Copenhagen Business School
Department of Finance
15^{th} May 2019

Gold Price Dynamics Around the Clock

Authors:
Francesco Donati (115765)
Johannes A. Jung (115540)

Supervisor:
Paul Whelan

Pages: 98 Characters: 183,273

Thesis submitted in partial fulfilment of the requirements for the degree of Master of Science in Advanced Economics and Finance (Cand.Oecon)

Acknowledgements

We want to thank Copenhagen Business School for the splendid learning opportunity. We express our deep gratitude to the thesis supervisor, Paul Whelan, for his guidance. We want to thank our friends and families for their precious support during this exciting last period of our student life. A special mention goes to our parents, of course. We want to thank the amazing people met in the program, their energy, drive and diversity inspired and improved us. We will be missing all the ups and downs of student's life. Further, we want to thank Beyza and Emanuela, for the laughs and joy they brought us every day. Lastly, Johannes wants to mention that his girl Ploy is more precious than gold to him.

Francesco & Johannes

Abstract

In this thesis we examine intraday behaviour of gold prices in the 24 hours day. We make a distinction between eastern world (China, India) and western world (US, Europe). We suspect that the intraday pattern may be affected by two factors: (*i*) large gold imports by eastern countries and (*ii*) manipulation of the London Gold Fix. We find a hat-shaped intraday seasonality, with gold appreciating during eastern trading hours in a robust way and depreciating for the rest of the day. Additionally, in the years of alleged manipulation gold prices drop around the London fixing times. In a multivariate regression analysis we find that East and West returns respond differently to the same shock, which means that eastern and western clienteles react asymmetrically in their gold consumption choices. Lastly, we backtest trading strategies trying to exploit the pattern. When transaction costs are not taken into account they outperform the market, with Sharpe ratios as high as 1.61. When taken into account, trading strategies underperform the market, but still show some profitability.

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Chapter 1

Introduction

1.1. Motivation

In the last 10 years, China and India's gold demand was roughly 50% of global demand. In the meantime, China and India's gold mining supply was less than 15% of global mining supply (Reuters 2018). These numbers imply that these two countries are the world's leading importers of gold and that gold moves from the western part of the world (America and Europe) to the eastern part of the world (China, India). In fact, China's central bank was steadily increasing its reserves over the last decade, and gold demand from the private sector increased as well (jewellery and investment). As for India, gold consumption is deeply embedded in its culture and while the economy grows, so does gold demand. From a trading perspective, this may suggest that gold demand during eastern trading hours should be higher than it is during western trading hours, which may result in an intraday price seasonality.

The primary benchmark for the gold spot is set twice every business day in the so-called London Gold Fix. After the Libor fixing scandal, also the gold fixing process came under scrutiny by financial authorities and press. In a Class Action, the five gold fix banks were accused of manipulating the London PM Fix between the years of 2004 and 2013. According to the plaintiffs, the banks had incentives to collude and set prices lower than their actual level. In fact, the PM Fix price is internationally used to settle derivatives contracts. Holders of short positions in those contracts would indeed benefit from the lower prices than normal. Apart from these allegations, yet to be confirmed/dismissed in court, another case is officially acknowledged: on the 28^{th} Jun 2012, a trader of Barclays' Precious Metal Desk, performed manipulation of the PM Fix by placing a sizeable sell order in the auction with the sole purpose of influencing the benchmark price. From a trading perspective, this means, if the manipulation was an ongoing process during this time period, rather than a one-time event, then we would see price drops around the fixing time more often than price increases.

The availability of high-frequency data gives us the chance to investigate if the assumed gold price behaviours exist, and if they do, how pronounced and robust they are.

1.2. Literature Review

Intraday seasonality is nothing new to the research in financial economics. In the past, especially during the 80's many theoretical and empirical studies have emerged investigating periodic behaviour of equity prices within a trading day.

Kyle (1984) built the foundation for later research on intraday seasonality by modeling the role of liquidity traders in a three period model with imperfect competition among the market makers and finds that both costly public information generation and liquidity trading improve the informativeness of prices. In Glosten & Milgrom (1985) the market marker faces an adverse selection problem, in which he cannot distinguish between the informed and liquidity traders. As a result, the market maker charges a spread to balance losses from the informed traders with profits from the liquidity traders. Thus, the bid-ask spread occurs because of an adverse-selection problem and is a measure for liquidity. Kyle (1985) models insider trading in a sequential auction setting, in which informed traders optimally exploit their monopoly power. Despite the dynamic optimizing behavior, markets are still efficient in a semi-strong sense. He finds that informativeness of prices does not change when liquidity trading increases, because trading by informed traders compensates for the loss of information. "Kyle's Lambda", developed in this paper, is a popular measure of price impact and used to measure informed trading. Even though the last three papers do not specifically model intraday seasonality, they contribute a great extent to the understanding of price formation and informational content of bid-ask spreads, which lays the foundations for Admati & Pfleiderer (1988) who postulate that trading activity from liquidity traders and informed traders together evokes intraday patterns in price variation and trading volume. Their main finding under the assumption of endogenous informed trading is that price variability increases in trading volume. The main difference of this paper compared to the others in that field, is that they distinguish between non-discretionary and discretionary liquidity traders among whom the discretionary ones can choose the timing of the trade to minimize transaction costs and they do so in a multiperiod model. This is a more reasonable assumption given that the liquidity traders are often large institutional traders.

Jain & Joh (1988) is a study from the same time period complementing the theoretical models above by empirical facts. Using hourly data on stock returns and stock trading volume of the NYSE from 1979 - 1983, they find a U-shaped trading volume pattern, with the largest trading volume during the first and the last hour of the day. Except for Monday, this result also holds for average stock returns during the day. They also find a strong positive correlation between absolute returns and trading volume. According to their analysis, the volume is Granger-caused by returns, but there is only weak evidence for the other way around.

(Heston et al. 2010) is a recent study that shows how trading behaviour evokes volume and return patterns. Fund flows, mainly from mutual funds, but also from pension funds, show large autocorrelation. In order to minimize trading costs, automated trading algorithms execute a sequence of trading orders to optimize the trade-off between trading costs and price uncertainty. They argue that due to a combination of autocorrelated fund flows which may be executed by trading algorithms, intraday periodicity in returns, order imbalances arise and last for up to 40 consecutive trading days using data in half-hour frequency. Periodicity in trading volume, order imbalances and volatility do not explain the return pattern, nor does firm size, systematic risk premia and the inclusion of the S&P500 as a proxy for the trading of index funds. Also, this pattern cannot be traded profitably after deducting the bid-ask spread as a proxy for trading costs.

Caminschi & Heaney (2014) study the effect of the London fixing procedure one the return, volume and volatility of the GC gold futures contract and the GLD gold ETF. They employ a data set of six years length in 1-minute frequency. In the time window 30 minutes prior to the fixing statistically significant changes in trading volume, volatility and returns occur. According to their analysis, the regularities around the London fixing can be profitably exploited in a trading strategy.

(Iwatsubo et al. 2018) is one of the few papers covering intraday seasonality in commodity markets, and specifically in the gold and platinum futures market. This paper studies the market microstructures of the TOCOM in Tokyo and COMEX in Chicago regarding the gold and platinum futures contract using 1-minute data from September 2014 to March 2015. They are aiming at understanding differences in informational efficiency, return volatility, trading volume and market liquidity to determine whether trading is predominantly driven by informed or liquidity traders.

Informational efficiency and return volatility follow a W-shape on both exchanges over the 24 hours of a day. Trading volume and liquidity do not show clear patterns for both exchanges.

The field of intraday seasonality's is well founded on theoretical and empirical grounds. In commodity markets however, it is sparsely studied to date. All empirical studies presented here capture either short time frames or use medium data frequencies to study intraday behaviour of market microstructure. We wish to complement that literature by analysing the market microstructure of the US gold futures market around the clock and set out to find explanations for the seasonal return pattern. We do that by means of a comprehensive high frequency data set covering 18 years in 5-minute intervals of almost 24 hours a day.

1.3. Research Questions and Methods

Based on the above presented qualitative and quantitative evidence we have developed three research questions we aim to answer in this thesis:

H_0^1 : There is intraday seasonality in gold prices driven by a West-East gold demand shifts.

H_0^2 : There are downward price movements around the London fixing times.

H_0^3 : If H_0^1 or H_0^2 or both prove to be true, then there exist trading strategies which profitably exploit these patterns.

To validate the three hypotheses, we collect high frequency data, reduce their frequency to 5 minutes intervals, and develop an outliers cleaning algorithm to set the foundation.

As for H_0^1, we first validate the existence of intraday seasonality in gold prices. Then we perform a number of robustness checks by dissecting the sample into various subsamples and test for economic and statistical significance in each of them. Further, we run multivariate linear regressions of gold returns earned during eastern and western trading hours on monetary and macroeconomic variables.

As for H_0^2, we first validate the existence of the downward price movements around the London fixing times. Then we perform a number of robustness checks by dissecting the sample into various subsamples and test for economic and statistical significance in each of them.

As for H_0^3, we backtest the trading strategies and compare their profitability and performance with those of traditional benchmarks. We first assume no transaction costs and then take transaction costs into account.

1.4. Main Findings

When plotting the average 24 hours cumulative return pattern of gold we notice two interesting features: (*i*) a hat shape and (*ii*) two downward spikes. (*i*) refers to the fact that gold returns on average appreciate by +18.6% (annualized) between 11:00 and 2:00 [New York time], and depreciate by -10.0% (annualized) in the remaining hours of the day. (ii) refers to the fact that gold returns on average drop by -3.7% and -3.9% in the half hour before the AM and PM London fixings respectively. While (*i*) appears to be more robust over time, (*ii*) seems to be pronounced only in some particular years. Setting up regressions using monetary and macroeconomic variables, we found that positive GDP growth in China and strengthening in Indian Rupee vis-a-vis the US Dollar positively affect gold returns earned during eastern trading hours but not during western trading hours. Also, we found that a strengthening in Japanese Yen and increase in Brent price positively affect gold returns earned during western trading hours but not returns earned during eastern trading hours. Finally, we construct four trading strategies to try to exploit the initial intraday return pattern optimally. When excluding transaction costs, all four trading strategies outperform the market with a maximum average Sharpe ratio of 1.61 achieved by the Combo strategy within 18 years. Including transaction costs, the four trading strategies perform poorly in the first half of the sample due to high bid-ask spreads. In the second half, bid-ask spreads are considerably smaller, and three of our four strategies become profitable despite not beating the market.

1.5. Structure of The Thesis

In Chapter 2 we provide a general overview of the gold market, in Chapter 3 we present the data and our cleaning methodology, in Chapter 4 we show intraday returns, volatility, liquidity and volumes for the whole sample. We perform a comprehensive set of robustness checks on intraday returns in Chapter 5. Based on this analysis we present a number of regressions of Close-to-Close, West and East returns on monetary and macroeconomic variables in Chapter 6. In Chapter 7 we continue with the construction and backtesting of six trading strategies. Chapter 8 concludes and gives an outlook for further research.

Chapter 2

Gold - An Overview

We start laying the foundation for our thesis by motivating the interest in gold from a physical, economic, and cultural perspective. We introduce the reader to basic chemical properties of gold and distil the most fundamental reasons why it is gold that stores value best and not, say, silver. Based on this understanding, we describe four monetary systems and the role of gold in each of them. Moving from public interest in gold to private interest, we connect behavioural implications of risk aversion with the capability of gold to store value to point out the role of gold as insurance. Rational choice is one category which entices individuals to demand gold; however, choices made based on cultural reasons is another, even more important category to do so.

Further, we want to give an overview of the scale and structure of the global gold market to put things into perspective. We disaggregate gold supply and gold demand from a global to a national perspective, as well as different product categories gold can be traded in. We also discuss the geographical distribution of trading venues and groups of buyers and sellers. This disaggregation bears a crucial implication in our final results.

We move further into detail and describe the functioning and mechanisms of the gold spot and futures markets. We describe the precise mechanisms of price creation and settlement in each of the markets. In the spot market, prices are historically set twice a day by an auction called the London Gold Fix, and we point out which incentives for the auction participants come along with that procedure. Finally, we establish a link between gold futures and physical gold, and we start motivating why the use of futures is appropriate in the proceeding of our thesis.

2.1. Why do People Trade Gold?

In this first section, we want to give a number of reasons why private individuals, investors, industrial companies and public institutions trade gold. We look into the fundamental properties of gold which make it valuable and provide an overview of essential motives behind gold trading.

Gold as Value Storage

Gold has been used for thousands of years as a store of value. Being a store of value is a property that originates from the chemical composition of gold. Gold does not corrode, which means, even after thousands of years, it does not react with oxygen or water and thus does not change its chemical structure. As a result of this, gold is immutable to environmental influences and, more visually speaking, gold just does not change its appearance. The colour plays a crucial role in the historical emergence as a store of value, because it is so easy to distinguish from other metals, whereas silver, platinum or white gold are hardly to differentiate for the layman. Another quality, that distinguishes gold from other precious metals is its high density. With a density of 19.3 g/cm^3, one liter of gold weights 19.3 kg. It becomes clear that even small quantities of gold amount for substantial weight and thus, small amounts of gold are enough to store for a significant value.

Gold in Industries

Despite its high density gold is a soft metal which makes it easy to manipulate as opposed to other metals. Also, gold is highly conductive to electricity and heat. Durability, conductibility and robustness against corrosion make it a versatile resource for many applications in different industries like electronics and dentistry. In all of them, it serves different and unique purposes which can hardly be served by another material.

