evidence of my thesis, I am going to use the Rotman Interactive Trader (RIT) software.[22] RIT is an order-driven market simulator, basically a real-time basis platform that replicate exactly a financial market and where I could implement a real algorithm that will trade orders in a quasi-real environment. There are many cases that RIT can simulate, for example different exchange such as oil and gas market and electricity market for commodities, fixed income pricing simulation for treasury and debt securities market and options simulator which allow the user to test his option pricing model (for example Black-Scholes model) on an underling stock with 10 different options at various strike prices.

In this simulation I run the “Algo 1 Trading Case” that basically simulate the pricing path of a stock in a main market (for example the NASDAQ) and in an alternative market (Dark Pool). There are exogenous shocks that create a “shift” of the stock price in alternative market (for example lack of liquidity of institutional tenders) and that cause some prices inefficiencies. Price inefficiencies in this case can be directly measured because are the difference of the price in the alternative market and price in the main market. My purpose is to show that the presence of my algorithm in this market will reduce this price inefficiency, reducing the shock affecting the alternative market and increasing the liquidity of the markets. Each simulation is 5 minutes long and represent in every aspect a trading session of a real market. Before to show the algorithm and to comment the results of my experiment I will give some information about the RIT software and the workspace that I use.

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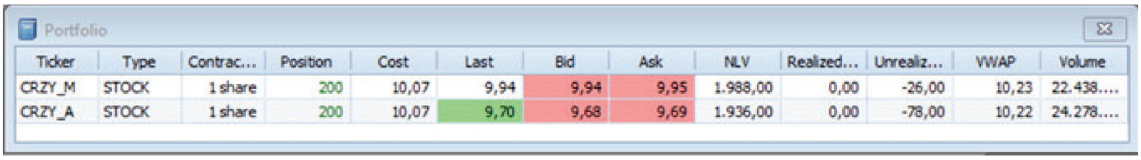
[22] Rotman School of Management, University of Toronto, website: http://rit.rotman.utoronto.ca/

Figure 3.1 Rotman Interactive Trader: Menu bar.


Portfolio

Ticker	Type	Contrac...	Position	Cost	Last	Bid	Ask	NLV	Realized...	Unrealiz...	VWAP	Volume
CRZY_M	STOCK	1 share	200	10,07	9,94	9,94	9,95	1.988,00	0,00	-26,00	10,23	22.438....
CRZY_A	STOCK	1 share	200	10,07	9,70	9,68	9,69	1.936,00	0,00	-78,00	10,22	24.278....

Figure 3.2 Rotman Interactive Trader: Portfolio.

Figure 3.1 shows the “Menu bar” that contains all the features of the software. As you can see some button are grey because in this simulation that features are disabled.

The “Portfolio” (Figure 3.2) shows all the stock traded in the market, that are called “CRZY_M” for the stock traded in the main market and “CRZY_A” for the alternative market (I chose only two to simplify the market environment as possible and to focus only on the arbitrage between the single stock traded in different exchange). In the table there are some information regarding respectively the typology of security, the contract size, the position of the trader (positive for long position and negative for short position), the cost that the trader paid for the trade (the average cost if the position is the result of various transactions), the price at which was closed the last trade in that market, the highest bid price, the lowest ask price, the net levered value of the position, the realized P&L,[23] the unrealized P&L, the Volume Weighted Average Price (an average of the prices weighted with their volumes for all the period), and the total volume exchanged in the simulation.

“Securities charting” (Figure 3.3) is useful for understanding how prices fluctuated in the period and can combined with some helpful indicator for example moving average and volumes. However, they are quite useless for the algorithm because it is really difficult for an algo to “read” a graph while it is really easier to download the time series data and read that. There could be useful for a human double check on the correct functioning of the algo because are really simple to understand. Candles are green then the price of that interval (I chose 3 second for each candle) increased and are red if the price decreased.

[23] Profit and Loss statement recap all the revenues, costs and expenses like fee or fines incurred during the specified period.

Figure 3.3 Rotman Interactive Trader: Buy/sell entry.

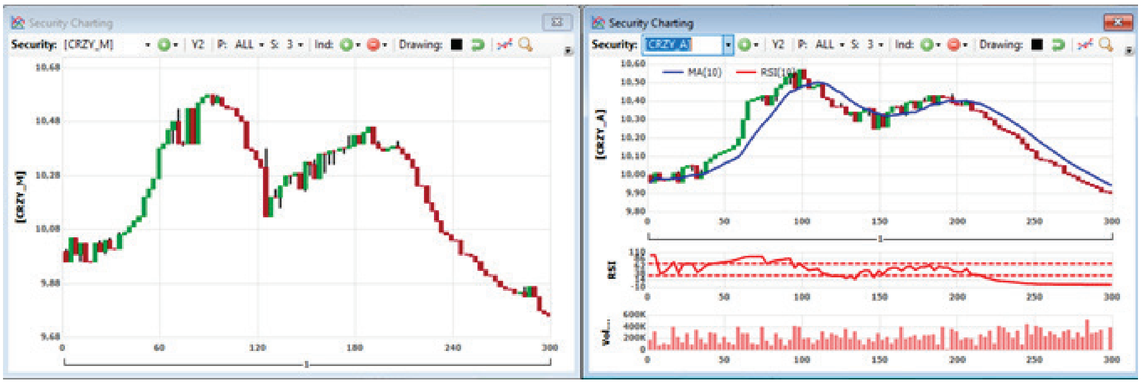
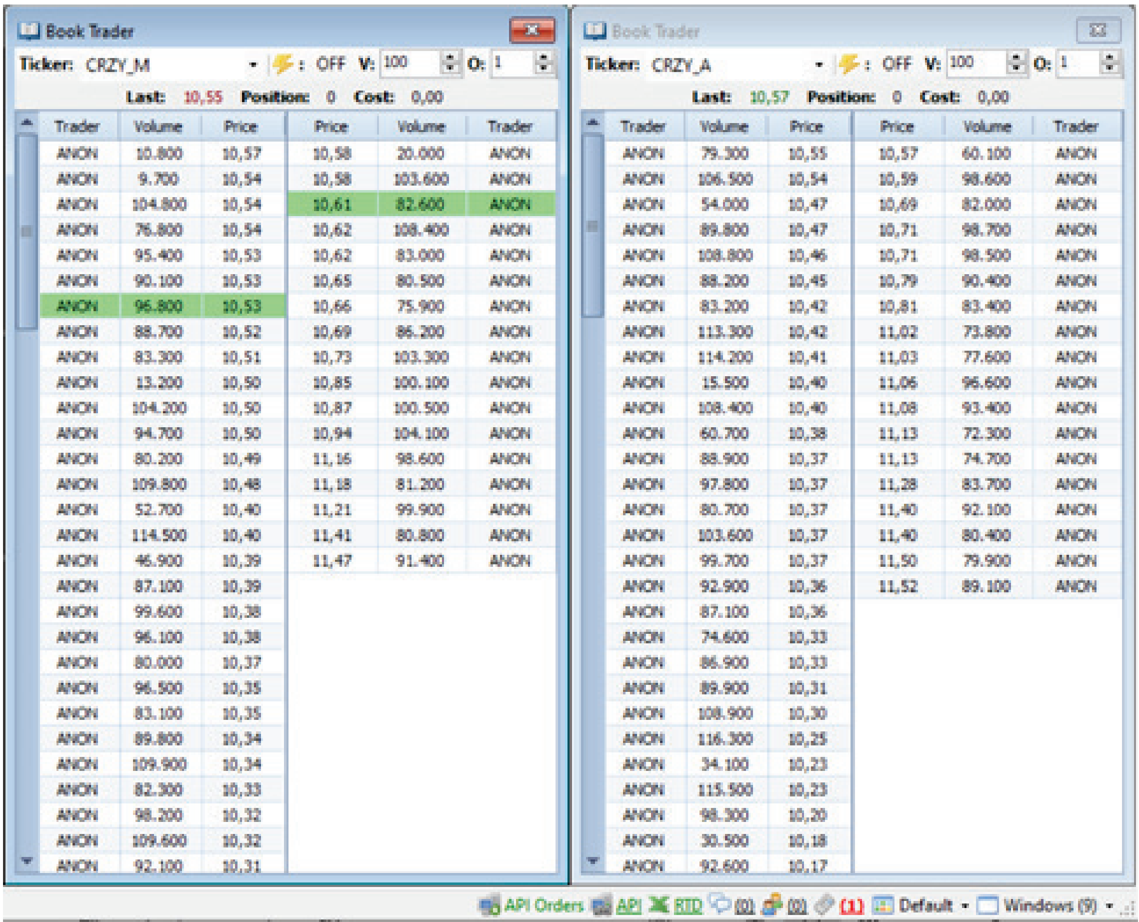


Figure 3.4 Rotman Interactive Trader: Securities charting.

So, if there is a green candle the price at "T-2" was the price at the bottom while the price in "T" was the higher point of the candle. If the candle has a line that means that in the "T-1" tick the price was above or below the initial and final price, but then inverted its trend. Anyway, graph are inconclusive because they only give use the "last price" of each tick, giving no information about the process that crossing demand and supply created that price. They give no information about the number of shares traded at that price in each second neither the liquidity situation of the markets.

The "Buy/Sell entry" (Figure 3.4) is the window that allow the user to send orders. In the first two rows there are two market orders for the main market. Market orders are immediately executed at the best possible price available in the book trader. The last two rows are sending limit orders. Limit orders are executed only when a counterpart match with their prices and volumes. For example, sending both the orders I will see on book my order at chosen prices, and I will sell or buy 150 shares only in the moment someone send a market order on the opposite side.



Book Trader

Ticker: CRZY_M ⚡: OFF V: 100 O: 1

Last: 10,55 Position: 0 Cost: 0,00

Trader	Volume	Price	Price	Volume	Trader
ANON	10.800	10,57	10,58	20.000	ANON
ANON	9.700	10,54	10,58	103.600	ANON
ANON	104.800	10,54	10,61	82.600	ANON
ANON	76.800	10,54	10,62	108.400	ANON
ANON	95.400	10,53	10,62	83.000	ANON
ANON	90.100	10,53	10,65	80.500	ANON
ANON	96.800	10,53	10,66	75.900	ANON
ANON	88.700	10,52	10,69	86.200	ANON
ANON	83.300	10,51	10,73	103.300	ANON
ANON	13.200	10,50	10,85	100.100	ANON
ANON	104.200	10,50	10,87	100.500	ANON
ANON	94.700	10,50	10,94	104.100	ANON
ANON	80.200	10,49	11,16	98.600	ANON
ANON	109.800	10,48	11,18	81.200	ANON
ANON	52.700	10,40	11,21	99.900	ANON
ANON	114.500	10,40	11,41	80.800	ANON
ANON	46.900	10,39	11,47	91.400	ANON
ANON	87.100	10,39			
ANON	99.600	10,38			
ANON	96.100	10,38			
ANON	80.000	10,37			
ANON	96.500	10,35			
ANON	83.100	10,35			
ANON	89.800	10,34			
ANON	109.900	10,34			
ANON	82.300	10,33			
ANON	98.200	10,32			
ANON	109.600	10,32			
ANON	92.100	10,31			

Book Trader

Ticker: CRZY_A ⚡: OFF V: 100 O: 1

Last: 10,57 Position: 0 Cost: 0,00

Trader	Volume	Price	Price	Volume	Trader
ANON	79.300	10,55	10,57	60.100	ANON
ANON	106.500	10,54	10,59	98.600	ANON
ANON	54.000	10,47	10,69	82.000	ANON
ANON	89.800	10,47	10,71	98.700	ANON
ANON	108.800	10,46	10,71	98.500	ANON
ANON	88.200	10,45	10,79	90.400	ANON
ANON	83.200	10,42	10,81	83.400	ANON
ANON	113.300	10,42	11,02	73.800	ANON
ANON	114.200	10,41	11,03	77.600	ANON
ANON	15.500	10,40	11,06	96.600	ANON
ANON	108.400	10,40	11,08	93.400	ANON
ANON	60.700	10,38	11,13	72.300	ANON
ANON	88.900	10,37	11,13	74.700	ANON
ANON	97.800	10,37	11,28	83.700	ANON
ANON	80.700	10,37	11,40	92.100	ANON
ANON	103.600	10,37	11,40	80.400	ANON
ANON	99.700	10,37	11,50	79.900	ANON
ANON	92.900	10,36	11,52	89.100	ANON
ANON	87.100	10,36			
ANON	74.600	10,33			
ANON	86.900	10,33			
ANON	89.900	10,31			
ANON	108.900	10,30			
ANON	116.300	10,25			
ANON	34.100	10,23			
ANON	115.500	10,23			
ANON	98.300	10,20			
ANON	30.500	10,18			
ANON	92.600	10,17			

API Orders API RTD (0) (0) (1) Default Windows (9)

Figure 3.5 Rotman Interactive Trader: Book trader.

If there is someone that is willing to pay more than $10.01 for a single share, my order will be filled only after that all the other orders will be filled, according with the best price execution system.

Looking at the "Book trader" (Figure 3.5) is easier to understand the mechanism behind the execution of orders. In the columns is possible to read the Trader name (ANON stand for anonymous, and in this case is an autonomous order-generation system that is set on the liquidity generation, to replicate ordinary market conditions), the size of each order and the price. At the left of the book there is the Bid side while on the other side the Ask side. This looks exactly as a real book trader in common exchange market. Sending a limit order, my order will appear immediately below other order with the same price (time priority rule). So, if for example I want to buy at $10.54 my order will be placed on the fifth position. Please note that in case I send a market order instead of a limit order, the execution price will be the lowest price of the Ask prices (right column) and not the first of the Bid side.

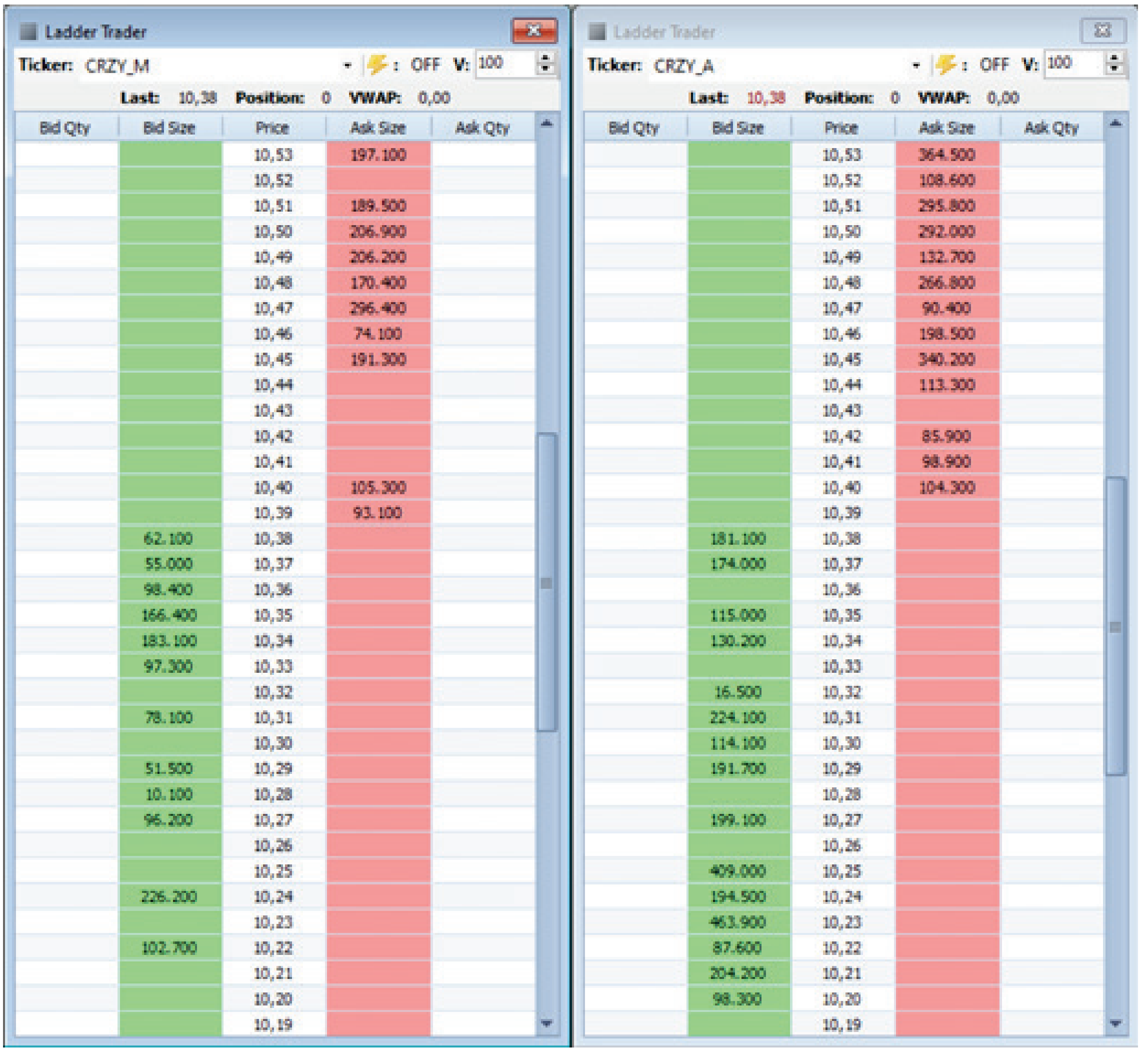


Figure 3.6 Rotman Interactive Trader: Ladder trader.

Exactly as the book trader, the "Ladder trader" shows prices for bid and ask side. The difference in this case is that orders are aggregated for prices, so even if there are 2 orders for 20'000 and one order for 22'100 stocks to buy at 10.38, we read only the aggregate volume for that price. It could be useful to calculate the average price at which a large order will be executed or to have an idea of the trend of the market if we assume that price fluctuations are influenced by the size of orders (many high frequency traders calculate the probability of raise and decrease in prices with market volumes).

Once we have explained the function of the various tools, I can show the whole RIT client's workspace (Figure 3.7). The workspace is exactly like in this frame, with the difference that graph and tables are continuously moving. The red button is the "kill button", the same described in MiFID II and mandatory for trading firms for the shutdown of all the outstanding orders in case of problems.

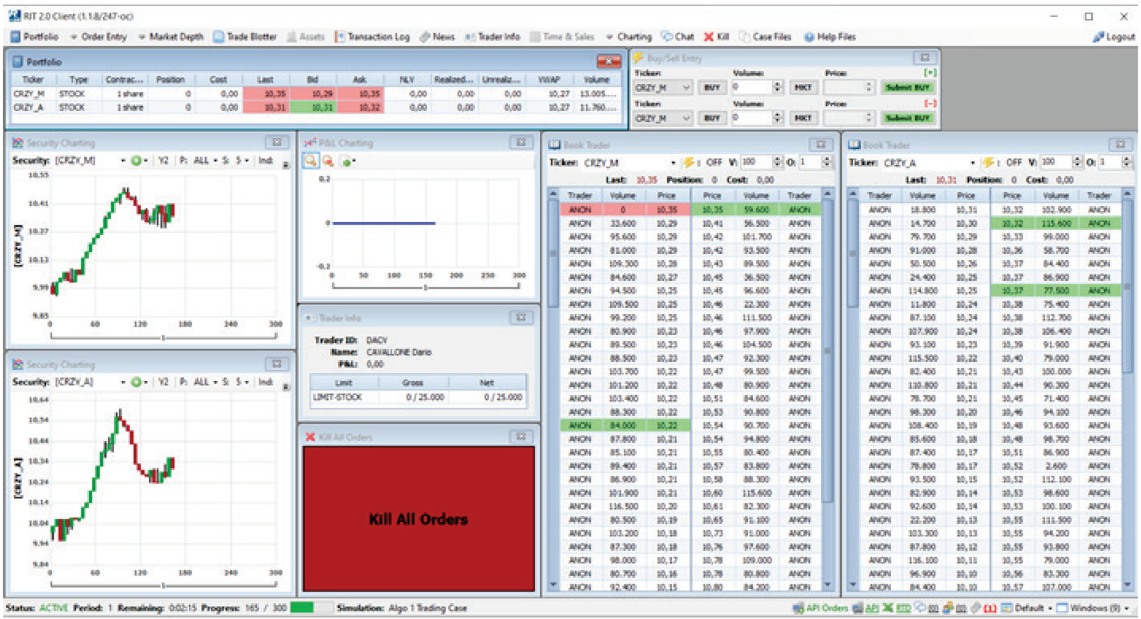


Figure 3.7 Rotman Interactive Trader: Workspace.

3.2 ALGORITHMIC ARBITRAGE

In our simulation, CRZY share are traded on two exchange, the Main market and the Alternative market. Since the stock is the same the position of the trader is the sum of the single position in each market. For example, buying 100 shares on main market and selling 50 on the alternative the trader will have a long position of 50 shares. Basically, the alternative market replicates the function of “new” type of exchange such as ECNs. As I said before, ECNs increased competition between NYSE and NASDAQ, allowing different order types and extended trader hours. When the NBBO[24] can not be applied, market could “cross” each other. A “crossed” market means that the bid price of that market exceeds the ask price of an alternative market as in Figure 3.8.

In this case the arbitrage opportunity is clearly visible. In fact, buying 1’000 shares in the alternative price at the best ask and selling them at the best bid generate a consistent profit. The best ask is \$10.39 while the best bid is \$10.45 (red orders has been already filled) so the total profit of the transaction would be

$$(\$10.45 - \$10.39) \times 1000 = \$600 \tag{3.1}$$

by a single trade.

[24] ECNs and NBBO are mentioned in Section 1.1

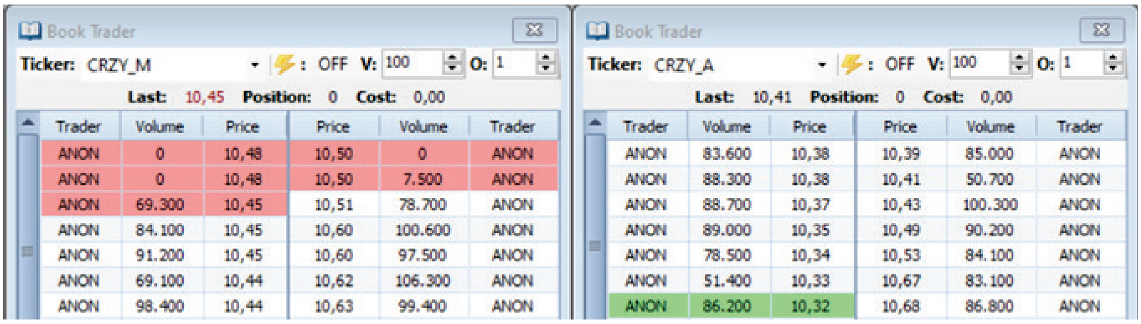
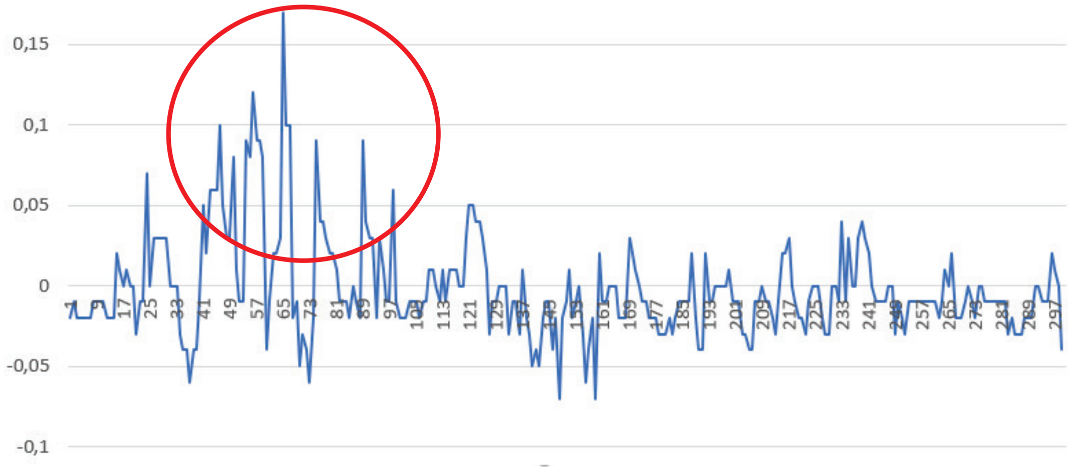


Figure 3.8 Rotman Interactive Trader: An arbitrage opportunity.