Gold as Currency

A monetary system that involves gold in some way is called a *gold standard*. We want to describe three types of gold standard systems that had been around in recent history: 1) the *gold coin standard*, 2) the *gold bullion standard* and 3) the *gold exchange standard*.

The gold coin standard is the most intuitive way to use gold as currency. In this monetary system, coins made from gold are used as the medium of exchange. A *formal* use of gold as a currency started in the 19^{th} and 20^{th} century. England was the first country to establish gold as their primary monetary unit in 1816. The US followed in 1873 with their "United States Coinage Act" which placed the nation's economy on a formal gold standard (*Commodity Trading Manual*

1997). This monetary systems are referred as *gold coin standard*, which simply means gold coins are the monetary unit used for transactions.

In 1922 the US modified the gold coin standard to a *gold bullion standard*. A more sophisticated monetary system which abandons gold coins for transactions and issues token coins and paper notes as a monetary unit. In other words, the money has a much lower intrinsic value than what it is denoted. Each monetary unit is backed by a fixed amount of gold, say 20 USD equals one ounce, which translates into $1/20^{th}$ of an ounce per USD. The central bank holds *gold reserves* in the form of bullion and issues as many token coins and banknotes as there is gold in their vaults to back it. So, the denoted nominal value of money is not necessarily fully backed by gold, in fact it merely guarantees full convertibility of money into gold bars (*Commodity Trading Manual* 1997).

Finally, there is the *gold exchange standard*, which is the most complicated of the three gold standards. In this monetary system, we are not only considering a domestic but an international monetary system with many participating nations. The most prominent example was the *Bretton-Woods System*, in which the USD was backed by gold through a gold bullion standard and all other currencies were pegged to the USD via a fixed exchange rate[1] (Iwami 1995, Kugler 2016). Exchange rates were allowed to fluctuate by not more than ±1% around the pegged rate. Only the US had to back its dollar with gold, while all other countries only needed to hold USD to back their currencies. The USD was therefore referred to as *reserve currency* and could be exchanged with gold for a fixed rate of 35 USD/ounce. Participating nations could exchange dollar notes for this given exchange rate with gold from the FED at any time. The *International Monetary Fund* (IMF) and an *International Bank for Reconstruction and Development* (IBRD) were established to overlook the functioning of the system and adherence to the rules by its members. Gold reserves dictated the money supply of USD which can only increase when gold reserves increase as well. Inflation can be efficiently controlled through this system; however, economic growth is hindered through limited money supply. The Bretton-Woods system was effective from 1952 to 1973. After the break down of the system, many countries decided to decouple their currency from the USD which lead to *free floating* exchange rates instead of fixed ones. The US decided to establish a *fiat currency* which is not backed by any commodity at all. The IMF and the IBRD (today known as the World Bank) still exist, however with different purposes.

[1] Pegged currencies include Japanese Yen, German Mark, Pound Sterling, French Franc, Italian Lira, Spanish Peseta, Dutch Guldier, Belgian Franc, Swiss Franc, Greece Drachma, Danish Krone, Finnish Markka, Norwegian Krone.

Even though gold does not back any currency these days, meaning that there is no gold stored in a vault which is dedicated to convert our money into gold, there is a more hidden role for gold in our current monetary system. Export and import activity of countries like China and US justify an interest to keep the exchange rate of domestic currencies in a certain range vis-a-vis other currencies. The value of a currency is determined on international foreign exchange markets in which the equilibrium of supply and demand pins down a price. Gold purchases/disposals can be used to regulate an exchange rate and therefore to stabilize a trade relationship. Another reason to hold gold is related to IMF Special Drawing Rights (SDR). The IMF requires countries to hold a minimum amount of gold reserves in order to have their currencies added to the SDR bucket, which eventually allows allocations of SDRs.

Gold as Insurance

Let us recall the difference between stocks and gold as financial assets. In a worst case-scenario, say a financial crisis, a stock, like Lehman Brothers, may lose its entire value when the company defaults. On the one hand gold never loses its entire value because it has an intrinsic value, and on the other hand gold is virtually uncorrelated with the stock market. Over the course of 50 years, stock returns are slightly negatively correlated with gold returns, having a correlation coefficient of $\rho(Gold, S\&P500) = -0.01\%$[2]. So, we may think of gold as an asset that pays out in bad states of the world and stocks as assets that pay out in good states of the world. Being an asset that pays out in bad states of the world offers an insurance against losses and can be used as a hedge. For this very reason, gold has a high value to risk-averse individuals who are about to enter a bad state - the opposite is true for the Lehman Brothers stock. Therefore, this justifies gold demand for investment purposes by private individuals, usually anti-cyclically done in gold bullion, coins or other financial gold products.

Gold in Politics

Table A.4 in the Appendix shows the gold reserves held per country as of 2018. These gold reserves are in fact central bank gold reserves. The United States holds more than 8,400 tonnes of gold in their vaults which is more than twice as much as Germany. Germany, Italy and France together

[2] Note we used daily S&P500 returns as a proxy for stock returns and the gold fixing price at 10:30 London time to compute $\rho(Gold, S\&P500)$.

hold roughly the same amount of gold as the United States. Russia and China also have one of the largest gold reserves taking rank 5 and 6. Noteworthy though, there seems to be a strong concentration of gold owned by Western governments.

China's reported gold reserves are not being trusted by politicians and investors, yet according to the IMF, China's gold reserves amount to 1,904.61 tonnes as of Nov 2018. Some professionals in the field of gold investing estimate China's gold reserves to be between 4,000 and 10,000 tonnes. For instance, Ross Norman, CEO of Sharps Pixley - a London based bullion broker - argues that China holds more than 4,000 tonnes of gold reserves. His argument is based on the estimations of China's gold production and the fact that none of that gold ever leaves the country. Another interesting fact is that compared to China's GPD, gold reserves of 1,904.61 tonnes make $\sim$0.7% which is way below the international average of 3%. China would have to hold more than 10,000 tonnes, to match the international average of 3% (Dominic Frisby 2018). By those estimates, China would be number one holder of gold reserves and outshine the US. Given China's huge trade deficit especially with the US, means that China holds vast amounts of USD in cash. Holding it and taking the risk of devaluation of the USD can be overcome by purchasing gold, which speaks in favor for much larger gold reserves than officially reported.

If it were true that China holds gold reserves somewhere between 4,000 - 10,000 tonnes, the country would play a leading role in the global monetary system soon. One step in this direction is the inclusion of the Chinese RMB as reserve currency to the SDR bucket since October 2016. Christine Lagarde said in July 2017 that the IMF headquarters could be based in Beijing already within the next decade because the fund has to increase the representation of growing economies (Reuters 2017). All of these considerations are speculative in nature, however, China has historically proven to plan carefully ahead into the future.

Gold in a Cultural Context

India and China are the world's top consumers of gold. Since 2010, those two countries increased their demand from 58% of global jewellery production to 66%. The main driver of this development is China which has increased its annual jewellery consumption from 492.7 to 743.0 tonnes in the same time period. At the same time, China and India have a population of $\sim$2.7bn which is roughly one third of the global population. In absolute terms it should not be surprising that gold demand from both countries is high - similar to the vehicle demand for instance - and in fact, in relative terms Chinese gold demand per capita (p.c.) is 0.7 grams and in India 0.6 grams for the year 2018. In comparison Germans purchase 1.3 grams p.c. in 2018. Accounting for income differences, Indians demand 0.280 grams per 1000$ GDP p.c., Chinese only 0.071 and Germans 0.027 grams.[3] Despite being a poor country compared to western standards, India seems to yearn for gold - even Indians themselves call it an obsession with gold (Miriam Jordan 1998). Two thirds of Indian gold demand originate from the rural areas, and due to poor banking services those people put their savings into gold which can easily be carried in times of floods and other environmental catastrophes and liquidated in times of financial distress. In other words, gold is the storage of wealth in areas with low trust in banks and poorly developed banking infrastructure. During the wedding season, gold demand rushes up because women receive a considerable amount of high carat gold from their own family as gifts (an average bride receives gold worth $2550). It should protect women from poverty when their husband dies or in case of divorce, and therefore it is seen as an investment for life (Atul Prakash 2007, Miriam Jordan 1998). Further purposes in Hindu rituals and spiritual roles of gold strengthen the cultural bonds with the shining metal. In Chinese culture gold symbolized good luck and it is used in garments of Buddhist monks. For weddings, gold holds a similar role for Chinese women as it does for Indian women, though, this time it is the husband who has to pay for generous gifts to his wife (The Economist 2019).

Both countries have religious bonds to gold, and for many occasions throughout the year, as well as life events like births or weddings, gold is bought for celebration. Apart from the cultural aspect, also the poor banking infrastructure in rural areas of both countries drive gold demand as a means to store value. In combination, the culturally embedded aspect of gold reinforces its financial role. As a matter of fact, this justifies gold jewellery demand.

2.2. The Global Gold Market

There is no clear consensus about the exact amount of gold that has been mined up until today due to the lack of precise historical documentation. According to the World Gold Council, there has been mined a total of 193,472 tonnes up until today (cf. Table A.1, World Gold Council (2019)). Put into perspective, the *monthly* global steel production in January 2019 amounted to 146.705 tonnes,

[3] GDP p.c. figures are taken from Statista for the year 2018, gold consumption figures are taken from World Gold Council which summarizes data from Metal Focus, Refinitiv GFMS, IMF WEO and own research.

which shows how little gold exits on earth (Worldsteel Association 2019). Due to its high density the amount of gold takes up relatively little space and thus we could fill 2.5 Olympic swimming pool with the entire gold stock existing above ground. At a spot price of \$1,298.18/troy ounce[4], all gold above ground has a value of ~7.9trn USD.

2.2.1. Supply

Gold supply comes from one primary source, namely mining, or from three secondary sources, namely recycling, producer hedging or public sector sales. Since 2010, governments around the globe are net purchasers of gold, and therefore there is no supply from that channel in recent years. Miners try to produce a steady amount of gold, which however depends to some degree on the probability of discovering a new gold source. Thus, the supply originating from mining cannot react immediately to changes in demand (due to economic shocks or price shocks). Recycling, however, can rather quickly react to demand changes and compensate for shortfalls in mining supply. Total gold supply has increased from 4,318.8 to 4,658.5 tonnes between 2010 and 2018. This development is driven by increased production through mining which overcompensates for a reduction in recycling supply in the same time period. Roughly speaking 75% of gold supply comes from mining and recycling makes up the remaining 25%, producer hedging only accounts for 0.2-2.5% (cf. Table A.3).

Mine Production

Mine production is different from secondary forms of supply in that gold produced from mining was not previously available for consumption in one or another form, which means that it is newly added to the above-ground stock of gold.

Starting from a high level, gold is produced in four steps: 1) prospecting, usually done by geologists identifying gold bearing soil, 2) mining, which is the process of extracting raw gold from deposits, 3) refining, which is where raw gold is purified to almost 100% pure gold, 4) final good production. In step 2) mining, there are two ways to mine gold which depend on the type of deposit: either lode deposits which ultimately is gold found in rocks also called gold-ore or placer deposits which is loose gold accumulated in sediments. Extracting gold from lode deposits, also called hard rock gold mining, requires the use of chemicals like cyanide, which are environmentally harmful.

[4]One troy ounce equals 31.10g

Schematically the "cyanidation" of gold ore works as follows: 1) gold ore rocks need to be finely ground to the size of beach sand, 2) a water-cyanide solution is added, and a mill further grinds the mixture to a mud-like pulp, 3) water and solid are separated, 4) air is blown into the remaining liquid so that the oxygen can set off a chemical reaction between cyanide and gold, 5) gold leaches into the surrounding water, 6) zinc powder solidifies the dissolved gold. Separating gold from placer deposits, called placer mining, is rather pedestrian and works as follows: 1) dig up sediments from a beach or creek, 2) grind rocks if needed, 3) generously add water to separate the heavier gold from lighter sediments. Most of the world's gold mining production comes from hard rock mining which is then more industrialized and systematic way of mining. In any case, after the gold has been extracted by one of the two methods, it needs to be refined by a certified refinery to meet the quality standards for investment grade bullion and coins. These refineries must be listed on the Good Delivery List by the London Bullion Market Association (LBMA)(O'Connor et al. 2015).

We find gold mines on every continent on earth except for Antarctica. Global gold mining production has increased from 2,748.5t to 3502.6t between 2010 and 2018. China, Australia, Russia, USA, Canada, Peru, and South Africa are the world's largest producers of gold. South Africa, being the world's largest producer in 1980 with 675 tonnes annually, has decreased its output to 129.8 tonnes in 2018. China had produced only 112 tonnes annually in 1992 and increased its output to 404.1 tonnes in 2018, which makes China the largest producer of gold today. In the last decade, gold mining supply has seen dramatic shifts. While traditional players like the US struggle to keep their production stable at around 230 tonnes, Canada has ramped up their output by 90% from 102.1 to 189.0 tonnes annually. Similarly, in Africa, while South Africa decreased output by 40%, Ghana had increased it by 40% at the same time. Also, Russia has increased their production by 50% from 203.1 to 297.3 tonnes (cf. Table A.6).

Recycling

Recycled gold originates from disposed final goods like jewellery or circuit boards in laptops or cell phones, etc. Therefore, this type of gold supply does not increase the above gold stock but is circulated back to the refining process of gold production. It is being melt and processed into gold bullion of a certain quality standard by one of the certified Good Delivery refineries. It is considerably easy to re-refine gold processed to jewellery because the *recycling-input-rate* (RIR)[5] is

[5]The RIR is the ratio of $\frac{\text{Metal Recycled}}{\text{End-of-Life Product}}$, the RIR is also known as Recycled Content(Graedel et al. 2011).

much higher than with electronics. Since gold is hard to recycle from electronics, a fair amount of gold is being lost permanently(O'Connor et al. 2015). Roughly 90% of recycled gold supply is made from jewellery and the remaining 10% stems from the technology sector.

Producer Hedging

Mining companies are interested in reducing their risk exposure to price fluctuations, which in part depend on the supply of gold. Futures contracts provide a hedge against market risk by locking in a fixed price today for settlement of the position in the future and thereby reducing risk exposure to future cash flows and expected equity returns(Chung 2003). The literature suggests that producer hedging increases physical gold supply, which is not *entirely* true, at least not until the contract is settled and gold is delivered. So, it is more of a commitment on the part of the mining company to produce the contractually stipulated quantity, which it has sold forward for a fixed price. To make this point clear: if the mining company was not agreeing upon a price, say 9 months ahead of now, and it is producing at costs close to breakeven, then it might run the risk of becoming unprofitable due to price fluctuations and would shut down operations – which ultimately reduces gold supply in the future (O'Connor et al. 2015).

2.2.2. Demand

Gold serves a number of purposes which include, jewellery, investment, public sector or technology. Jewellery accounts for 51%, investment for 26%, public sector for 15% and industry demand for 8% (cf. Table A.2). Demand from each of those four categories originates from different motives depending on the consumer group.

Jewellery in developed countries is a discretionary good with a high price elasticity, which means it is bought from excess income and serves as a luxury good. In developing countries in contrast, jewellery rather serves the purpose to store precautionary savings due to under developed credit and financial markets, also due to the lack of investment alternatives in these countries. Additionally, jewellery can be worn and enjoyed during economic well-being and liquidated in times of financial distress. In any case, jewellery demand is physical gold demand(Starr & Trand 2007).

In contrast to that, there exist non-physical investments which securitize gold to a financial product. Most prominently was the introduction of Gold Exchange Traded Funds (ETF), which were initially issued in 2003 by the World Gold Council. The Gold Buillion Securities ETF marked a turning point for investors, because gold was easily accessible also in small amounts and without imposing any storage costs. Also, they allowed speculation on gold more easily without taking the risk of a forward contract. According to Ivanov (2013) ETFs have changed the role of price discovery and by replacing gold futures as the leading price discovery product. However, there exists also physical investment demand in the form of gold bullion or coins. Bullions are bars available in various sizes from a few grams to 13.4kg bars, called Good Delivery bars[6]. There is a vast variety of coins available, of which the South African Krueger Rand the American Eagle, the Canadian Maple Leaf and the Australian Kangaroo represent the most famous examples. In addition to the nominal value a coin, it is an official means of payment and the owner may benefit from a collectors' value. Both facts may change the motive to purchase coins instead of bullion.

Central banks around the world are net purchasers of gold having bought 656.9 tonnes in 2018, a record amount since 2010. They buy gold in bars and use them as a monetary reserve even though we are not in a gold standard monetary system anymore. Strategic implications of central bank gold purchases are discussed in section 2.1 above. Apart from central banks, also other public institutions like the IMF purchased gold historically, though, these days they sell off their gold reserves to serve their income model from April 2008 [7].

Despite of being an investment good, gold serves also some limited purposes in industrial applications like electronics and dentistry. Due to its high price, both industries have put effort in the development of alternative materials. In dentistry gold is more and more replaced by ceramics or sophisticated plastics which has led demand to decrease by 66% since 2010. In electronics gold was mostly used for circuit boards or bonding wires, both have been reduced to a minimum use and replaced where possible with copper or other materials, which has ultimately decreased demand by 18% since 2010, in total 334.8 tonnes are used in industrial applications.

Recent demand trends show that Asia consumes 66.5% of global jewellery production of which China and India are the largest markets. In total 2,241.8 tonnes have been produced in 2018. Interestingly, there has been historically a move of gold to Asia which may be due to sociocultural habits in Asian countries (Bernstein 2006).

Investments in bars and coins has tripled between 2006 and 2013 which is also when demand

[6] http://www.lbma.org.uk/gdl-gold-bar-specifications

[7] https://www.imf.org/en/About/Factsheets/Sheets/2016/08/01/14/42/Gold-in-the-IMF

peaked at 1730.4 tonnes. Much of this demand came from Asian investors, and some of the European investors in the aftermath of the global financial crisis. In 2013 there was a large sell off of gold ETFs and one year later, in 2014, demand dropped to 1066.1 tonnes and has remained there since then (O'Connor et al. 2015). After the third quantitative easing program investors had learned that increased money supply does not shoot up inflation, which may have been a reason for the divestment wave during that time. In total private investment (bars and coins + ETFs) amounted to 1,165.3 tonnes in 2018.

2.2.3. Trading venues

The main gold trading venues are: the London Bullion Market (LBM), the Commodity Exchange (COMEX), the Shanghai Futures Exchange (SHFE), the Shanghai Gold Exchange (SGE), the Tokyo Commodity Exchange (TOCOM), the Multi Commodity Exchange of India (MCX). Since LBM, which is an OTC market, is publishing data rarely, it is difficult to make comparisons. Table A.7 in the Appendix shows trading volumes of the 4 main gold markets, using the latest data available (November 2018). Table A.8 in the Appendix shows a more accurate overview, excluding LBM. These numbers suggest that more than 2,000 tonnes of gold are traded globally each day. To put this into perspective, only about 3,400 tonnes of gold is mined globally each year.[8]. We observe that the two largest trading venues (COMEX and LBM) make roughly 80% of the global gold market trading volume. COMEX trades primarily futures, while LBM is mainly focused on spot transaction. Nevertheless, none of them trades large amounts of physical gold. In fact, the first global physical gold market is the SGE, which starting from 2014 opened an international division (SGEI) to attract foreign investors.

Through COMEX the most liquid gold futures contract (with ticker symbol "GC" and denoted in USD) is traded. Another type of gold futures contract (with ticker symbol "AU" and denoted in RMB) is offered by the SHFE. The AU contract is also traded on the Dubai Gold & Commodity Exchange (here denoted in USD). Also, the TOCOM offers a gold futures contract (with ticker symbol "JGA" and denoted in JPY). These 3 futures (GC, AU, JGA) are 3 different contracts, which means different trading hours, different gold bars specification, different settlements and different delivery processes. However, intuitively, gold is always gold and their prices should (and

[8]https://www.bullionstar.com/blogs/ronan-manly/lbma-trading-volume-data-confirms-the-paper-gold-casino-in-london/

they indeed do) move in lockstep.

On a side note, one of the easiest ways to invest in gold is to take a position in a gold Exchange-Traded Fund. The dominant gold ETF is SPDR Gold Shares (ticker "GLD"), launched by State Street Global Advisors in 2004 and now traded on several exchanges. SPDR Gold Shares invests in physical gold and its market price is often used as a proxy of spot gold price.

2.3. The London Bullion Market

In the last 3 centuries the London Bullion Market (LBM) has developed as the world center of gold trade. Only recently COMEX surpassed LBM in terms of trading volumes. Other than gold, the LBM also trades silver, platinum and palladium.

In 1984 the Bank of England established the London Bullion Market Association (LBMA) as an umbrella association for the LBM. Among other things, the LBMA sets the characteristics of "London Good Delivery" gold bars and maintains a "Good Delivery List" of approved refineries meeting LBMA standards. As of May 2019, The LBMA has 145 members: 86 full members (of which 12 are market makers), 56 associates and 3 exchange affiliates[9]. In practice, the London gold market is a decentralized OTC market spinning around the 12 market-making banks, each of them offering bids and asks for different products (spot, forwards and options). The other non market-making bullion banks are not required to offer two-side quotes at any point.

The LBM is not to be confused with the London Metal Exchange (LME), which is a London-based exchange that launched a gold futures contract in 2017. As earlier mentioned, the LBM is predominantly a spot market, with 63% of transactions being spot trades. However, this does not mean that the LBM is predominantly a physical gold market as well. We now put aside derivatives and focus on spot transactions.

2.3.1. Unallocated and Allocated Gold

Market participants interested in taking a position in spot gold need to set up an account with a bullion bank. Bullion accounts allow customers to buy allocated or unallocated gold.

Allocated gold is actual physical gold, meaning that the customer becomes the owner of specific bars and at the same time enters a storage agreement with the bank, which becomes the custodian

[9] http://www.lbma.org.uk/current-membership

of the bars. In the remote case of bankruptcy, the creditors of the bank cannot access the customer's allocated gold, since it is not part of the bank's assets. Allocated gold transactions represent only a small part of the London OTC gold market.

More common are unallocated gold transactions, in which the customer enters an agreement with the bullion bank, paying cash and receiving a claim of unallocated gold. The term *unallocated* here means that the customer does not own any specific gold bars, but they have a general entitlement of an amount of metal. This happens in the form of an unallocated account. However, the customer may at any point in time ask and have their unallocated gold converted in allocated gold. This whole set up results in the bullion banking system not being fully backed by physical gold, but only fractionally backed, since banks are under no obligation of physically owning the amount of metal their customers have on their unallocated accounts. Owners of unallocated gold are unsecured creditors of the bank, and in the remote case of bankruptcy, they are treated accordingly.

A relevant difference between the two types of bullion accounts is that the allocated account requires the customer to periodically pay a *storage* fee, while the unallocated account requires a smaller *maintenance* fee.

All the bullion banks and the unallocated accounts of their clients are connected to each other through a central clearing system: AURUM. AURUM is a platform maintained by London Precious Metal Clearing Limited (LPMCL), a private company owned and managed by 5 major bullion banks[10].

2.3.2. The Fixing Process

The London Gold Fix, also known as the *fixing process*, was originally set up in 1919, to provide a benchmark price for gold that isolated market participants from the noise of the OTC trading day. Five gold bullion traders and refiners,[11] encouraged by the Bank of England, established a free gold market which would produce an official price on any single day. For the first few days, the auction was made by telephone, but it was then decided to proceed with daily formal meetings in the London office of NM Rothschild & Sons Limited. The London Gold Fix was only interrupted during the war in 1939 and reopened later in 1954.

The London Fix consists of a Walrasian auction every morning at 10:30 [London time], with

[10]HSBC, JP Morgan, Scotiabank, UBS, and ICBC Standard Bank
[11]NM Rothschild & Sons, Mocatta & Goldsmid, Pixley & Abell, Samuel Montagu & Co. and Sharps Wilkins

each of the 5 members gathering and channeling all the orders of their traders and clients in the process. The chair starts by announcing a price close to what is believed as the current spot price, the price is then raised if bids exceed asks or decreased if asks exceed bids, until they come into equilibrium and the price is finally fixed.

In 1968 an additional afternoon fix was introduced at 15:00 to benefit the New York market. In 1994 the 5 current members of the fixing founded the London Gold Market Fixing Limited (LGMFL) to better administrate the process. In 2004 NM Rothschilds, the last original member, sold its seat to Barclays, and the fixing procedure was switched to a telephone conference call. Continuously from 2004 to 2013, LGMFL was owned by the 5 new fixing members,[12] which later were accused of manipulating the process.

The Gold Fix Price became more and more important since many types of spot transactions are now explicitly tied to it, with parties agreeing to use the next Gold Fix Price. Additionally, the Fix governs unallocated gold accounts. Furthermore, many derivatives have their cash flow calculated using the Fix Price as settlement reference.

Starting from 2012, rumors and formal investigations regarding the LIBOR and FX manipulation started spreading, which brought attention also to the other benchmark rates. In November 2013, the German financial authority BaFin confirmed to investigate possible manipulation of the Gold Fix by Deutsche Bank. The German bank later tried to sell its seat in the auction and, after failing to do so, voluntarily resigned from it in May 2014, leaving the Fix with 4 members only.

In November 2014, as a result of the controversies around the London Gold Fix, the LBMA appointed ICE Benchmark Administrator (IBA) as a third-party administrator of the process. In March 2015, the historic London Gold Fix Price was discontinued and replaced by the new "LBMA Gold Price", determined in a Walrasian auction occurring on an electronic trading platform developed and maintained by IBA. Like before, the LBMA Gold Price is fixed twice a day at 10:30 and 15:00. The price is set in USD. The auction now involves 16 members, while earlier only 5. The main 3 Chinese banks are now part of the auction as well. The average volumes traded in the IBA auction are now almost double of those traded before in the London Gold Fix auction (170k vs 93k) [13].

[12] The Bank of Nova Scotia, Barclays, Deutsche Bank, HSBC and Société Générale

[13] https://www.theice.com/article/iba-lbma-gold-price

2.3.3. Manipulation of the Fixing

In the last few years, the fixing members were repeatedly accused of manipulating gold prices through the fixing process. We now summarize the two most famous episodes: a regulatory fine and a class action. The first is the only confirmed episode of manipulation to date. As for the second, the lawsuit is still ongoing.