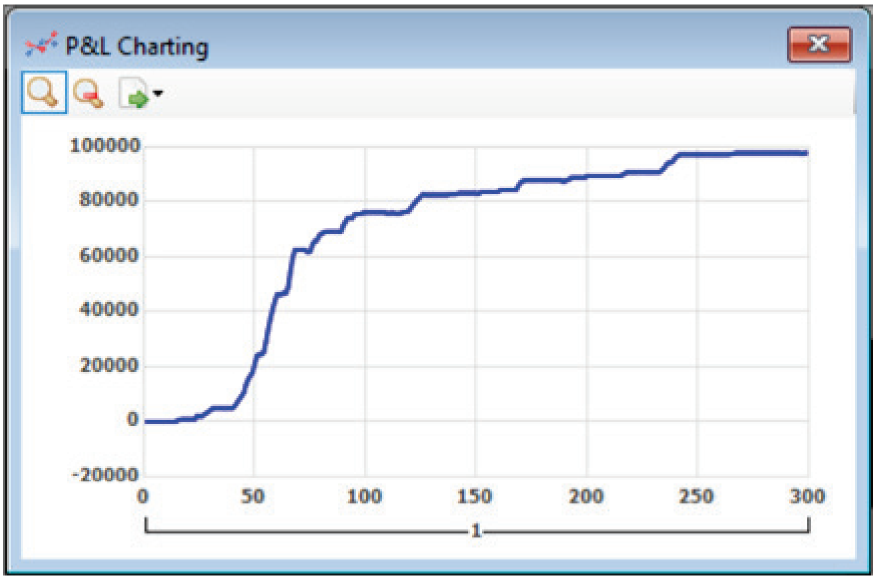
In order to deal with real time data from RIT client, I used Application Programming Interface (API) that can both recover information and send orders from the client. API are really common in the community of computer technology, because allows the user to access to the developer software without modify directly the code. There are some “communication protocols” in computer programs that simplify the implementation of some actions. In this case I used the API to download the real-time data in my excel worksheet, I replicated the “book trader” and then I wrote in Visual Basic Advance (VBA) a code that discover cross in markets quote and trade sending market orders that employ those cross to make a profit. Attached in the Appendix there are all codes I wrote to download, analyse and send orders to RIT.

This is the worksheet in excel with the various useful cells, and the two trader books. At the right there is a graph which shows in every tick the difference between the Max Bid price and the Min Ask price. On another sheet I use a formula from VBA to print my data and then I save them to analyse. My basic algorithm buy at the ask price and sell at the bid price every time it found profitable, decreasing liquidity in the market (in this chapter I do not want to show how algorithms increase liquidity in the market, but only how the “cross” market arbitrage windows are reduced significantly in the presence of these algorithms.

It is immediate to see on the chart below the difference in the cross spread in presence and absence of algorithms. Obviously two single measures do not mean nothing, in fact I have collected many data from various simulation, and I analyzed to have an empirical demonstration of my hypothesis. So, what I want to prove in this paragraph is my null hypothesis “H_0: *“cross” spread is reduced in presence of algorithms*” against the hypothesis “H_1:*”cross” spread is not affected by the presence of algorithms*”. To do that I did two proofs. The first one is a graphical proof.



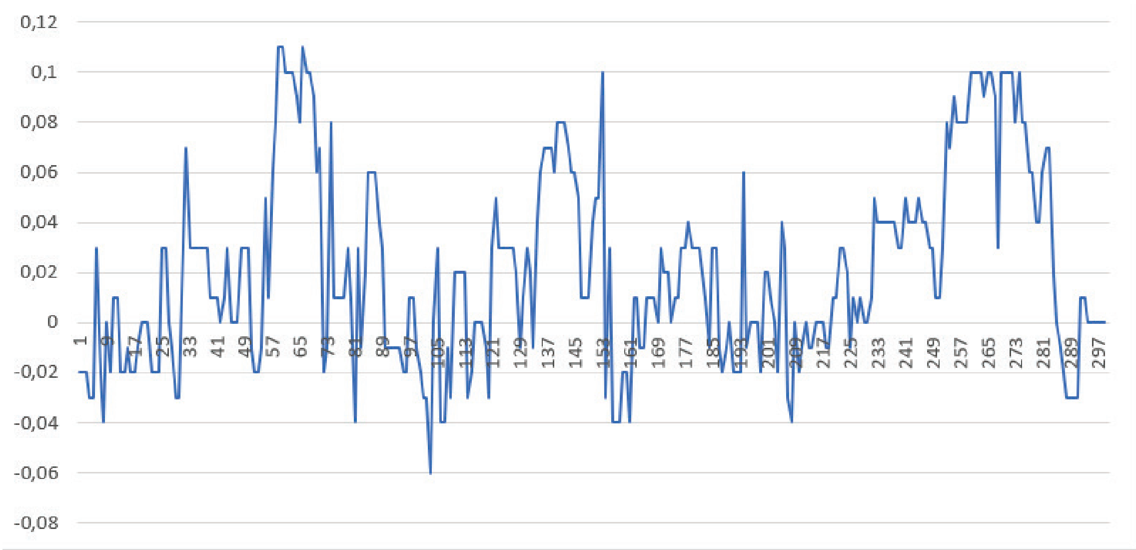
(a) arbitrage spreads



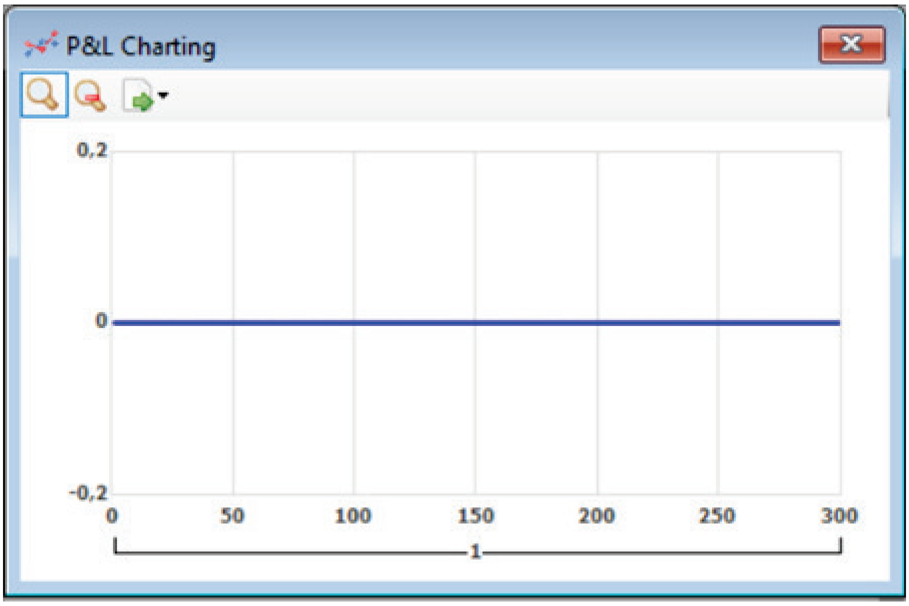
(b) P&L

Figure 3.9 Arbitrage spreads (lowest ask minus highest bid) and P&L with algo.

I combined all data collected from various simulations (to give significance to the test I used two samples of 5000 measurements) to write a graph which represent the distribution of the arbitrage across a range that goes from -0,15 to +0,35. Figure 3.9a and Figure 3.10a show the width of the maximum spread between the lowest ASK and the highest BID. Basically, when the difference is negative (or approximately around 0) there is no arbitrage opportunity, while in the case the difference is positive and significantly different from zero, that difference is exactly the possible profit that algorithmic traders can earn with the optimal strategy. In a perfect market, or in presence of powerful algorithms, this difference would be always negative or close to zero (actually, considering transaction cost the difference should be exactly the transaction cost).



(a) arbitrage spreads



(b) P&L

Figure 3.10 Arbitrage spreads (lowest ask minus highest bid) and P&L without algo.

The main problem that I had is that the software gives some constrains about the position, so I could not trade all the volumes I will, but only a small part of them. With a most powerful computer, co-location, and bigger size of volumes my results would be significantly different, and potentially I could reduce to zero the arbitrage in every single second. However, despite all those factor that impacted on the correct execution of my algorithm, significant results came up.

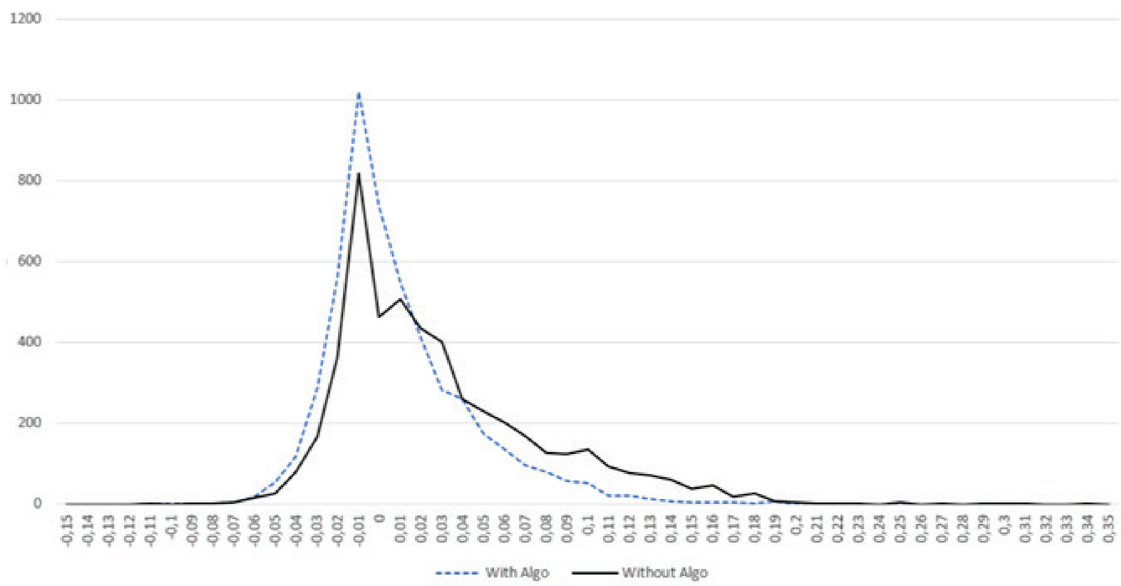


Figure 3.11 Cumulative distribution of arbitrages with and without algo.