Barclays Fined by FCA

In May 2014, the Financial Conduct Authority (FCA) fined Barclays for £26m FCA (2014*b*), because one of its traders (Daniel Plunkett) manipulated the Gold Fix Price on the 28^{th} Jun 2012. Mr Plunkett, Director of Barclays' Precious Metals Desk, 12 months before sold to a client a digital call option with a barrier at 1,558.96 USD. Digital options have binary payoff and Plunkett's desk would have lost £2.3m if the PM Fix Price would have been above the barrier on the 28^{th} Jun 2012. Figure 2.1 shows the gold price movements on that day. When London opened, the gold price was 17 dollars above the barrier. The PM Fix started as usual at 10:00 [New York Time]. FCA provides a detailed explanation of the events FCA (2014*a*), stating that Mr Plunkett initially placed a large sell order with Barclays' Gold Fix representative at 10:06, trying to drive the price below the barrier. He later withdrew the order at 10:07, confident that the Fix was going to be below the barrier anyways. However, when the auction price rose again, Mr Plunkett decided to put in another sell order at 10:09. This time he did not cancel it and the price was ultimately fixed at 1,558.50 USD at 10:10.

Mr Plunkett's client however, found the sudden drop of prices suspicious and sought explanations from Barclays. The British bank launched an investigation, suspended Mr Plunkett and reported its findings to the FCA. The authority banned Mr Plunkett from working in the financial industry and fined him for £96k. More importantly, the FCA decided to fine Barclays as well because of the poor system of controls the British bank put in place when first joined the London Gold Fix in 2004. The authority did not launch a broader investigation towards other fixing panel members.

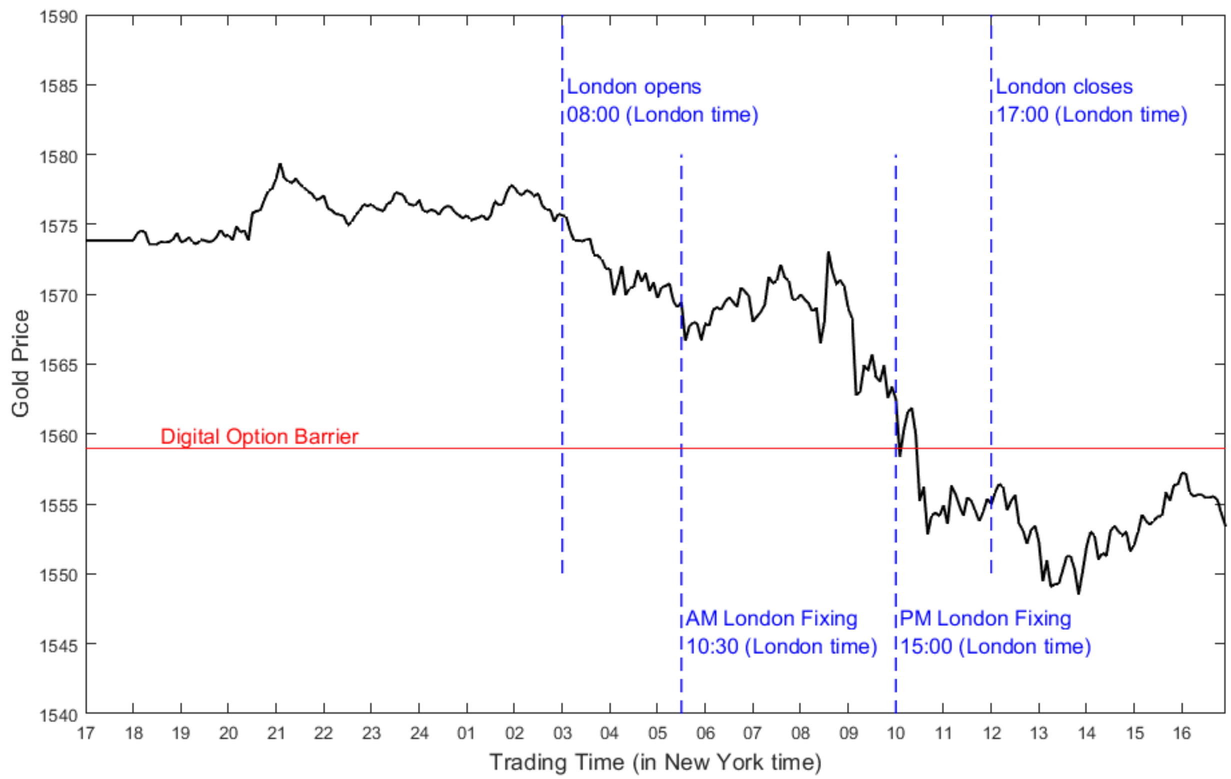


Figure 2.1. Barclays Manipulation Case
The figure shows gold prices between 17:00 of 27^{th} Jun 2012 and 17:00 of 28^{th} Jun 2012. In particular the PM Fix starts at 10:00 and ends at 10:10. Prices shown in this Figure are of COMEX Gold Futures, and are derived shortly in Chapter 3. For a more zoomed in analysis refer to Nanex Research (2014).

Class Action

The five fixing banks (plus UBS) were accused of manipulating the London Gold Fix in a New York based Class Action[14] against them. Case documentation is publicly available Court Listener (n.d.). A similar Class Action[15] was open for Silver Fixing as well. The plaintiffs claimed that the anachronistic gold fixing meetings represented for the banks “a ready-made process” for collusion. In particular they pointed out that the six banks jointly drove gold prices downwards around the PM Fix, “first by moving the spot and futures markets for gold in advance and even during the auction”. The Bank Defendants reportedly profited from the manipulation because they were holders of massive short positions in the derivatives market. Deutsche Bank settled with the plaintiffs for $60m in December 2016 Reuters (2016*a*), before the beginning of any litigation. In October 2016

[14]Case No. 14-MD-2548 (VEC)
[15]Case No. 14-MD-2573 (VEC)

Judge Valerie Caproni dismissed entirely UBS but granted *some* of the plaintiffs' claims against the other four banks to move forward to the litigation phase Reuters (2016*b*). To date, the case continues.

2.4. The COMEX Gold Market

In this section we describe the Commodity Exchange (COMEX), division of the Chicago Mercantile Exchange (CME) group, focused on precious metals (gold, silver, platinum and palladium). COMEX represents the first world gold trading venue in terms of volumes. COMEX is an exchange, meaning that its products are highly standardized, and consist solely of futures and options. We now provide a brief explanation of both and then turn our attention to the futures delivery process, which represents the link between gold futures and physical gold.

The COMEX gold contracts are traded 23 hours a day, 5 days a week, on the CME Globex electronic trading platform. Trade is suspended in the maintenance period between 17:00 and 18:00 in week days, and between 17:00 on Friday and 18:00 on Sunday in weekends [New York time]. Gold futures and options used to be traded in the COMEX open outcry as well, however due to low trading volumes (less than 1% of total volumes), CME recently removed all its futures and options from the traditional trading pits[16].

2.4.1. Gold Options

Options are the right but not the obligation to buy or sell a certain quantity and quality of an underlying asset in a certain time in the future, T at an agreed-upon strike price, K. Since options ensure an always non-negative pay-off, the buyer pays a premium to the seller when acquiring the option. A call option gives the right to buy. A put option gives the right to sell.

Interestingly, the underlying asset of the COMEX gold options is not physical gold, but COMEX gold futures. COMEX options are American, giving the opportunity to exercise at any point in time before maturity.

[16]Futures stopped trading in open outcry in July 2015 and options stopped in February 2016

2.4.2. Gold Futures

Forwards and futures are agreements made in time t to deliver a certain quantity and quality of an underlying asset in a certain time in the future T at an agreed-upon price $F_{t,T}$. A long (buy) position is an obligation to accept delivery and pay the price, a short (sell) position is an obligation to make delivery and receive the price. Forwards and futures are different because, while the first have no cash exchange until delivery, the latter are marked-to-market, meaning that the net present value of each position is paid out every day at the end of the day. Other than this, futures are exchange traded, meaning that they are more standardized and have virtually no counterparty risk.

The COMEX gold futures (ticker symbol "GC") are one of the most traded futures contracts and the second most traded commodity futures in the world, with 33 million USD traded on average every day, following the 69 millions of crude oil CME (n.d. *d*)(Q4 2018 data).

Not all maturities can be traded. Between 72 and 24 months, only June and December contracts are traded. Between 23 and 4 months, only February, April, June, August, October and December contracts are traded. Between 1 and 3 months all contracts are traded.

GC futures are daily settled every day at 13:30 [New York time] using the current futures price. Trading terminates at 13:30 on the third last business day of the contract month. Interestingly, COMEX gold futures do not use a spot gold price fixing (e.g. the London Gold Fix Price) for their final settlement. In fact, the CME group determines the final settlement of the expiring GC futures from the Volume-Weighted Average Price (VWAP) of the GC futures itself in the settlement period (13:15-13:30), in accordance with CME rules CME (n.d. *c*). This has the fascinating implication that COMEX gold futures do not derive their prices from the price of the underlying physical gold. Perversely, since the GC futures play such a key role in terms of price discovery, one may almost say that it is the other way around. At any rate, the COMEX gold futures are of course to some extent related to physical gold, as explained shortly.

2.4.3. The Delivery Process of Futures

The delivery process is the mechanism of transformation of gold futures into physical gold. This process is what ensures a convergence between futures and spot prices. The procedure here outlined is described in the CME Rulebook CME (n.d. *a*) and applies solely to GC futures, however similar procedures apply to futures of TOCOM and SHFE.

Refineries produce gold bars to the standard and specification of the exchange where the gold futures is traded. COMEX futures require gold bars to be in the 100 ounces format with a minimum fineness of 99.5%. Once these exchange-approved refineries have produced the exchange-approved gold bars, these are transported to an exchange-approved warehouse by an exchange-approved carrier. Once the gold bars are in one of these warehouses, they can be moved to another exchange-approved warehouse only using the same exchange-approved carriers. In practice, only a few reputable refineries, carriers and warehouses are trusted and therefore approved by the exchange. The overall process ensures the integrity of the gold. If gold bars are ever removed by an investor from this "chain of integrity", they cannot enter again unless the process mentioned above is re-started from the beginning.

Gold bars are sold by refineries to investors and then held in warehouses. Whoever owns warehouses-held gold bars must pay storage cost to the warehouse. Gold bars in these warehouses are "eligible" for settlement of gold futures contracts. This means that the owner of the bars may choose to give up the control of the gold bars (i.e. the power of choosing how to move around the gold bars) and "register" them with the exchange, a process referred to as placing the metal on "warrant". A warrant is an electronic legal document of ownership. Eligible gold bars may or may not ever be registered. In fact, an owner may not be interested in using their gold for settlement of futures contracts: they may simply want to store their precious metal securely in the warehouse. In this case, they would prefer not to give up the control of the gold bars.

Warrants are used as the means of delivery in COMEX futures contracts, meaning that in case of delivery, the physical gold will change ownership without being physically moved around. Thus, a trader with a long position in a gold futures standing for delivery, rather than cash payment, will take delivery of the warrant at settlement. The gold to which the warrant is referred will remain in the same exchange-approved warehouse and will remain registered. Once the trader receives the warrant he may keep it or break it. In the latter case he will de-register the gold. Once the gold is de-registered, the trader may keep the gold in the circle of integrity (in the same or a different exchange-approved warehouse) or break the circle and vault the gold bars somewhere else.

The holder of a short position in the futures starts the delivery process by formally issuing a "notice of intention to deliver" to the exchange. This can be issued on any business day of the contract month. The exchange will then assign that notice to a holder of a long position. The selected warrant will be transferred after two business days. The settlement price is set by the exchange at 13:15-13:30 on the day the notice of intent is issued.

Only a very small fraction of futures contracts is physically settled, the great majority is closed by taking an offsetting position or by being rolled over onto the next month. Data on contracts delivered and on gold stocks (registered or eligible) is available on CME website CME (n.d.*b*). Interestingly, the exchange reports are only very recent data, and overwrites the new data each time new figures are available.

Undoubtedly, registered gold represents only a small fraction of long positions in GC futures, meaning that if those positions would all want to take delivery at the same time, they could not. Nevertheless, eligible gold stocks could be quickly registered in case of shortages and therefore the integrity of the system preserved.

Chapter 3

Data

In the current chapter we present the data used in the different analyses of the thesis. We rely on two different types of data: Gold data, used in Chapter 4, 5, 6 and 7, and Macro data, used exclusively in Chapter 6.

3.1. Gold Data

In the current section we present the main 2 data sets used in the thesis: quotes data and trades data of the COMEX gold futures (ticker symbol "GC"). Data source is DataScope, [1] a Reuters service.

Among different maturities we consider only GC1 and GC2, these are the contracts with settlement at the end of current and following month respectively. At the and of each month GC2 rolls over onto the new month and becomes GC1. For our purposes, we download quotes and trades of both GC1 and GC2 from DataScope. The heart of our thesis is based on crafting and analysing these high frequency data sets. Main variables in the quotes data set are bids and asks. Main variables in the trades data set are trading prices and trading volumes.

When it comes to prices, we prefer mid prices (constructed as averages of bids and asks) over trading prices because of more data availability. This is due to a very practical reason: a seller asks for a price and buyer bids for a lower price. Only when both, the bid and the ask, are same, a trade takes place and a trading price is recorded. Therefore we disregard trading prices and use mid prices instead. At each point in time we construct mid prices only considering bids and asks of the most liquid contract between GC1 and GC2, and we disregard those of the less liquid contract.

When it comes to volumes, we extract these from the trades data, which is the only purpose we use this data for. From now on, when we consider volumes, we always intend the sum of the GC1

[1] https://hosted.datascope.reuters.com/DataScope/

and GC2 contracts traded, regardless of which of the two is the most liquid.