In Figure 3.9 and Figure 3.10 two things are evident. The first one is that the presence of algorithms reduced significantly the size of arbitrage. The second is that the algorithm had a profit that was strictly related with the presence itself of the inefficiency. In the red circle of Figure 3.9 I evidenced an example of this correlation. Obviously, a single period, is not statistically significant for a demonstration, that's why I grouped a lot of samples of data and I studied them all together in matrix form.

The cumulative distribution is more useful to understand how arbitrages are distributed. In particular, from Figure 3.11 the first thing that we can note is the absolute value of 0 in the presence of algo. On a total of more than 5000 measurements, the 0 appears 200 times more in presence of algorithms. Another fact is that the blue line is always over the black one in the interval -0.07/0.01, while is always under from 0.01 until the end. This means two things, the first is that the presence of arbitrage greater that 0.01 is consistently higher in the case of no-arbitrage, and that the second is that all the difference between the two cases has been "compressed" in the "non-arbitrage" interval in presence of algorithmic trader.

The second is a more theoretical proof, obtained directly analyzing data that I used to create previous figures. I analyzed the four moments of the distributions. My findings are reported in Figure 3.12.

	With Algo	Without algo
Std. dev	0,03520	0,05060
Average	0,00921	0,02932
Skewness	1,35108	1,29044
Kurtosis	2,98525	2,17662

Figure 3.12 Cumulative distribution of arbitrages: moments.

The first moment is really important because gives us a significantly lower average, and the second refers to a lower expectation of square dispersion from the mean. This means that in mean, in presence of arbitrage the arbitrage has a spread of only 0.00921, too low to be defined profitable, while in the other case is more than three times that value. Even the standard deviation is lower, contributing to confirm the hypothesis of lower dispersion and so of lower arbitrage opportunities across the time. As regard skewness, the algorithm increased the third moment, in fact we can see in the figure above how the data are concentrated at the left of the mean, while in the right there is a lower slope. The fourth moment again confirm the hypothesis, describing a leptokurtic distribution, with an higher value in the "algo case" because of the tight of the distribution curve, due to the "compression" of the arbitrage by the algorithmic trader.

3.3 OPTION ARBITRAGE

In the second case, I want to prove the dependence of some markets (in this case the derivative market) from the algorithmic traders. In this paragraph I will analyze an option pricing model, with the help of an "Options simulation" case from the RIT.

Options are financial instruments based on the value of underlying securities such as stocks. An options contract offers the buyer the opportunity to buy or sell depending on the type of contract they hold the underlying asset. Unlike futures, the holder is not required to buy or sell the asset if they choose not to. To make an example, if the price of a stock is \$50, and I want to buy it at the same price a month from now. Paying a "fee", the price of the option, I receive the right (not the obligation) to pay that stock exactly \$50. Option can be traded in markets just like other securities, and prices fluctuate every minute due to several market conditions. To understand how option change its price I used the famous Black–Scholes–Merton model. It is a mathematical model for the dynamics of a financial market containing derivative investment instruments. From the partial differential equation in the model, known as the Black–Scholes equation, one can deduce the Black–Scholes formula, which gives a theoretical estimate of the price of European-style options and shows that the option has a unique price regardless of the risk of the security and its expected return.[25]

Before to proceed in the explanation of Black-Sholes model, it is important to define Greeks. The “Greeks” is a term used in the options market to describe the different dimensions of risk involved in taking an options position. Delta (Δ) represents the rate of change between the option’s price and a $1 change in the underlying asset’s price, so it represent the price sensitivity of the option relative to the underlying. Delta is positive for Call-option and negative for Put-option. Moreover it can assume values from 0 if the option is Out-of-the-Money (means it is far from is exercise price[26]) is 0.5 or -0.5 if it is At- the-Money (at the strike price) and 1 or -1 if it is deep In-the-money. Gamma (Γ) represents the rate of change between an option’s delta and the underlying asset’s price. This is called second-order (second-derivative) price sensitivity. Gamma indicates the amount the delta would change given a $1 move in the underlying security. Theta (Θ) represents the rate of change between the option price and time, or time sensitivity - sometimes known as an option’s time decay. Theta indicates the amount an option’s price would decrease as the time to expiration decreases, all else equal. Vega (V) represents the rate of change between an option’s value and the underlying asset’s implied volatility. This is the option’s sensitivity to volatility. Vega indicates the amount an option’s price changes given a 1% change in implied volatility. Rho (p) represents the rate of change between an option’s value and a 1% change in the interest rate. This measures sensitivity to the interest rate.

The assumptions of the model are that the price of heavily traded assets follows a geometric Brownian motion with constant drift and volatility. When applied to a stock option, the model incorporates the constant price variation of the stock, the time value of money, the option’s strike price, and the time to the option’s expiry. The Call option formula is calculated from the cumulative standard normal probability distribution multiplied by the stock price. The NPV (net present value) of the strike multiplied by the c. s. n. d. is subtracted from the resulting of the previous calculation.

---

[25] American options can be exercised any time, while European only at the expiration day

[26] Also called strike price

The formula is

$$C = S_0\, N(d_1) - Ke^{-rt}N(d_2) \tag{3.2}$$

where:

$$d_1 = \frac{ln\frac{S_0}{K} + \left(r + \frac{\sigma_s^2}{2}\right)t}{\sigma_s\sqrt{t}} \tag{3.3}$$

$$d_2 = d_1 - \sigma_s\sqrt{t} \tag{3.4}$$

with:

C = Call option price

S_0 = Current stock price

K = Strike price

r = Risk-free interest rate

σ = stock's volatility

t = Time to maturity

N = The normal distribution

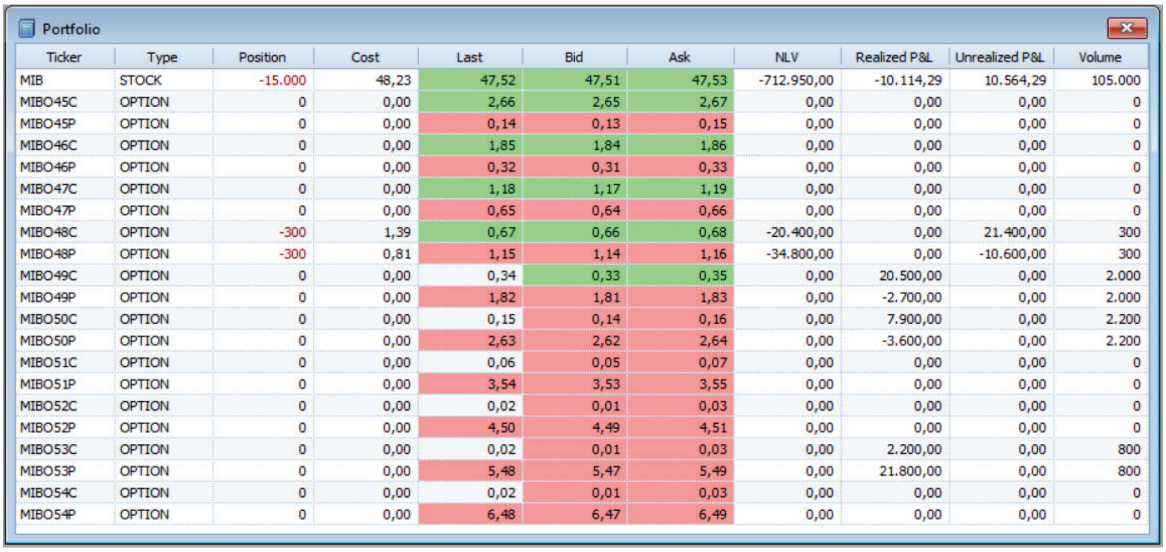
The RIT software offers the opportunity to trade by applying options trading strategies in a market with an underlying stock index, the MIB, that is generated with a random-walk process that follows the formula

$$P_{MIB,t} = P_{MIB,t-1} * (1 + r_t) \tag{3.5}$$

where $r_t = N(0, \sigma)$. Basically, there is no opportunity to generate profit from exogenous factors that can influence the MIB, but the only profit derives from the arbitrage that are randomly generated in the quotation of options. Through the Black-Sholes formula[27] I found all possible arbitrages across different options and with an algorithm I can make profits from them. The main problems are two. The first one is that the simulation presents an infinite liquidity, so as much as I may individuate arbitrages, I can not contribute to reduce them. The second main problem is that the simulations are limited, so I can not collect a significant sample of data from this case. I will just show that find those arbitrage opportunities would be impossible without a super-fast calculator, and without automatization, in the meanwhile a human trader can send orders, those arbitrage are gone.

---

[27] In Appendix there is the full code that replicate the Black-Sholes-Merton formula



Portfolio

Ticker	Type	Position	Cost	Last	Bid	Ask	NLV	Realized P&L	Unrealized P&L	Volume
MIB	STOCK	-15.000	48,23	47,52	47,51	47,53	-712.950,00	-10.114,29	10.564,29	105.000
MIBO45C	OPTION	0	0,00	2,66	2,65	2,67	0,00	0,00	0,00	0
MIBO45P	OPTION	0	0,00	0,14	0,13	0,15	0,00	0,00	0,00	0
MIBO46C	OPTION	0	0,00	1,85	1,84	1,86	0,00	0,00	0,00	0
MIBO46P	OPTION	0	0,00	0,32	0,31	0,33	0,00	0,00	0,00	0
MIBO47C	OPTION	0	0,00	1,18	1,17	1,19	0,00	0,00	0,00	0
MIBO47P	OPTION	0	0,00	0,65	0,64	0,66	0,00	0,00	0,00	0
MIBO48C	OPTION	-300	1,39	0,67	0,66	0,68	-20.400,00	0,00	21.400,00	300
MIBO48P	OPTION	-300	0,81	1,15	1,14	1,16	-34.800,00	0,00	-10.600,00	300
MIBO49C	OPTION	0	0,00	0,34	0,33	0,35	0,00	20.500,00	0,00	2.000
MIBO49P	OPTION	0	0,00	1,82	1,81	1,83	0,00	-2.700,00	0,00	2.000
MIBO50C	OPTION	0	0,00	0,15	0,14	0,16	0,00	7.900,00	0,00	2.200
MIBO50P	OPTION	0	0,00	2,63	2,62	2,64	0,00	-3.600,00	0,00	2.200
MIBO51C	OPTION	0	0,00	0,06	0,05	0,07	0,00	0,00	0,00	0
MIBO51P	OPTION	0	0,00	3,54	3,53	3,55	0,00	0,00	0,00	0
MIBO52C	OPTION	0	0,00	0,02	0,01	0,03	0,00	0,00	0,00	0
MIBO52P	OPTION	0	0,00	4,50	4,49	4,51	0,00	0,00	0,00	0
MIBO53C	OPTION	0	0,00	0,02	0,01	0,03	0,00	2.200,00	0,00	800
MIBO53P	OPTION	0	0,00	5,48	5,47	5,49	0,00	21.800,00	0,00	800
MIBO54C	OPTION	0	0,00	0,02	0,01	0,03	0,00	0,00	0,00	0
MIBO54P	OPTION	0	0,00	6,48	6,47	6,49	0,00	0,00	0,00	0

Figure 3.13 Portfolio of RIT with Options

Figure 3.14 MIB pricing during the simulation.

In Figure 3.13 there is an example of how the portfolio looks during this case. Figure 3.14 shows the path of the stock during the case. In Figure 3.15 and Figure 3.16 we see the correlation of the profits with the arbitrages' presence. In this case, arbitrages are defined as the difference of the real Black-Scholes based prices and the market prices.