3.1.1. Why COMEX Gold Futures

When looking for high frequency data of gold prices, the GC futures is the obvious choice. In fact, as outlined in Chapter 2, the two biggest gold markets - Chicago and London - make 80% of the world gold trading volumes. While COMEX is a exchange, where quotes and trades are publicly available, London is a OTC market and therefore it has no publicly available data[2]. Moreover GC futures are traded 23 hours a day for 5 days a week on the CME Globex electronic trading platform. These reasons make the GC futures contract a benchmark in the gold market.

It could be argued that prices of gold futures are different than the spot price of gold. This is true. However gold futures curves are not particularly steep, and since we are considering only futures with short maturities, we shouldn't expect big differences. When comparing the prices of GC1 and GC2 to the AM London (spot) Gold Fix Price, these appear very similar. In fact, using our data, correlation between mid-prices of GC futures (at 5:30am, New York time) and AM London Fix Prices (i.e. 5:30am, New York time as well) is 99.997%. As for daily returns, these have correlation of 92.281%.

All in all, we argue that, when it comes to analysing the behaviour of gold prices around the clock, the closest maturities of the GC futures offer the best proxy for gold prices in general. Our second choice would be using high frequency quotes of SPDR Gold Shares, which tracks spot gold, however its volumes and liquidity are way smaller than GC futures, and therefore we focus on the latter.

3.1.2. Reducing Frequency

The 2 data sets have the advantage and the complication of storing information with tick-by-tick granularity, meaning that e.g. in some 1 minute intervals we may have more that 100 quotes and in some we may have nothing. This creates the necessity of changing the structure of the data.

In order to do so, we use the same approach used in Krohn et al. (2019): we reduce the frequency of the data to intervals of 5 minutes, and then aim to build 3 matrices (one for bids, one for asks, and one for volumes)[3] with size of $D \times 288$. 288 is the number of 5 minutes intervals in a 24 hours

[2]Except for the two daily Gold Fix Prices

[3]We actually build a forth matrix with dates and time to keep track of the observations

day. D is the number of days in the sample period. The sample period that we use for the analysis goes from 1^{st} Jan 2001 to 31^{st} Dec 2018. We didn't select a longer data sample due to scarce frequency of observations in years before 2001.

As for bids/asks, for each 5 minutes interval [4] we select the first bid/ask in that interval, and we neglect all the other information. As for volumes, for each 5 minutes interval we select the sum of (GC1 and GC2) contracts traded in that interval. Once we reduced the frequency in this manner, we have 3 long vectors in 5 minutes frequency. From here we proceed as follows:

(*i*) Reshape vectors into matrices, after doing this, matrices size is 6574×288.

(*ii*) Change the time of the data from GMT to New York time[5].

(*iii*) Reshape matrices so that the first column contains values at 17:00 and the last contains values at 16:55 of the next day. We do this so that each row has 23 hours in which the GC futures is continuously traded. After this transformation matrices size is 6573×288.

(*iv*) Drop weekends and US public holidays[6]. These are rows in which GC futures are not traded. After this transformation matrices size is 4528×288.

(*v*) Fill empty intervals. As for bids and asks, we fill with previous values available. As for volumes, we fill with zeros.

We are aware of the fact that we introduce a sampling error by filling gaps, yet dropping entire days from our data set would reduce information to a greater extent than the introduced error is distorting them.

We could now technically proceed with the core of the analysis. However, there are several outliers that need to be cleaned first. In the following sections we explain how we detect and clean outliers in quotes and volumes.

[4] e.g. 3^{rd} Feb 2001, 10:15-10:20, that we denote as 3^{rd} Feb 2001, 10:15

[5] Matlab automatically accounts for daylight savings when using the "*datetime*" function to redefine time zones.

[6] Matlab automatically detects holidays and non trading days when using the function "*holidays*"

3.1.3. Cleaning Quotes

This section focuses on cleaning bid and ask outliers, coming from quotes data. Since in Chapter 4 and 5 we are plotting averages of returns around the clock, our results may be greatly affected by outliers.

Figures B.4 and B.5 in the Appendix provide two time series examples of how bids and asks look like before (top panels) and after (bottom panels) filling gaps and removing outliers. These two figures are zoomed subsections of the whole sample period. In particular, Figure B.4 provides a early sample example and Figure B.5 provides a late sample example. Observing top panels of the two figures gives an immediate understanding of the two problems of the data: (*i*) gaps and (*ii*) wrong observations.

As for (*i*), we can observe that the early parts of the full sample are more often characterized by gaps than late parts of the sample. As explained before, our solution to missing bids/asks is forward filling. The effect of this solution is more evident in the bottom panel of Figure B.4.

As for (*ii*), we can observe that both early and late parts of the sample are characterized by massive spikes. This suggests some data quality problem. These observations are clearly wrong information and therefore should be considered as outliers and corrected. The two bottom panels in the figures show the effect of our cleaning procedure: all the biggest and most unreasonable spikes are gone, all the small and most reasonable spikes stay. In order to obtain this result we had to set specific cleaning rules. These cleaning rules are applied both to the bid and to the ask time series individually. In setting these cleaning rules we were conservative. In fact, we know that in some specific times of the 24 hour day prices behaviour can be hectic and therefore we have been cautious of not correcting non-wrong data. The cleaning rules are meant to correct quotes when they rise/dive too much or when they rise/dive and then immediately come back to the previous level. These rules are:

- if a quote is 10% greater than previous quote, use previous quote instead.
- if a quote is 10% smaller than previous quote, use previous quote instead.
- if a quote is 4% greater than previous and next quote, use previous quote instead.
- if a quote is 4% smaller than previous and next quote, use previous quote instead.
- if a quote is 7% greater than previous and than the quote after the next, use previous quote.

- if a quote is 7% smaller than previous and than the quote after the next, use previous quote.

The above rules together considered correct 0.11% of bids and 0.10% of asks.

Once bids and asks are individually cleaned, we can compare them to each other and apply two additional cleaning rules:

- If in a specific interval the ask is smaller than the bid, set both the ask and the bid equal to their average. This rule corrects 2.19% of quotes.
- If in a specific interval ask is 2% greater than previous ask and bid is 2% smaller than previous bid, use previous ask and bid instead. This rule corrects 0.01% of quotes.

From clean bid and ask time series, we obtain a mid prices time series as their average. These mid prices are the prices from which we will compute returns and returns' volatility in Chapter 4.

Also, once bids and asks are clean, we can compute their spreads. However, when observing these spreads, they don't seem to be outliers-free. In Figure B.6 in the Appendix we show average daily relative[7] spreads (top panel), average monthly relative spreads (mid panel), and average yearly relative spreads (bottom panel). From the top panel we can notice a few isolated spikes, suggesting that our cleaning procedures employed so far were not enough to correct all the wrong observations in the data. Since we need to use spreads for the purposes of the thesis[8], we impose one additional cleaning rule:

- individual spreads greater than 1% of mid prices, are set to 1% of mid prices instead.

The above assumption makes economically sense considering that *before* imposing it, the average relative spreads in the full sample was 0.144%. The above assumption makes also statistical sense, since corrects only 2.1% of spreads, of which, many were generated by forward filling. Figure B.6 shows average relative spreads before and after imposing this cleaning rule.

[7] i.e. as % of current mid prices

[8] We use spreads in Chapter 4 to analyse liquidity around the clock and in Chapter 7 to incorporate transaction costs in the backtesting of active trading strategies

3.1.4. Cleaning Volumes

This short section focuses on cleaning outliers of volume observations, coming from trades data. Since in Chapter 4 we are plotting averages of trading volumes around the clock, our results may be greatly affected by outliers. Therefore after obtaining the volume matrix, as described in 3.1.2, we set the following cleaning rule:

- each interval with volume greater than 10,000 contracts, is set to 10,000 instead.

This cleaning rule corrects 0.03% of observations.

3.1.5. Data Properties

Among other things, we notice a decreasing pattern in the average spreads over time. This is most likely driven by the increase in trading activity: more bids and asks, and therefore more trading volumes. Figure 3.1 shows that in the early part of the sample average relative spreads were higher and contracts traded were less, with respect to the late part of the sample. These are properties of the data we should be aware of moving forward with our analyses.

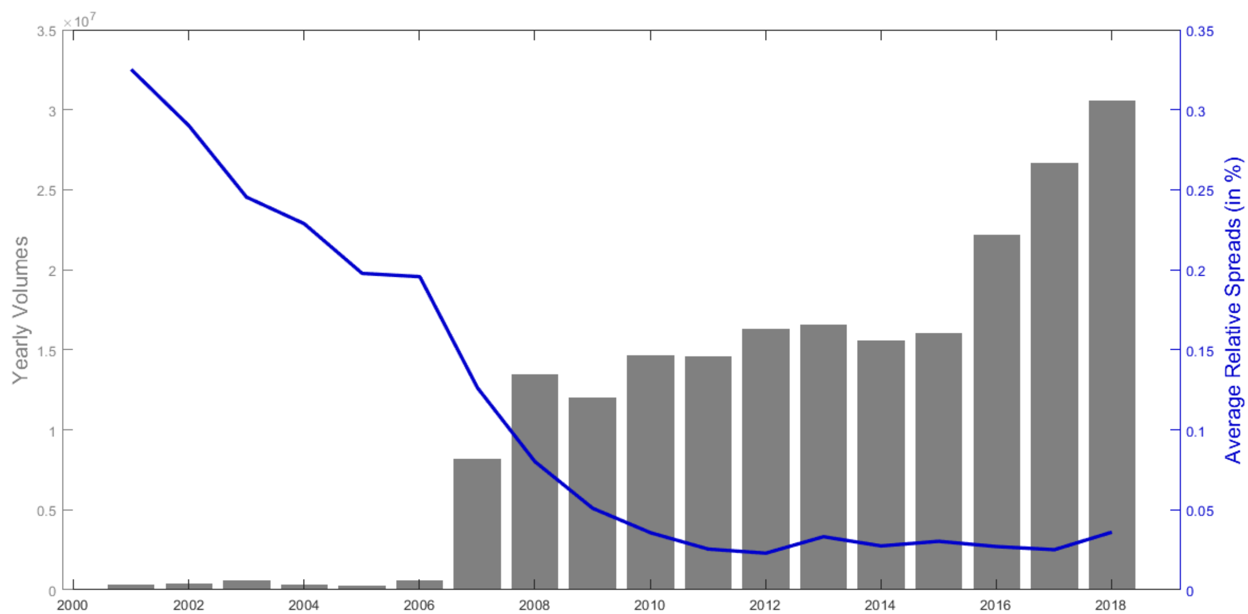


Figure 3.1. Volumes and Spreads, Year by Year
The figure shows, for each year, total contracts traded and average of relative spreads.

3.2. Macro Data

To analyse the relationship between gold returns and macroeconomic variables, we source corresponding data from FRED database provided by the Federal Reserve Bank of St. Louis and data provided by OECD website. In total we consider 48 macroeconomic variables which can be categorized into (*i*) Foreign Exchange (FX), (*ii*) Consumer Price Index (CPI), (*iii*) Real GDP Growth, (*iv*) Unemployment Rates, (*v*) LIBOR Interest Rates, (*vi*) Real Estate Investment (REI) and (*vii*) Crude Oil Price (Brent). We extract all variables from January 2001 to December 2018 in monthly frequeny (CPI, Real GDP Growth, Unemployment) or in daily frequency (FX, LIBOR rates, REI, Brent). For a detailed list of variables, we refer to Table A.9 in the Appendix.

Also, we do a number of transformations to the data. In Chapter 6 we relate gold returns to macroeconomic variables. To do so we use quarterly gold returns obtained from aggregating daily log returns by summing them up. We also need to construct quarterly percentage changes for both, daily and monthly data. For daily data, we take the log-difference between the last observation of the quarter and the first observation of the quarter: $r_t^q = ln(x_t^{loq}) - ln(x_t^{foq})$, where x_t^{loq} stands for *last-of-quarter* value and x_t^{foq} for *first-of-quarter* value at quarter t. We do this transformation for FX, LIBOR rates, REI and Brent. For monthly data, we take the log difference of values between end of quarter t and end of quarter $t-1$: $r_t^q = ln(x_t^{loq}) - ln(x_{t-1}^{loq})$. Variables we transform by this are CPI data. Quarterly real GDP Growth data is provided by OECD and must not be transformed at all. Important to mention is, that we are using two different measures for GDP growth, one is GDP growth in terms of percentage changes from quarter to quarter and the other one is percentage changes between one quarter and the same quarter of the previous year.

Chapter 4

Market Microstructure

In a first step, we want to understand how gold prices behave within the 24 hours of a day. As the world is rotating, a number of trading venues are opening, and some others are closing, which means for instance that Asia is trading at a different period during the day than the US. Consequently, demand and supply for gold should change as one trading venue opens and another one closes. Such demand and supply shifts materialize through intraday changes of market microstructure characteristics like returns, volatility, trading volumes and liquidity. Constructing and analysing each of those market microstructure characteristics provides a fundamental understanding of gold price dynamics within a day and their associated *technical* underlying driving forces.

We start with the previously cleaned data matrix of 4528×288 (4528 days, and 288 5-minute intervals) quotes, bids, asks and trading volumes at 5-minute frequency - thus we start with four separate matrices. In our analysis we construct annualized cumulative returns, volatility measured by absolute returns, liquidity measured by standardized bid-ask spread and trading volume extracted from trade data for each day. For each of the 4 matrices, we then take averages across days which leaves us with four 1×288 vectors, each one describing a market microstructure characteristic during the 24 hours time span. All figures of microstructure characteristics show a 24 hours time span on the horizontal axis, starting from 17:00 on one day and ending at 17:00 the day after in New York time. Throughout this chapter we employ the full sample ranging from January 2001 to December 2018.