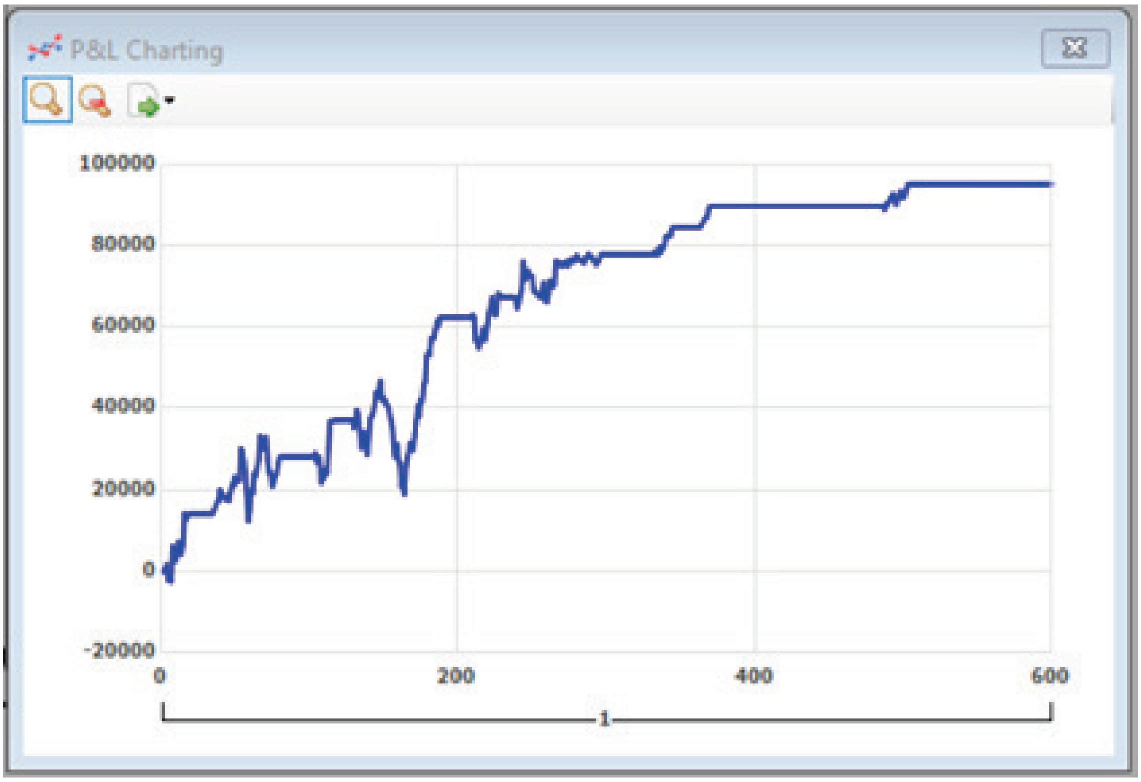


Figure 3.15 P&L

Figure 3.16 Distribution of the arbitrages across the period

Chapter 4

Conclusions and Personal Views

Global financial market is becoming more and more complex, and this evolution is strictly related with the Innovation Technology sector and with the famous Moore's law about the exponential rate of increase of computers' calculus power. We have seen the reasons that lead to the spread of algorithmic trading across markets and countries, and their importance in every aspect of our every-day life. For financial markets the presence of algorithmic traders had a significant impact on the market structure. The massive expense in infrastructure, regulation and regulation is a good proxy to understand the importance of those traders. In particular, High Frequency Trading has markedly changed how financial markets operate, transforming noisy rooms in silent "beeping" servers, creating a lot of new figures that operate in many different ways in markets. We have seen how was possible that a professor from his house in suburban London created panic in the other side of the world pressing a button, and how could a hacker be accused of terrorism just for stealing some codes, or again an employee that caused an half billion loss and a rollercoaster in pricing of hundreds of shares for an absent-mindedness. Otherwise, we have seen how a billion-dollar industry has born thanks to the new technology, and the deregulation of 90' that allowed new type of orders and new exchange such as dark pools. All these new developments caused lack in regulation, and as often happen when there is possibility to have a profit because regulation failed, someone took advantage at the expense of the "average investor". However, SEC and EU commission reacted with new laws (Dodd-Frank act and MiFID II for example) and tried to prevent possible disaster that HTF would cause without the right control. In fact, we have seen the massive volume that HTF has reached on total market volume, the big interconnection, and its capacity to influence prices of companies or of entire sector in the markets. This capacity could be controlled to ensure the right price discovery, efficiency of markets, and reflecting all public information in very short time but could also cause catastrophic collapse of entire sectors and potentially cause the biggest financial crisis we have ever seen.

The scope of this dissertation is to give food for thought to the reader about pros and cons of HFT. Solve all the problems that they could cause is not in my faculty, because I am just a Finance Student and not a regulator, but anyway I tried to give some opinion about how the regulation could contain future disaster, just like we did thousandth of time with all new technology that become part of our life. Instead, what I can do is to give to the reader instruments to judge the effective benefits that HFTs have had in the financial markets. I showed how, with a really simple algorithm, I can modify a virtual market's behavior, that was voluntarily pushed to be inefficient. I used the logic and basic economics and coding concepts to analyze a common market situation where the latency and the inadequacy of telecommunication system, combined with the presence of a sort of liquidity provider's computational error could lead to an error in the quoting prices and so to a situation of disadvantage for an uninformed investor. After have proved the best efficiency of prices in a algorithmic trader presence, I showed how some derivatives such as are necessarily dependent from a continuously quoting algorithms system, because in this case the incorrect pricing of some of those securities could cause a chain reaction (for example a big firm that use an incorrect model for his risk management division) that could have a huge impact on the financial stability of the firm and its subsidiaries.

Last but not least, I would like to end with a quote of one of the founders of the modern economy: Henry Ford once said, "Real progress happens only when advantages of a new technology become available to everybody". Maybe in an hypothetical future, benefits from those HFT will be accessible to everyone, just like today everyone can buy a treasury bond and receive their interest in the future. Maybe one day even for minimal trade the "average investor" could use the HFT software that his bank provided him, who knows? What is sure is that this is a reality, and we can not simply act as it does not exist only because we can not see it or we can not understand it. Probably in next fifty years the word "trader" will be associated only to a new form of Artificial Intelligence or Machine Learning that will become thousands times faster and smarter than us, and we need to define what will be our position as human in that future. I'm saying that, looking at the past, and taking into account the speed of evolution of technology and innovations, not only financial markets will be replaced by enormous servers, but many of actual jobs will disappear, creating a massive job-offer lack. So, to all the people that says that we should be alarmed because of the possible speculation that firms can do with their super-fast HFT, I respond that the only reason to be alarmed is because those machines are faster, smarter and infallible, and the only risk for us is that they will took over most of our jobs before we even realize it.

Appendix

VBA Code

A.1 ARBITRAGE CODE

In this appendix I show the formulas that I used to download data, to analyze them and to send orders to the RIT.

The first step is to create, in VBA, a variable that allows us to stop the calculus of Excel and VBA for a given number of millisecond (Figure a.1).

```
Option Explicit
Private Declare PtrSafe Sub xLib "Kernel32" Alias "Sleep" (ByVal dwMilliseconds As Long)
```

Figure a.1 RIT: Sleep command.

Then I go back to the Excel worksheet, where I need to have the information needed to be analyzed later in VBA. To download data, the RIT software give to users some useful functions that allows to retrieve all information needed in real-time. To do that it is enough to enable Macros in the file and add RIT to the instrumental variables. After that, Excel is able to receive all information needed simply writing the function below:

$$= \text{RTD(rit2.rtd; ;TICKER;INFO)}. \qquad \text{(a.1)}$$

where “ticker” must be substituted with the name of the stock I am considering, and “info” with the kind of information I want to read. For example, if I want to know the actual bid for the stock in the main market I write:

$$= \text{RTD(rit2.rtd; ;”CRAZY.M”;”BID”)}. \qquad \text{(a.2)}$$

Since I needed to print my values, in order to collecting them I wrote another Sub on VBA. Basically this Sub print the highest bid price (actually I wrote other sub very similar to this to print other values such as ask price and P&L) that change every second (or less) in columns so I can associate to each row a tick or a position in the time of my simulation. This could be very useful to study historical data that are not saved automatically in matrix or vector (such as in Yahoo Finance for example).

The code starts with the definition of the method to "count" the time, the tick update (1 second) in this case. Then I indicated both the cells that contains the tick, and the cell I want to print on my sheet. The "if" function define the interval in which Excel must update the information, printing a new value in a new cell every time the tick is changing. At the end there is the starting time for the Sub.

```
Sub PrintValues()
Dim ticktoupdate As Double
ticktoupdate = Application.Workbooks("Algo_excel.xlsm").Worksheets("Main").Range("currenttick").Value
highestbid = Application.Workbooks("Algo_excel.xlsm").Worksheets("Data").Range("highbid").Value

On Error GoTo Errorhandler


        If IsError(ticktoupdate) = True Then
        Else

            If ticktoupdate > 0 Then
                If IsError(highestbid) = False Then
                    Worksheets("Data").Cells(ticktoupdate + 2, 2).Value = highestbid
                End If

            End If
        End If



On Error GoTo Errorhandler



    RunWhen = Now + TimeValue("00:00:01")
    Application.OnTime RunWhen, "PrintValues", , True
Errorhandler:
Exit Sub

End Sub
```

Figure a.2 RIT: Error handler.

To create a connection between the computer and the market, RIT documentation provide different ways. I chose VBA because it is really simple to understand and to program. In every function or Sub it is necessary to initialize the connection with the strings

$$\text{Dim API as RIT2.API} \tag{a.3}$$

$$\text{Set API = New RIT2.API} \tag{a.4}$$

Then it is possible to send an order with the code:

status = API.AddOrder("ticker", "size", "price", "buy/sell", "market/limit price" (a.5)

For example, to Buy 100 stocks in the alternative market at 10.02, I write:

status = API.AddOrder("CRZY_A", 100, 10.02, "API.BUY", "API.LMT" (a.6) or, alternatively

$$\text{status} = \text{API.AddOrder}(\text{“CRZY\_A”}, 100, 10.02, 1, 1) \quad \text{(a.7)}$$

while the code to Sell 10 stocks in the alternative market at the market price or the highest bid is

$$\text{status} = \text{API.AddOrder}(\text{“CRZY\_A”}, 100, 0, \text{“API.SELL”}, \text{“API.MKT”} \quad \text{(a.8)}$$

or

$$\text{status} = \text{API.AddOrder}(\text{“CRZY\_A”}, 100, 0, -1, 0) \quad \text{(a.9)}$$

The code used to prove the price efficiency is reported in Figure a.3:

```
Function algo(timeremaining, tickerM, tickerA, bidM, askM, bidA, askA, Size)

Application.ScreenUpdating = False
Application.DisplayStatusBar = False
Application.Calculation = xlCalculationManual
Application.EnableEvents = False

Dim API As RIT2.API
Set API = New RIT2.API
Dim status As Integer

If timeremaining < 300 Then


    API.ClearQueuedOrders

    If askM < bidA Then

        status = API.AddOrder(tickerM, Size, 0, 1, 0)
        status = API.AddOrder(tickerA, Size, 0, -1, 0)
        Sleep (10)
        status = API.AddOrder(tickerM, Size, 0, 1, 0)
        status = API.AddOrder(tickerA, Size, 0, -1, 0)

    ElseIf askA < bidM Then
        status = API.AddOrder(tickerM, Size, 0, -1, 0)
        status = API.AddOrder(tickerA, Size, 0, 1, 0)
        Sleep (10)
        status = API.AddOrder(tickerM, Size, 0, -1, 0)
        status = API.AddOrder(tickerA, Size, 0, 1, 0)
    End If

End If

Application.ScreenUpdating = True
Application.DisplayStatusBar = True
Application.Calculation = xlCalculationAutomatic
Application.EnableEvents = True

End Function
```

Figure a.3 RIT: Detecting arbitrage opportunities.