4.1. Returns

To compute cumulative returns within 24 hours, we put ourselves in the shoes of a New York (NY) trader who is investing *one* USD in the GC gold futures contract at market closing time 17:00 and holding it until the next day when markets are closing again at 17:00 New York time.[1] During that 24 hours time span, we construct the cumulative return for every 5-minute interval as follows:

$$r_{d,t|t_0} = m_{d,t} - m_{d,t_0}, \tag{4.1}$$

where $r_{d,t|t_0}$ denotes the cumulative return at day d and time of the day t given an investment at t_0 and $m_{d,t} = ln(M_{d,t})$ denotes the natural logarithm of quoted mid-price $M_{d,t}$. In our case $t_0 =$ 17:00, as this time corresponds to the starting point of each day. A cumulative return at time t is simply the log difference between the quoted price at time t and the quoted price at 17:00 when the trader started going long the GC future. We now average those returns by day in the following way:

$$\hat{\mu}_t = \frac{1}{D} \sum_{d=1}^{D} r_{d,t|t_0} \tag{4.2}$$

Figure 4.1 shows average annualized cumulative 5-minute returns, $\hat{\mu}_t$, for every point in time during the 24 hours period. An alternative representation of that pattern is given by Figure B.1 in the Appendix which shows prices normalized by their daily average. Two distinct patterns stand out, firstly cumulative returns show a sine-like waveform. Secondly, there are two distinct downward spikes around the London fixings.

Considering the sine-like waveform, the steady increase from 18:00 to 2:30 shows two small jumps, one at 19:00 which is when trading starts in Tokyo during winter time and another one at 20:00 which is when trading starts in Tokyo during summer time. Apart from these jumps a strong upward trend continues until 2:30 with a small dip right after 2:00. This means, in a time span of eight hours between 18:00 and 2:00 annualized cumulative returns rise from 0% to 12.3% in total of which 8.7% can be attributed to trading activity in Tokyo and Shanghai during their day sessions. The upward rally in cumulative returns is followed by a period of falling returns for the next nine and a half hours starting when Tokyo and Shanghai close their day trading sessions and London OTC and COMEX open outcry start.[2] During this period cumulative returns fall from 12.3% to

[1] New York changes twice a year its time zone, because of daylight savings. New York time zone is therefore different from EST.

[2] COMEX gold futures stopped being traded in open outcry in July 2015. Nevertheless, we consider these as the main "work hours" of an American trader trading COMEX gold futures on the electronic Globex platform

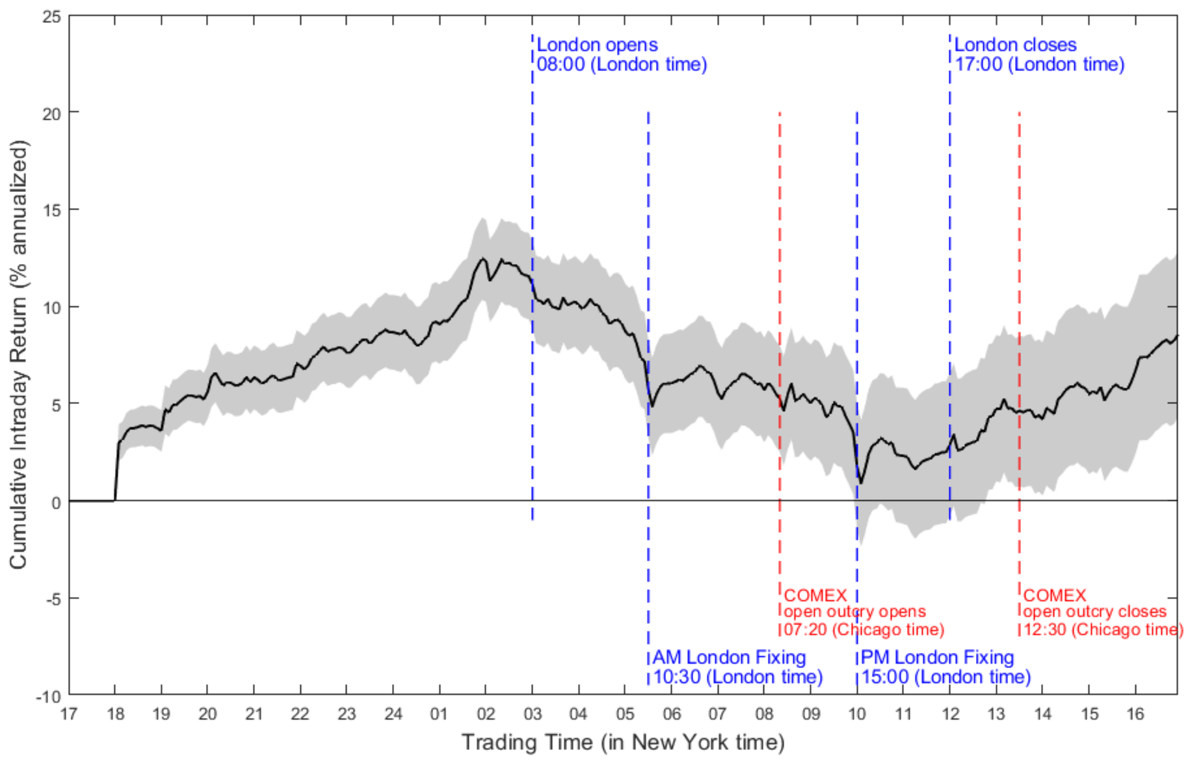


Figure 4.1. Average Daily Cumulative Returns
This figures shows the 24-hours pattern of cumulative log-returns. The sample period is from 3^{rd} Jan 2001 to 31^{st} Dec 2018. On the horizontal axis we have *trading time* in New York time zone. The blue line represents the average cumulative log-returns for each trading time of the day. The grey zone represents the standard error around the mean.

a local minimum of 0.9 % at 10:00 which marks a turning point for returns from where they enter a period of upward movement until the end of the day when cumulative returns amount to 8.3%. Worth mentioning is, that from 3:00, when London OTC opens until the end of the day at 17:00, returns show a wide spread U-shape. Taking a closer look, we realize that, when *only* London OTC is trading, returns are falling. As soon as open outcry at COMEX commences returns move sideways and finally when London OTC closes returns rise.

Also, there are two steep downward spikes at 5:30 and 10:00 which coincide with the two gold price fixings in London. Within 30 minutes returns first drop by 3.7 percentage points at 5:30 and in a second downward spike returns drop within 30 minutes by 4.2 percentage points at 10:00. On a close-to-close basis (17:00 of one day to 17:00 the next day), we find a positive average annualized return of 8.3%, which coincides with the historical development of gold over the course of the sample period 2001 to 2018.

Unfortunately, the interpretation of the return pattern around Asian trading hours is slightly distorted because Asian exchanges are located in time zones without daylight savings. Since we are assuming the perspective of a New York based trader, who changes time zones twice a year due to daylight savings, Asian trade venues shift their opening hours relative to New York time also twice a year. This issue will be further discussed in Chapter 5.

4.2. Volatility

Measuring volatility around the clock provides insights into the riskiness of trading gold within a day. We use the absolute value of annualized 5-minute returns, from time $t-1$ to t, to construct volatility at each 5-minute time interval in the following way:

$$\sigma_{d,t} = |r_{d,t|t-1}| \tag{4.3}$$

where $r_{d,t|t-1}$ denotes the log return for day d between time $t-1$ and t as defined by equation 4.1. Taking averages over days, d, produces a volatility estimate for each time interval during the day, $\hat{\sigma}_t$. It is constructed as follows:

$$\hat{\sigma}_t = \frac{1}{D}\sum_{d=1}^{D}\left[\sigma_{d,t}\right] \tag{4.4}$$

where D denotes the number of days and $\hat{\sigma}_t$ denotes the average volatility at time of the day t. We can interpret the volatility estimate as *average absolute percentage change* of the gold price at any given point in time t. Figure 4.2 shows the estimate of volatility in gold prices, $\hat{\sigma}_t$, within the 24 hours of a day: Going from left to right, the first thing we notice after a one-hour gap is the largest spike in volatility during the day at 18:00. Right after, there are three spikes at 19:00, 20:00 and 21:00 which can be attributed to the opening hours in Tokyo and Shanghai. There are three spikes because New York time undergoes daylight saving twice a year whereas Japan and Shanghai do not. Noteworthy though, the third spike is comparably smaller than the other two ones, which means Shanghai trading drives up prices by less than Tokyo trading does. From 21:00 until 2:30 volatility drops and follows a U-shaped process hitting a high of 4% as London OTC opens. From 3:00 onwards we enter London trading hours and volatility remains on an increased level. There

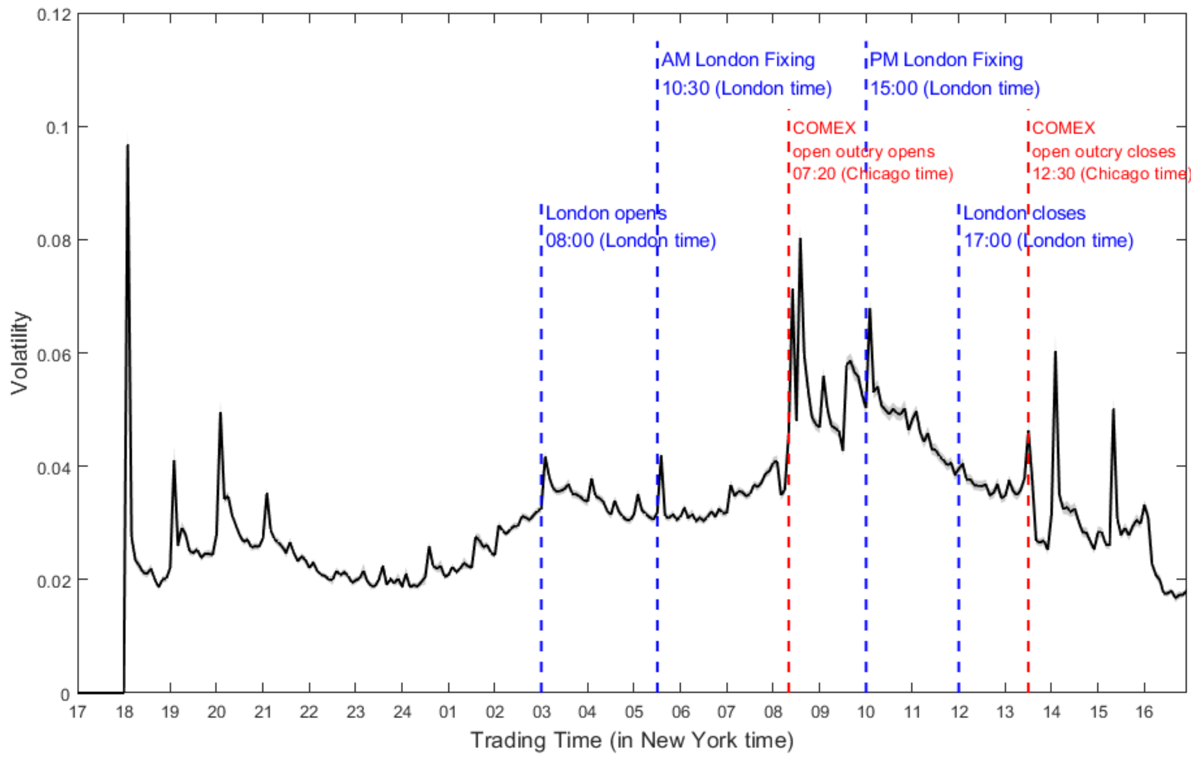


Figure 4.2. Volatility in Gold Prices
This figures shows the 24 hours pattern of a volatility measure in gold prices $\hat{\sigma}_t$. The sample period is from 3^{rd} Jan 2001 to 31^{st} Dec 2018. On the horizontal axis we have *trading time* in New York time zone. The black line represents the average volatility for each trading time of the day. The grey zone represents the standard error around the mean.

are two interesting upward spikes at 5:35 and 10:05 which is right after the London AM and PM fixings. Interestingly, the PM Fix comes along with much higher volatility. While London traders are coming back from lunch at 8:00 (13:00 London time) volatility drops and suddenly picks up again when Chicago open outcry starts at 8:20. As we pass the PM London Fix, volatility slowly decays even after London trading closes. At 1:30pm COMEX open outcry ends and volatility shortly peaks. This peak is probably not only due to closing of the open outcry, but also because COMEX futures are settled with the price at 13:30.[3] Two distinct spikes occur at 14:05 and 15:20, however, to date we cannot explain what causes them. Volatility spikes shortly at 16:00 which is when trading at NYSE stops for the day and volatility gradually declines for the next hour in which it also reaches its lower value for the day.

[3] In fact, there are more sophisticated rules for the settlement of COMEX futures. One is that the volume weighted average price (VWAP) of 13:15 - 13:30 is used for settlement. Another one is that the price between 13:29 -13:30 is used. The first rule is used for terminal settlement and the second one for daily settlement.