I used the firsts four rows to deactivate some Excel functions, for example the screen update. This can speed up the calculus of the rest of my function because it stops the updating of the screen (lock what the user can see). Then there are the strings that create the link between VBA Excel and the RIT, and after that there is the "brain" of the function. The "If" function is active only when the time remaining for the simulation is < 300 (check if the simulation is active). The first order cancels all previous orders that were unfilled or that were in queue. RIT allows external program to send only a few numbers of orders every second, so it could happen that some "old" orders were sent and are still not executed. If the price fluctuated this could cause a massive lose in portfolio. With another "if" function, VBA check every time that the bid-ask spread is "crossed" and sent automatically two opposite orders in the different markets, then "sleep" for 10 millisecond and repeat the operation. The "Sleep" is useful to avoid the creation of a queue of orders, so it gives to RIT the time to execute previous orders and to repeat the strategy. The market can be "crossed" in both directions so there could be two situations:

1. BID_Main>ASK_Alternative → I buy at ask in alternative and sell at bid in main;
2. BID_Alternative>ASK_Main → I buy at ask in main and sell at bid in alternative.

Then the function deactivates the initial commands that lock the screen upload because I need to print the real-time values in columns that I studied to give a significance to the analysis. Clearly, all those operations could be much faster with the ultra-low latency servers and using a dedicated computer only for trading. There are many things that slow my PC for example firewall, Wi-Fi connection, latency (servers of Rotman are located in Canada) and the different operations that can stress my hardware and reduce the efficiency of the code.

A.2OPTION CODE

Since I have already introduced the RIT and the commands necessary for initialize information and orders from Excel to RIT and from VBA to RIT, I suddenly start with the Black-Scholes formula that I used to calculate the correct Option prices.

```
Function Black_Scholes(S, K As Double, r, q, vol, t, IsCall As Boolean, _
                IsFut As Boolean, Divs_in As Variant, result As Long)
    Dim d1, d2, t_Div, Divs As Variant, nDiv, xx()
    Dim disc, pv_X, pv_Div, Sig_Root_T, i, d_sigma
    Dim ImplyVol As Boolean, test_price
    Dim price, delta, gamma, vega, theta, rho
    Dim temp As Variant, Iteration
```

Figure a.4 RIT: Define variables

```
'Calculate option price (or delta etc.) using a binomial tree.

'   S: value of underlying
'   K: option strike price
'   r: continuously compounded interest rate
'   Q: dividend yield
'   vol: volatility of underlying
'   T: life of option in years
'   IsCall: if TRUE a call; otherwise put
'   IsFut: if TRUE underlying is a futures price
'   Divs_in: array of discrete dividends, if any. Omitted if no discrete dividends
'   result: 0->value; 1->delta; 2->gamma; 3->vega; 4->theta; 5->rho; 6->Imply vol

    If IsMissing(Divs_in) Then      'If not discrete divs set up fake dividend array
        ReDim xx(0 To 0, 0 To 1)
        xx(0, 0) = 0#
        xx(0, 1) = 0#
        Divs = xx()
        nDiv = 0                    '... and set number of dividends to zero
    Else                            'otherwise check input data and count number of dividends
        Divs = Divs_in
        Check_Input_Div_Data Divs, nDiv
    End If

    If IsFut Then           'If underlying is a future no discrete dividends are allowed and
        q = r               '   dividend yield is set to interest rate
        nDiv = 0
    End If
    If nDiv > 0 Then        'If we have discrete dividends the dividend yield is set to zero
        q = 0#
    End If
```

Figure a.5 Black-Scholes: manage dividends.

```
    'Check input data
    If K <= 0 Then
        Black_Scholes = CVErr(xlErrValue)
        Exit Function
    End If
    If t <= 0 Then
        Black_Scholes = 0#
        Exit Function
    End If
```

Figure a.6 Black-Scholes: check input data.

```
'If we are implying vol the value input as volatility is the price we are to fit
If result = 6 Then
    ImplyVol = True
    test_price = vol
Else
    ImplyVol = False
End If

If ImplyVol Then
    vol = 0.1
    Iteration = 0
End If
```

Figure a.7 Black-Scholes: manage implied volatility.

```
Do
    'Calculate all values (price, delta, gamma, etc.) for Black-Scholes option
    BS_compute S, K, r, t, q, Divs, nDiv, vol, IsCall, price, delta, gamma, vega, theta, rho

    If ImplyVol Then
        'Calculate implied volatility using Newton-Raphson method

        'Update vol to level necessary to fit price assuming linear price-vol relationship
        d_sigma = (test_price - price) / (vega * 100# + 0.0001)

        'Limit permissable change to avoid shooting off to infinity
        If d_sigma > 0.1 Then
            d_sigma = 0.1
        ElseIf d_sigma < -0.1 Then
            d_sigma = -0.1
        End If
        vol = vol + d_sigma

        'Don't let vol get down to zero
        If vol < 0.00001 Then
            vol = 0.00001
        End If
        Iteration = Iteration + 1
    End If
Loop While ImplyVol And Abs(price - test_price) > 0.000001 And Iteration < 25

If IsFut Then
    rho = -t * price * 0.01
End If
```

Figure a.8 Black-Scholes: calculate all values.

```
    'Return requested value
    Select Case result
    Case 1
        Black_Scholes = delta
    Case 2
        Black_Scholes = gamma
    Case 3
        Black_Scholes = vega
    Case 4
        Black_Scholes = theta
    Case 5
        Black_Scholes = rho
    Case 6
        Black_Scholes = vol
    Case Else
        Black_Scholes = price
    End Select

End Function
```

Figure a.9 Black-Scholes: return requested value.

To respect the privacy of the Luiss Blue Team that is going to compete in next years in the Rotman International Trading Competition, I cannot publish the entire code that I used for my algorithms. However, I can publish a “censored” version of it, that helps the reader to understand the logic behind my algo.

```
Function optionalgo2(ticker1, ticker2, Positionc, cella, cella2)

Dim API As RIT2.API
Set API = New RIT2.API
Dim status As Variant

    API.ClearQueuedOrders

    If Positionc < 600 And [redacted] Then
        status = API.AddOrder(ticker1, 100, 0, 1, 0)
        status = API.AddOrder(ticker2, 100, 0, 1, 0)

    ElseIf Positionc > -600 And [redacted] Then
        status = API.AddOrder(ticker1, 100, 0, -1, 0)
        status = API.AddOrder(ticker2, 100, 0, -1, 0)

    ElseIf Positionc < 600 And [redacted] Then
        status = API.AddOrder(ticker1, 100, 0, 1, 0)
        status = API.AddOrder(ticker2, 100, 0, 1, 0)

    ElseIf Positionc > -600 And [redacted] Then
        status = API.AddOrder(ticker1, 100, 0, -1, 0)
        status = API.AddOrder(ticker2, 100, 0, -1, 0)


    ElseIf Positionc < 300 And [redacted] And [redacted] Then
        status = API.AddOrder(ticker1, 100, 0, 1, 0)
        status = API.AddOrder(ticker2, 100, 0, 1, 0)

    ElseIf Positionc > -300 And [redacted] And [redacted] Then
        status = API.AddOrder(ticker1, 100, 0, -1, 0)
        status = API.AddOrder(ticker2, 100, 0, -1, 0)

    ElseIf Positionc < 300 And [redacted] Then
        status = API.AddOrder(ticker1, 100, 0, 1, 0)

    ElseIf Positionc > -300 And [redacted] Then
        status = API.AddOrder(ticker1, 100, 0, -1, 0)

    End If
End Function
```

Figure a.10 RIT: An option trading strategy on straddle

```
Function hedging(ticker, delta, [redacted])

Dim API As RIT2.API
Set API = New RIT2.API
Dim status As Variant

    If [redacted] Then
        If delta [redacted] Then
        status = API.AddOrder(ticker, 5000, 0, -1, 0)


        ElseIf delta [redacted] Then
        status = API.AddOrder(ticker, 5000, 0, 1, 0)

        End If
    ElseIf [redacted] Then
        If [redacted] Then
        status = API.AddOrder(ticker, 5000, 0, -1, 0)

        ElseIf [redacted] Then
        status = API.AddOrder(ticker, 5000, 0, 1, 0)

        End If
    End If
End Function
```

Figure a.11 RIT: An hedging strategy based on Delta

```
Function closeposition(ticker, position, Esse)

Dim API As RIT2.API
Set API = New RIT2.API
Dim status As Variant

   If Esse = "chiudi" Then
        If position > 0 Then
        status = API.AddOrder(ticker, 100, 0, -1, 0)
        ElseIf position < 0 Then
        status = API.AddOrder(ticker, 100, 0, 1, 0)
        End If
    End If

    If Esse = "compra" Then
        status = API.AddOrder(ticker, 100, 0, 1, 0)
    ElseIf Esse = "compra tutto" Then
        status = API.AddOrder(ticker, 100, 0, 1, 0)
    ElseIf Esse = "vendi" Then
        status = API.AddOrder(ticker, 100, 0, -1, 0)
    ElseIf Esse = "vendi tutto" Then
        status = API.AddOrder(ticker, 100, 0, -1, 0)
    End If


End Function
```

Figure a.12 RIT: A simplified version of an algorithm to close positions

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LIBERA UNIVERSITÀ INTERNAZIONALE DEGLI STUDI SOCIALI
"LUISS - GUIDO CARLI"

Department of Economics and Finance
Chair in Computational Tools for Finance

ALGORITHMIC TRADING:
HOW HIGH FREQUENCY ALGORITHMS CAN IMPROVE MARKET EFFICIENCY AND REDUCE ARBITRAGE OPPORTUNITIES

SUPERVISOR:
PROF. VALERIO MARCHISIO

CO-SUPERVISOR:
PROF. EMILIO BARONE

CANDIDATE:
DARIO CAVALLONE

ACADEMIC YEAR 2018-19

Contents

Summary

This dissertation explains the circumstances that lead to the revolution of the financial industry during the past fifty years. I focus on the evolution of the environment that brought the rise of the new financial industry, based on sophisticated computer, quantitative analysis, big data analysis, high frequency trading algorithms ending with the development of artificial intelligence. The following pages will introduce the automated transacted operations, starting from the first, portfolio balancing quantitative software, passing through the sophisticated calculators that allowed market makers and big dealers to raise liquidity of markets reducing overall costs, and ending with more complex high frequency trading algorithms, used for example to catch arbitrage opportunities and short misalignment in two or more prices in capital markets.

Nowadays, for most of us, it could result obvious the use of computer, or software and algorithms that transact operations in order to buy and sell currencies, or stocks in markets and stock exchange all around the world. But until fifteen years ago, the 100% of transaction where made by human, using calculators only as support of their methodologies and strategies. It is immediate to imagine what may have been the causes that led to the massive use of computer and algorithms in the financial operations. Obviously, one of the reasons is that developing and use algorithms is cheaper because it has no need of offices, wages, insurances and material needs that an employee must have. But, apart from a budget constrains point of view, what makes the difference between "classical" trading system and the new one? The breakthrough is the fact that modern computer can trade with strategies that humans could never apply, because of the speed of the machines and calculus power. In fact, they can receive, read, analyze, and take decision on information in few milliseconds, but even another important aspect must be considered. We are reducing the impact of human feeling, whose effects have been the

center of many studies in the field of Behavioral Finance, explaining many markets anomalies by human psychological influences and biases. And maybe one day someone will find absurd that economy, and in particular financial markets has been susceptible to human sentiments for a while.

But not everybody is convinced that the spread of automatized transaction will have a positive impact on markets. There is no doubt that algorithmic trading development is strictly related with the great innovation of Information Technology, including hardware, software, infrastructures, that made relatively easier for everybody to write a code than before. This innovation follows the famous Moore's Law, the founder of Intel and pioneer of modern semiconductor industry, a several billion dollars market that is the heart of the modern technology. Moore stated two different laws, the first one says that the number of microprocessors double every year (after '80 the effective time was 18 months). The second law is about the costs, in fact he sustained that the cost of a processor doubles every 4 year (every generation), but this means that the growth rates are not related, and so they are destined to stop. The aspect he didn't considered was the fact that the high entry barriers, the growing demand and the very low production cost for the old generation, made this sector much more profitable than he imagined. Moreover, we can apply Moore's Law to financial system, in fact from 1929 the total market capitalization of US stock doubled every decade, and meanwhile the total trading volume doubled every 7,5 years, accelerating during the last period until 2,9 year. Basically, we can say that both markets are growing at exponential rate.

Another important aspect that we must consider is the increased demand for financial services, caused by the population growth and the economic complexity that lead to a much more complex, interconnected and coordinated financial system. The globalization increased the number of market participants, the variety of financial transactions, with globally interconnected counterparties. All institutions benefit from the financial technology and that is why it becomes indispensable.

From a pure economic point of view, the most important developments that contributed to the rise of the algorithmic trading are five. The first one is the Quantitative Finance breakthrough, thanks to modern portfolio theory pioneers such as Markowitz, Sharpe, Rosenberg and Black Sholes. Some years later, Sharpe (1964), Lintner (1965) and Mossin (1966) developed the Capital Asset Pricing Model (CAPM). They started by the assumption of portfolio selection theorem and with empirical studies on the Markowitz's theory concluded that all investors hold the same tangency portfolio, that is composed by all assets traded in market, weighted according with their market capitalization. Basically, the total market portfolio is the tangency portfolio. This is also known as the evolution of the Two-Fund Separation Theorem. The second innovation came from the same period and is a consequence of the study we mentioned above, the index funds. The third milestone is strictly related with the focus of this thesis: the arbitrage opportunities. The truly innovation during the '80s was the use of modern algorithms, in a context of fast computers advanced telecommunications and electronics markets, that can detect, identify and generate profit in a split second, operating contemporary in all markets around the world. Another important breakthrough was the application of automatized computer-made quotation to exchange-traded equities, allowing institutions to implement execution strategies in order to reduce the volume impact on prices. Strictly related with the automated execution of large market orders is market-making. The main role of market-makers is to give liquidity to markets, constantly quoting two prices at which they are willing to buy (Bid price) and sell (Ask price). And, last but not least, the biggest innovation that contributed in large part to the widespread of automated financial markets is the consequence of modern and sophisticated telecommunication systems combined with fasters than ever computers.

Automatized transaction systems are well known phenomena by all market participants, but it is not as new as we could imagine. The digitalization of order flow began in the 1976 by the implementation of the "Designated Order Turnaround" system by New York Stock Exchange, that changed drastically the methods of trading. Through electronic workstation called "display book", orders to buy and sell securities were executed electronically. Before 1971, traders were displayed in the famous trading-floors, screaming prices and information across the room or using expensive telephonic communication to communicate each other. National Association of Securities Dealers (NASD) in 1971 created the first Automated Quotation system (NASDAQ) that became the first electronic stock market. During 70' and 80' NYSE and NASDAQ dominated computerized trading markets, until the SEC authorized the existence of Electronic Communication Network (Regulation Alternative Trading Systems 1992). Duopoly, in fact, was not beneficial for financial markets, and the introduction of this new system was destined to revolutionize the financial market. Those ECNs facilitate negotiation of financial products, in after-hours outside of the traditional stock exchanges and with the use of algorithms to execute orders. . Another important event for financial markets occurred in 2001 when stock exchanges changed their quoting methods from fractions (the minimum tick was 1/16th of a dollar, that is $0,0625 cents) to decimals (now traders can negotiate in the order of $0,01). This meant that the minimum bid-ask spread was reduced from 6,25 cents to a single penny, an incredible advantage for algorithmic trading. The last important progress in the history of automatized trading came in 2005 with the Regulation National Market System, a series of implementation for equity markets designed by SEC. The most important laws were two, the Sub-Penny Rule (Rule 612) that introduced the thousandths of dollar in quoting systems, and the Older Protection Rule (Rule 611) which allowed market orders posted electronically to be immediately executed at the best price nationally (National Best Bid and Offer).

Because of the highly technical know-how requirement in informatics and quantitative analysis, the current trend is to search traders with degrees or PhD in Math, Computer Engineering, Data Science, Statistics and even Physics. Innovation is a keyword in this sector, and to stay ahead of the competition algorithms must be updated, changed and adapted to different market condition, sometimes even in few days. Algorithms are used to analyze market dynamical and determine timing, price, quantity in order to impact optimally on markets. A diffused practice that is spreading across trading firms is the “co-location” which consist in the purchase of real estate near to the physical exchange buildings. This allows HF firms to be a fraction faster than competitors located in the next city, or even some kilometers down the street, in order to make possible all that strategies that I discuss below. The close location of servers and the high investment in infrastructure between exchange and traders, enables firms to access stock prices some thousandths of seconds before other investors, enough to allow algorithms to implement their strategies and obtain large profits. This delay between the moment an information is sent to the moment the same information is received from another operator is called “latency”. The strategies used by traders can be very different each other. I will discuss briefly some of the most popular strategies, describing their mechanism and trying to provide some example about them. The first and easier strategy is the “passive arbitrage”. As I said above, if we think to arbitrage as the simple trade of a good, without bearing any risk, arbitrageurs are as old as the first exchange, or even older. But even if it could seem easy to understand, is not so easy to improve. The second strategy is based on the rebate, that basically are refund of a fraction of penny, that exchange provide to trading firm for adding liquidity to the market. Both exchange and firms have a profit because firms, the *liquidity providers*, can improve strategies offering shares at same prices and collecting this small amount of dollar from each transaction, and on the other side exchange platforms benefits from the presence of this firms because they provide liquidity to their market. Next strategy used by HFTs is called *flash trading*. Flash trading is based on orders that are sent before information goes public, in the sense that are placed in few milliseconds after information is published, even before it appears on other traders' monitors. It is clear that the low-latency and co-location are the keys for the success of the strategy, in fact very fast computers can use some computational tools to conduct statistical and econometric analysis of the market behavior before the information goes public. Predatory strategies consist in to post and cancel orders to buy or sell a security, causing small fluctuations in prices and volumes and allowing the trader to collect a profit from this temporary misalignment. A category of predatory algorithms is the SOAS bandits. *Spoofing* is illegal since 2010 with Dodd-Frank Act. Other markets participants will notice the big volume on the top of the bid side and will recalculate their prevision. In fact, most forecasting pricing models are based on volumes and in particular the first rows of the book are the ones that impact more on the future price forecast. For this reason, to anticipate the bullish trend of the market, some traders will post their own order at a price even higher of our initial order. Strictly related with spoofing is the *pinging*. Pinging consist in place different quantities of orders, but without the intention to manipulate prices or make profits from price fluctuations. The only aim of this strategy is to monitor and study the behavior of other traders, in particular other HFT in order to respond to their strategies, basically implementing a kind of "reversal engineering".

Layering is really similar to spoofing and pinging, with the difference that a large quantity of orders is sent to the market with the hope to influence stock prices. The mechanism used to speculate on the prices fluctuations is the same that we described for the others aggressive HFT strategies. Market manipulation become illegal in 2010 with Dodd-Frank Act but this did not stopped some traders to practice it. In fact, thanks to anonymous dark pools, it is really difficult for regulators to control every single transaction of market participants, and check continuously the order placed and suddenly cancelled could result even more difficult. Last practice that I touch in this thesis is the *quote stuffing*. With quote stuffing the objective is to slow competitors' capacity to analyze books, and to do that HTF sent an enormous quantity of orders that are cancelled immediately, in a loop cycle that has two effects. The first one in so slow directly the other algorithms that are forced to process, analyze and rebalance their strategy to respond to the variation of markets conditions and so losing a lot of time, and the second effect is to impact to exchange market itself, that could suffer from the massive number of operation that is required to process.

Even if a lot of bad practices such as sniffing, quote stuffing, latency arbitrage are illegal, there are warries about the fact that still much predatory algorithms are currently running on principals financial markets.

If, until now we have described how and why automatized transaction raised in the last fifty years, we cannot forget to describe the dark side of this innovation. As I said above, computers have improved efficiency of markets, reduced transaction costs, increased productivity, allowed to implement strategies that where unthinkable to do by humans, thanks to their speed and their insuperable calculus power. But what we forgot is that, exactly like humans, computers can fail, and when they do, consequences are devastating. Traders often fall in what is called "fat-finger error", in fact most stock-exchange implemented different deadline in order to cancel and repair to human error. But what happens if algorithms, for example a High Frequency Algorithm, fails?

On August 10, 2007 the Wall Street Journal reported a series of loss of the most successful hedge funds in the US. Renaissance Technologies Corp. lose the 8.7% of its capital, Highbridge Statistical Opportunities Fund declared losses for the 18%, Tykhe Capital LLC, a quantitative hedge-fund institution suffered losses for the 20% and on August 14, Goldman Sachs Global Equity Opportunities Fund lost the 30% of its capital in a week. What surprised analyst is that quantitative hedge-funds applying statistical-arbitrages strategies suffers the biggest losses, and that's why this episode has the nickname "Quant Quake" of 2007. The managers of hedge funds refused to comment publicly on the events, but later studies attributed the cause of the fall to the liquidation of one or more large market-neutral hedge fund's portfolios. This massive operation moved down the prices of most stock, triggering a loop where the value of quantitative funds' portfolios dropped, forcing them to reduce leverage selling part of portfolios, pushing the prices down and reducing further the value. The connection between the quantitative fund's strategies, that suffered the biggest depreciation, is the common use of some ratios, for example book-to-market ratios where highly used to build their strategies. Summing up the large prices' fluctuations fueled across markets and institutions, and algorithmic trading where the oil that feed the fire.

Moreover, the years 2007 and 2008 were the period of the most serious financial crisis since the Great Depression, and, even if officially no one shift the blame to algorithms, and the ignorance towards the private-owned firm's strategies let impossible to blame algorithm trading, this could be an inspiration for in-depth studies.