4.3. Liquidity

Turning our attention now to liquidity, we may think of this microstructure characteristic as a measure of ease to turn gold futures into cash. We approximate a liquidity measure from bid-ask spreads at every point in time, which is constructed as follows:

$$\hat{\lambda}_t = \frac{1}{D}\sum_{d=1}^{D}\left[\frac{\Delta_{d,t}}{\hat{\Delta}_d}\right] \tag{4.5}$$

where $\Delta_{d,t} = ASK_{d,t} - BID_{d,t}$ denotes the bid-ask spread at day d and time t and $\hat{\Delta}_d$ denotes the daily average bid-ask spread and D is number of days. This means $\hat{\lambda}_t$ is the bid-ask spread at time t relative to its daily average. A low bid-ask spread means that market makers have small mark-ups on their prices, which only happens when much trading is going on and market makers are competing with each other. Therefore, liquidity is high when the measure $\hat{\lambda}_t < 1$, which means the bid-ask spread in t is below its daily average. Analogously, liquidity is low when the measure $\hat{\lambda}_t > 1$. Figure 4.3 shows the intraday pattern of the measure for liquidity, $\hat{\lambda}_t$. Most strikingly is the U-shape it takes over the day. At 17:00 the day is starting with a relatively high $\hat{\lambda}_t$, indicating low liquidity. At 20:00, when Tokyo trading starts, the market becomes more liquid than its daily average and continues like that until 24:00 mid-night, i.e. the spread closes gradually until mid-night. From mid-night until 8:20, when COMEX open outcry starts, the spread evolves hump-shaped reaching its lowest level at 8:00. From this point in time, the spread opens up gradually until COMEX open outcry ends at 13:30 The remaining time of the day the market is drying up and liquidity is below average.

4.4. Trading Volume

Trading volume is different from the other three microstructure characteristics because we source it from data on executed trades instead of quoted bids or asks. Thus, the intraday pattern reflects actual volumes traded in gold futures contracts. To find the average trading volume at every 5-minute interval, we construct it as follows:

$$\hat{\nu}_t = \frac{1}{D}\sum_{d=1}^{D}\left[\frac{\nu_{d,t}}{5}\right] \tag{4.6}$$

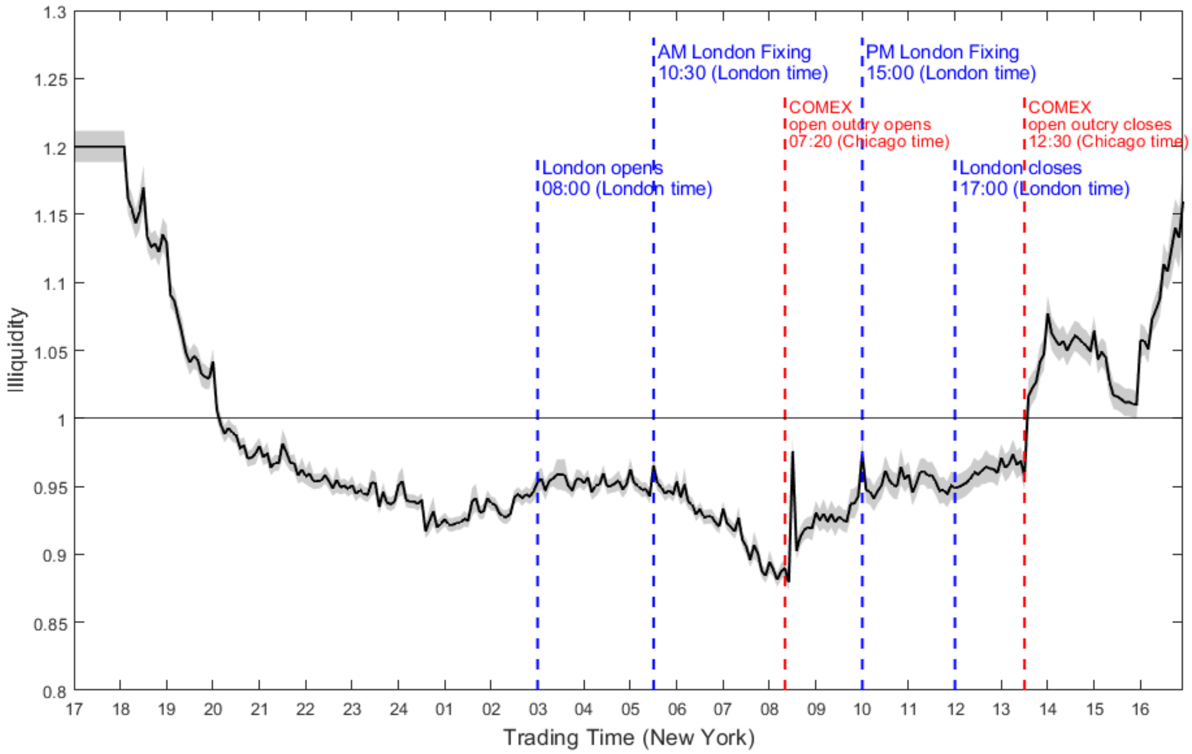


Figure 4.3. Liquidity in Gold Prices

This figures shows the 24-hours pattern of liquidity in gold prices. The sample period is from 3^{rd} Jan 2001 to 31^{st} Dec 2018. On the horizontal axis we have *trading time* in New York time zone. The black line represents the average liquidity for each trading time of the day. The grey zone represents the standard error around the mean.

where $\nu_{d,t}$ is the trading volume at day d and time of the day t. To obtain contracts traded in per minute units, recall that we employ data in 5-minute frequency which is why we divide the RHS by 5. After all, $\hat{\nu_t}$ is the average daily trading volume per minute which is depicted in Figure 4.4.

Most notably, the highest volumes are turned over between 8:00 and 13:30 which corresponds to open-outcry hours in Chicago. Other than that, we see minor spikes scattered throughout the day. Worth mentioning is that there is only one spike at 19:00, which corresponds to Tokyo opening hours in winter time. Shanghai enters the market one hour later than Tokyo, however this does not materialize in increased trading volume, which is probably due to their comparably small size. Between 21:00 and 3:00, there is only little trading activity following a U-shape with a local minimum at 00:30. At 3:00 London OTC opens and volume follows a U-shape until 8:00. Within half an hour between 8:00 and 8:30 volume shoots up and four folds. The next five hours, the market turns over its highest volumes and the PM London Fix materializes in high trading volume at 10:00. Volume

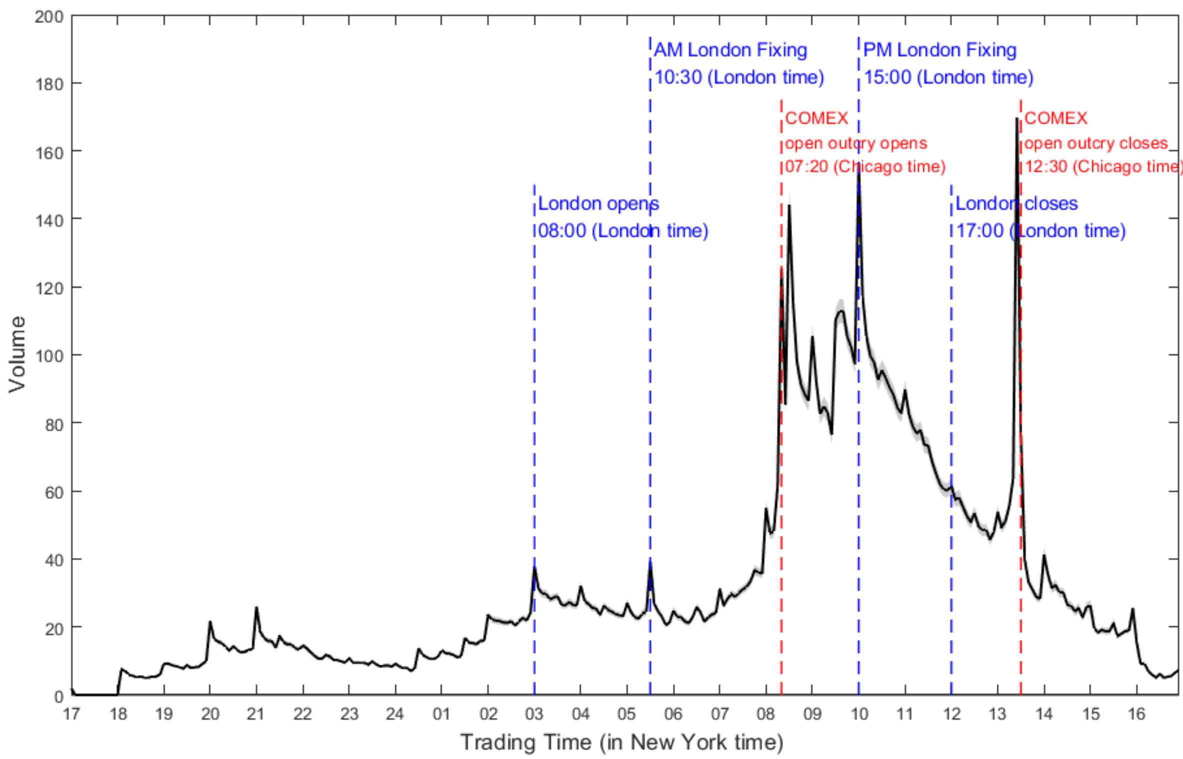


Figure 4.4. Volume in Gold Prices
This figures shows the 24 hours pattern of volume in gold prices. The sample period is from 3rd Jan 2001 to 31st Dec 2018. On the horizontal axis we have *trading time* in New York time zone. The black line represents the average trading volume for each trading time of the day. The grey zone represents the standard error around the mean.

peaks one last time at 13:30, which is when settlement prices are set. Overall, we find that during Asian main trading hours, traded volumes are comparably low, which makes sense since Chinese traders have limitations regarding transactions in foreign financial markets. The largest volumes are traded during London trading hours and COMEX open outcry.

4.5. Interrelations

Having studied each microstructure characteristic separately, we are now equipped with a basic understanding of how returns, volatility, volume and liquidity behave during an average trading day. However, we do not know yet, how these measures are interrelated, which means for example how does the return pattern relate to trading volume, liquidity and volatility.

Turning our attention to the relationship between returns and volatility, one would expect that when volatility is high, investors claim higher returns as compensation for taking higher risk. However, we find the exact opposite, returns increase but volatility remains on a low level. Another risk investors may be compensated for is liquidity risk. However, in the first 15 hours of the day liquidity and returns move in opposite directions, only in the last 9 hours of the day returns rise as the market dries up. It seems as if there is no constant liquidity risk premium on gold throughout the day. In the big picture, returns seem not to compensate for risk due to volatility or liquidity. Trading volume and bid-ask spreads move together as expected. In the first ten hours, bid-ask spreads close while trading volume gradually increases and volume is highest when bid-ask spreads are lowest and the day ends by falling volumes and rising spreads. Also, return volatility is to some degree mirroring trading volume, which is what we expected. Trading volume and returns are hard to relate because volume regards only contracts traded on the COMEX but not globally traded gold contracts. Gold prices however, are global measures since arbitrageurs are trading the same asset for the same prices on different exchanges.

4.6. Summary of Results

So far we have understood how returns in gold futures are related to volatility, trading volume and liquidity and how all of them behave around the clock. There are a number of main take-aways from this chapter. First and foremost we find a "hat-shaped" intraday seasonality in returns, with prices rising between 11:00 to 2:00 and falling the remaining time of the day from 2:00 to 11:00. This means that in main eastern trading hours returns steadily increase and during main western trading hours returns follow a U-shape with an overall decrease. We aim to explain the return pattern by relating it to volatility, liquidity and volume, which does not help to understand the hat-shape because they are seemingly unrelated. However, the interraltion between liquidity and volatility with volume is as expected. Second, there are two steep downward spikes around London fixing time which might have occurred because of manipulation of gold prices. Both facts support our conjectures in H_0^1 and H_0^2. We refer to the intraday return pattern in Figure 4.1 as baseline result/case in later chapters.

Chapter 5

Robustness Checks

The analysis so far involves two main problems: (i) it does not address the timing of daylight savings within each year and (ii) it does not consider environmental changes. Issue (i) refers to a structural problem with the data and can be solved by splitting up the sample into two appropriate subsamples. Issue (ii) refers to changes over time in trading activity of gold futures, economic conditions and regulations.. As we will demonstrate in this chapter, constructing average returns across the *whole* sample "averages out" important dynamics within certain periods of time which affects the validity of inference we can draw from numeric results. Thus, precipitately jumping to further examination of the pattern would lead to a flawed understanding of underlying causes and ultimately to flawed conclusions on how to proceed. In this chapter, we therefore address the two problems by dissecting the full sample by (a) daylight saving time, (b) three subsamples, (c) year-by-year, (d) month-of-the-year and (e) day-of-the-week samples.

We test for economic and statistical robustness of the hat-shape and the fixing spikes. In Chapter 2 we discussed that world's gold is moving from western countries (US and Europe) to eastern countries (China and India). We try to put this economic intuition in relation to the return pattern by splitting the day into eastern and western trading hours.[1] In particular, we want to understand if prices rise during eastern hours and fall during western hours in a robust way. While providing visual and statistical evidence, we give preliminary explanations for the pattern by relating our findings to geographical clientele and historical economic events. If the pattern was robust, then there must be a time-independent underlying driving force, if not, then there must be other economic or behavioural driving forces at play.

[1] We relate the rising leg of the hat-shape to returns earned during trading hours mainly associated with Tokyo and Shanghai trading (eastern trading venues) and the falling leg to returns earned during trading hours mainly associated with London and New York (western trading venues).