The famous "Flash Crash" of May 6, 2010 reflect, in my opinion, the concept of "velocity". At 2:42 PM the Dow Jones Industrial Average, a stock market index representing 30 large companies listed in NYSE and NASDAQ, dropped 600 points, in addition to the previous 300 points daily fall, losing a total of near 1'000 points in a day. However, in twenty minutes he recovered from its one-trillion-dollar value fall, closing at "only" 300 points under its opening price. The causes of the Dow crash, the biggest decline on an intraday period in the index history, are a mystery. Several theories were published, and many studies tried to analyze and to find a responsible, but until now there is no agreement about the cause of this event. The firsts reports explained facts of 6 May as the fat-finger error consequences, suddenly denied by Chicago Mercantile Exchange that would avoid this error with "anti-fat-finger-trade" systems. In July 2011 a report of International Organization of Securities Commissions affirmed that High Frequency Traders shorted aggressively in order to liquidate their position and withdrew from the markets to avoid uncertainty. Even in this case, Nanex, a high-frequency data analysis firm, pointed out some inconsistency of the study, including the fact that the majority of the HFT sell orders were never executed because of the lack of liquidity. The third theory is based on a large E-Mini S&P 500 sell, attributed to Waddell & Reed for 75'000 contracts valued around 4 billion dollars. Lastly, there were reported some technical glitches that affected NYSE and various Alternative Trading Systems, that created some problems on the Consolidated Quotations System for example latency and errors in prices of some stocks. On September 2010 U.S. Securities and Exchange

Commission and the Commodity Futures Trading Commission published a joint report about the Flash Crash and arguing that a large fund (Waddell & Reed Financial Inc.) started a hedging strategies, selling E-Mini S&P contracts for a value of 4.1 billion dollars, drying up liquidity, in particular buy-side, and triggering computer algorithms that had just bought this massive volume, generating the so called “hot-potato” effect. Because of insufficient demand from fundamental buyers and institutions, HFT started to negotiate contracts to each other. But when algorithms reached the threshold price, they stopped trading and abandoned the markets altogether. In those minutes over 1 trillion dollars in market value vanished and meanwhile something of even more extraordinary happened. Stocks of some of the major companies in S&P 500, for example Accenture and Exelon, started to be quoted at 0.01$ while others, such as Sotheby’s, Apple Inc. and Hewlett-Packard, raised to 100’000$. When trading on E-Mini was paused for five seconds, the sell-sides of order books were partially repopulated, and when finally trading resumed, prices recovered most of their consensus values. Some critics were moved against SEC and CFTC report, for example the fact that they took five months to analyze five minutes of market data, or the fact that the Waddell & Reed short sale correspond to the 5% of the total volume of market trades. Again, Nanex analyzing W&R orders showed that none of the 6’438 orders were posted in the Ask side, that means that they were executed only when a buyer hit that ask price, and not lowering the bid price. On 2015 the US Department of Justice arrested Navinder Sarao for 22 criminal counts including market manipulation and fraud. He was a professor and trader operating from his house in London, that through spoofing algorithms sent orders for 200 million dollars, modifying and replacing them 19’000 times before they were cancelled. Whit his strategy he was guilty of pushing down market prices, cancelling orders and buying during the fall, generating a profit of 40 million dollars in few minutes. However, someone claims that blaming a single trader for a trillion-dollar stock market crash is “a little bit like blaming lightning for starting a fire". Concluding, even if we can not blame a single firm, or a single factor that caused the Flash Crash on May 2010, we must highlight the impact of algorithms involved in that trades. During that twenty minutes, over 85% of the transactions has been from HTF to HTF seeking to take advantage of temporarily profitable market condition and blowing the crash out of proportion.

The benefits of High Frequency Trading are different, and there were many researchers that studied the effects of HFT in particular on the stock market. They showed the great role of algorithms in different aspects of financial markets. The increase in liquidity of the markets (Boehmer, Fong e Wu 2015) due to the higher interest and competition that grew around this new sector made the execution of transaction easier and faster than ever. The decrease of the bid ask spread (Conrad, Wahal and Xiang 2015) was observed both in US and Japan markets, is strictly related with the reduction of transaction costs, result of the increased level of transaction and the greater number of exchanges. Speeding up the velocity of execution of orders improved the price efficiency of markets giving an higher level of information about present and future prices (*price discovery* was the subject of the study of Brogaard, Hendershott and Riordan of 2014). Information are immediately absorbed by high frequency traders and prices immediately reflect the new data reducing possibility of shock in the markets. Basically, price efficiency across different financial markets improved thanks to the growing of inter-markets connections derived from strategies such as passive arbitrage. Moreover, respect to the past liquidity providers, with HFT the conflict of interest of this practice is reduced. The reduced spread between buy side and sell side cut trading costs for fund investors. Increasing competition among HF traders helps prices to be more stable, and spreads to be narrow, and so not only high-tech firms benefits from those practices, but also all investors such as pension funds and individual can take advantage of best conditions.

On the other hand, many studies tried to explain negative aspect of algorithmic trading, analyzing different effects. Van Kervel in 2012 showed that the increase in liquidity on most exchange is only an illusion (*ghost liquidity*). The behavior of HFT lead to overestimate the market liquidity because many orders are sent only to improve strategies such as spoofing or layering, or in other cases when one order is executed in one exchange all other "twin" orders disappear from all other platforms. Other studies demonstrated how the presence of high frequency traders, in particular circumstances such as uncertainty, could have the opposite effect that we said above diminishing liquidity in markets and increasing intraday liquidity. The same prices that we said should be more efficient could result affected by aggressive and predatory strategies, causing the effect of the distortion in the price discovery. The increasing use of dark pools, that are non-transparent platform means that more and more trader prefer to stay anonymous, which allows them to set up unethical practices such as the ones that I described above with negative effect for markets efficiency. Moreover, others argue that they push “classical” investors to dark pools to avoid the issues of HFT on “normal” regulated markets, like the very small size. In fact, the average volume of a single order decreased from 19’400$ per order in 1995 to 6’400$ in 2011 (according with Deutsche Bank Research). If initially the electronification of financial system led to a sort of “democratization” of the business, allowing all investors to trade without the physical presence, or lowering transaction costs, the evolution of more complex, expensive and sophisticated technologies is exacerbating the conflict between the average investor and who can benefits from those innovation, giving an advantage to high-tech big firms. Another trouble is that HTF, in contrast to the classical regulated broker-dealer, are not obliged to provide liquidity in case of bad market condition, just like 6 May 2010. In summary, the debate about the benefits and problems of HFT will continue for a long time.

High Frequency Traders are continuously challenging against the new regulation, because even if regulators are continuously enacting new laws and rules about this sector, the practice of HFT is incessantly evolving and increasing its volume and its complexity. Furthermore, many institutions keep their algorithms secrets, and they are so cutting edge that only a few mathematicians and computer engineer able to understand them. If we add the fact that conceptually is possible to use algorithms to manipulate markets, obtain unfair advantage and specially to cause a huge financial crisis we understand why in this specific case regulators are subjected to efforts and hard work to keep up with innovation. The fact is that, thanks to dark pools, this form of trading is really difficult to check, and combined with flash orders practices and manipulative strategies, the illegal activity of traders becomes object of suspicious. Predatory trading also cause price fluctuations without a real reason could be really dangerous for markets.

Starting from January 3, 2018 in Europe MiFID II and MiFIR has revolutionized financial markets regulation and HFT as well. The article 4(1)(39) identifies algorithmic traders as those traders whose computer algorithm autonomously decide parameters of orders as the size, the timing and prices managing order after its submission with limited or total absent human intervention. The objective of those traders is not necessarily to maximize profits but rather to obtain lower costs and contain market risk. Only the commission sector associated with algorithmic trading is calculated about half billion dollars per year. High Frequency Traders are identified as a particular category of algorithmic traders that is characterized by infrastructure on purpose to minimize latencies (we already talked about colocation, but there are other practices for example proximity hosting and high-speed direct electronic access), autonomous system determination of order generation and execution and high message intraday rates. The risk deriving from HFT traders could be of various types: the systemic risk is the risk generated when a possible crash in one or more single institutions could spread across markets and affect the whole system, causing a catastrophic event. To show empirically the evidence of my thesis, I am going to use the Rotman Interactive Trader software. RIT is an order-driven market simulator, basically a real-time basis platform that replicate exactly a financial market and where I could implement a real algorithm that will trade orders in a quasi-real environment. In this simulation I run the "Algo 1 Trading Case" that basically simulate the pricing path of a stock in a main market (for example the NASDAQ) and in an alternative market (Dark Pool). There are exogenous shocks that create a "shift" of the stock price in alternative market (for example lack of liquidity of institutional tenders) and that cause some prices inefficiencies. Price inefficiencies in this case can be directly measured because are the difference of the price in the alternative market and price in the main market. My purpose is to show that the presence of my algorithm in this market will reduce this price inefficiency, reducing the shock affecting the alternative market and increasing the liquidity of the markets.

Global financial market is becoming more and more complex, and this evolution is strictly related with the Innovation Technology sector and with the famous Moore's law about the exponential rate of increase of computers' calculus power. We have seen the reasons that lead to the spread of algorithmic trading across markets and countries, and their importance in every aspect of our every-day life. For financial markets the presence of algorithmic traders had a significant impact on the market structure. The massive expense in infrastructure, regulation and regulation is a good proxy to understand the importance of those traders. In particular, High Frequency Trading has markedly changed how financial markets operate, transforming noisy rooms in silent "beeping" servers, creating a lot of new figures that operate in many different ways in markets. We have seen how was possible that a professor from his house in suburban London created panic in the other side of the world pressing a button, and how could a hacker be accused of terrorism just for stealing some codes, or again an employee that caused an half billion loss and a rollercoaster in pricing of hundreds of shares for an absent-mindedness. Otherwise, we have seen how a billion-dollar industry has born thanks to the new technology, and the deregulation of 90' that allowed new type of orders and new exchange such as dark pools. All these new developments caused lack in regulation, and as often happen when there is possibility to have a profit because regulation failed, someone took advantage at the expense of the "average investor". However, SEC and EU commission reacted with new laws (Dodd-Frank act and MiFID II for example) and tried to prevent possible disaster that HTF would cause without the right control. In fact, we have seen the massive volume that HTF has reached on total market volume, the big interconnection, and its capacity to influence prices of companies or of entire sector in the markets. This capacity could be controlled to ensure the right price discovery, efficiency of markets, and reflecting all public information in very short time but could also cause catastrophic collapse of entire sectors and potentially cause the biggest financial crisis we have ever seen.

The aim of this dissertation is to give food for thought to the reader about pros and cons of HFT. Solve all the problems that they could cause is not in my faculty, because I am just a Finance Student and not a regulator, but anyway I tried to give some opinion about how the regulation could contain future disaster, just like we did thousandth of time with all new technology that become part of our life. Instead, what I can do is to give to the reader instruments to judge the effective benefits that HFTs have had in the financial markets. I showed how, with a really simple algorithm, I can modify a virtual market's behavior, that was voluntarily pushed to be inefficient. I used the logic and basic economics and coding concepts to analyze a common market situation where the latency and the inadequacy of telecommunication system, combined with the presence of a sort of liquidity provider's computational error could lead to an error in the quoting prices and so to a situation of disadvantage for an uninformed investor. After have proved the best efficiency of prices in a algorithmic trader presence, I showed how some derivatives such as are necessarily dependent from a continuously quoting algorithms system, because in this case the incorrect pricing of some of those securities could cause a chain reaction (for example a big firm that use an incorrect model for his risk management division) that could have a huge impact on the financial stability of the firm and its subsidiaries.

Last but not least, I would like to end with a quote of one of the founders of the modern economy: Henry Ford once said, “Real progress happens only when advantages of a new technology become available to everybody”. Maybe in an hypothetical future, benefits from those HFT will be accessible to everyone, just like today everyone can buy a treasury bond and receive their interest in the future. Maybe one day even for minimal trade the “average investor” could use the HFT software that his bank provided him, who knows? What is sure is that this is a reality, and we can not simply act as it does not exist only because we can not see it or we can not understand it. Probably in next fifty years the word “trader” will be associated only to a new form of Artificial Intelligence or Machine Learning that will become thousands times faster and smarter than us, and we need to define what will be our position as human in that future. I’m saying that, looking at the past, and taking into account the speed of evolution of technology and innovations, not only financial markets will be replaced by enormous servers, but many of actual jobs will disappear, creating a massive job-offer lack. So, to all the people that says that we should be alarmed because of the possible speculation that firms can do with their super-fast HFT, I respond that the only reason to be alarmed is because those machines are faster, smarter and infallible, and the only risk for us is that they will took over most of our jobs before we even realize it.

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