5.1. Daylight Savings

In this section we address problem (i): daylight savings. Daylight savings are distorting the return pattern due to a problem rooted in the structure of our data. To further understand that problem, we want to have a closer look into *when* and *where* daylight saving time occurs and what consequences come along with it. Regions that use daylight savings are North America, Europe, South Australia and New Zealand, a few countries in South America and the Middle East. All other countries in the world do *not* use daylight savings. Every year in Spring, at around end of March/beginning of April, countries in the northern hemisphere advance their clock by one hour[2], entering the time of the year with daylight savings, called daylight saving time (DST). They reverse this procedure in Autumn at around end of October/beginning of November and go back to Standard Time (ST). Global time zones are measured in two components: (i) Coordinated Universal Time (UTC) and a (ii) UTC offset. UTC never changes and is therefore universally used to express time around the world, e.g. New York summer time is UTC-4 (DST) and New York winter time is UTC-5 (ST), where UTC offset varies between -4 and -5 depending on summer time or winter time. This means, countries in the northern hemisphere with daylight savings are half of the year one hour ahead of their UTC time zone, and the other half of the year right in their time zone. This, in turn, means that countries practicing daylight savings also change their UTC offset relative to the rest of the world, not in DST, for one half of the year[3].

For instance, Tokyo is in time zone UTC+9 and does not change that one throughout the year. The time difference to New York in summer time is -13 hours and in winter time -14 hours. Assume that Tokyo trading starts at 9:00 Tokyo time. Provided New York is 13/14 hours ahead, Tokyo trading starts at 19:00 in New York winter time and at 20:00 in New York summer time. This is exactly what we have observed earlier in Figure 4.1, when there were two upward jumps at 19:00 and 20:00. As a result, we cannot capture the full effect on returns when Tokyo trading starts. In a broader sense, we cannot fully capture the effect on returns when *any* country not using daylight savings enters the market. For this very reason, we dissect the return pattern in 2 subsamples: one when US and UK are in DST, one when US and UK are in ST

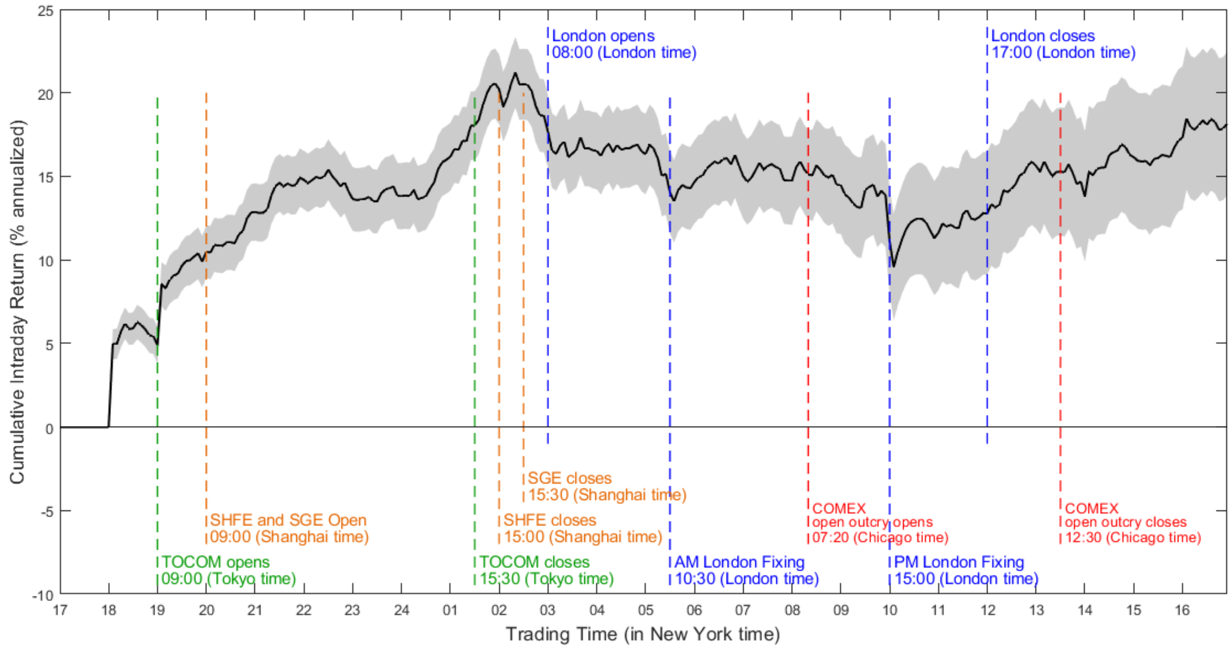
[2]Countries in the southern hemisphere turn it back by one hour and are in ST.
[3]Since UK is also practicing in daylight savings, the London gold price fixing is not affected by this distortion.

Standard Time

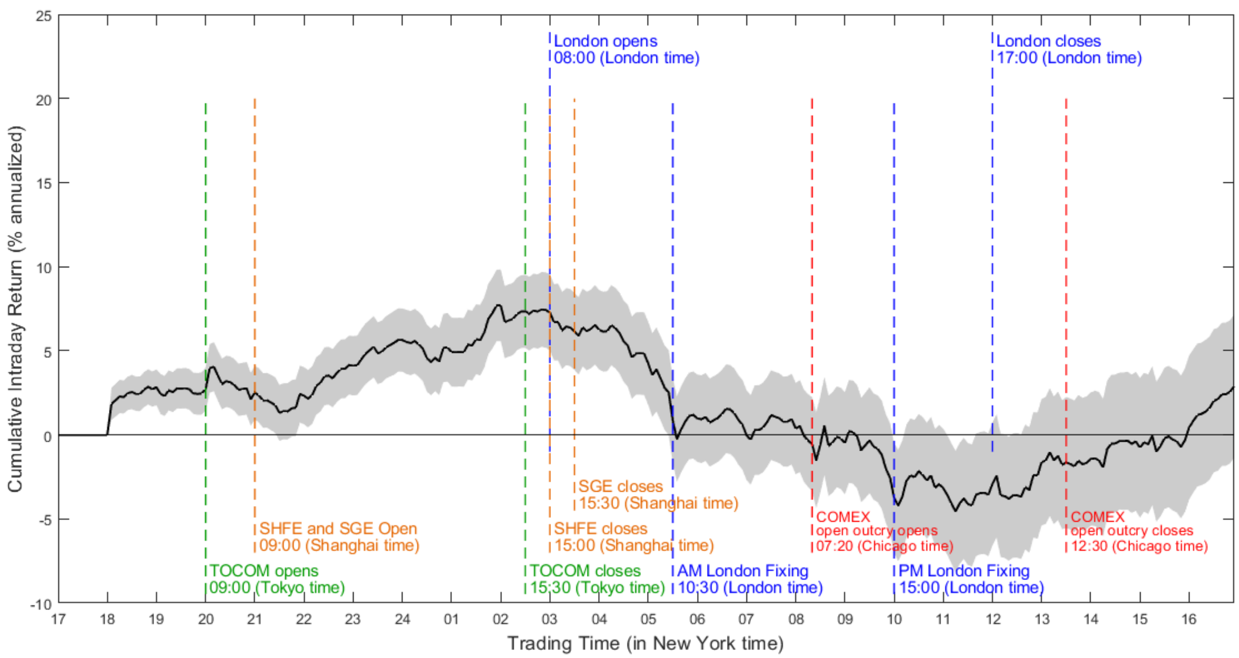
Figure 5.1, Panel (a) shows cumulative returns when there is no daylight savings, i.e. winter time for the full time span from 2001 to 2018. There are some differences to the baseline case. Now, there is only one single upward jump when Tokyo trading starts at 19:00. There is no sign of increased returns when Shanghai enters the market an hour later though. For the next three and a half hours, returns go up from 7.4% to 14.9%. While Tokyo is out for lunch from 22:30 to 23:30 (12:30 - 13:30 Tokyo time), returns recede to slightly by 3.3%, and remain there during afternoon sleepiness. An hour before Tokyo closing, at 00:30, returns pick up again and reach their highest level of around 21.7% between 2:00 and 2:30 which corresponds to Shanghai markets closing time. For the remaining time of the day, Europe and America start trading and returns follow a widely stretched U-shape, with two downward spikes at London fixing time. Worth mentioning, is that close-to-close returns amount to 17.8% on average, which is almost twice as much as in the baseline case. All in all, during winter time we can earn higher average returns than during the whole year.

Daylight Saving Time

Figure 5.1, Panel (b) shows cumulative returns when there is daylight savings, i.e. summer time for the full time span from 2001 to 2018. Now, Tokyo trading starts at 20:00 and Shanghai does not have an effect on returns. The pattern looks profoundly different though, firstly, right after the jump when Tokyo commences trading, returns start to drop for two hours and then pick up for the next two hours. In other words, there is no afternoon sleepiness anymore during summer time. Returns peak at 2:00 right before Tokyo closes. Noteworthy at this point is, that SHFE traders hand over the baton to London traders, because closing of SHFE and opening of London OTC happen both at 3:00, which had not happened during DST. From this point in time, returns drop from 7.4% to -0.2% at 5:30 (London AM Fix). For the rest of the day returns follow a widely stretched U-shape and dip below zero most of the time and close with a close-to-close return of 3.1%. All in all, during summer time we can earn much lower average returns than during the whole year.



(a) Standard Time (2001-2018)



(b) Daylight Saving Time (2001-2018)

Figure 5.1. Returns Around the Clock: ST vs DST
The two panels in the figure show two subsamples: one in which New York is in ST (between November and March) and one in which it is in DST (between March to October).

5.2. Different Sample Periods

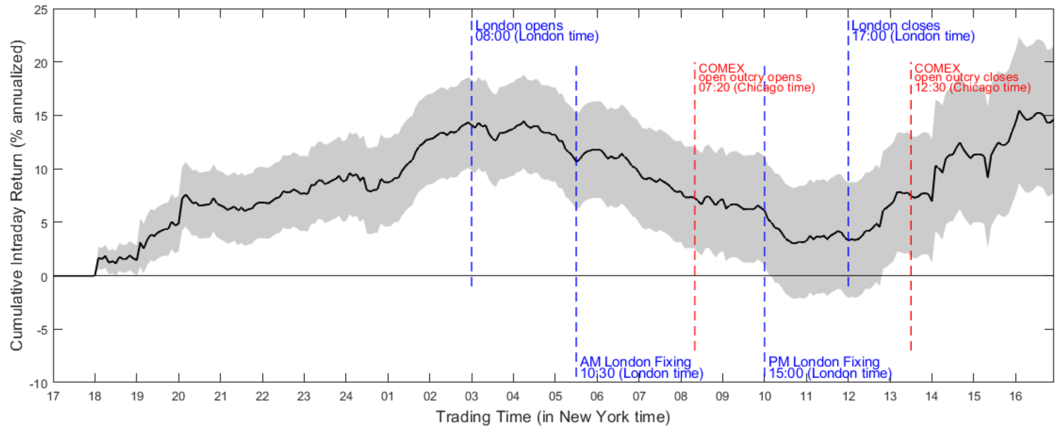
In this section we address problem (*ii*): environmental changes. We first split the data into three subsamples and relate them to considerable economic events, and second into year by year samples.

5.2.1. Three Sub Periods

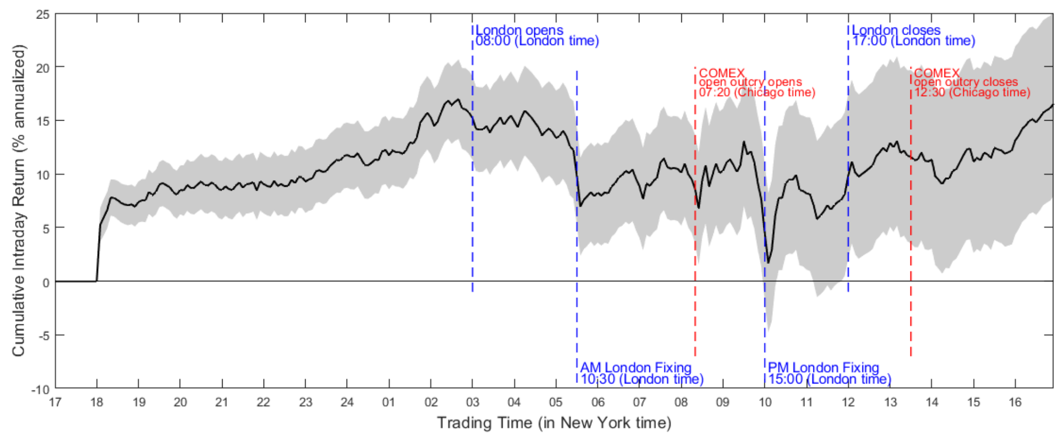
We show the return pattern for each of the three time frames and each of the three subsamples is six years long. The new sample periods are denoted by $\mathcal{A}$ (2001 - 2006), $\mathcal{B}$ (2007 - 2012) and $\mathcal{C}$ (2013 - 2018). In period $\mathcal{A}$, our data shows profound gaps indicating little trading activity in early years. Yet we decided not to discard these years of data because they can provide some additional insights and this sample covers the recovery phase from the dot-com bubble and QE in Japan. From 2007, data quality considerably improved, meaning that there are fewer gaps which indicates higher trading activity. This time frame also captures the onset of the global financial crisis and their recovery phase with QE by various central banks. In 2012, allegations against the group of banks participating in the gold price fixing have come up and they were accused of manipulating the London PM Fix. Starting from March 2015, IBA, an independent third-party selected by the LBMA, is administrator of the fixing process and provides an electronical platform. Before this review of the fixing there was no independent organization reviewing the process. All three subsamples capture a distinct change in economic conditions or regulation and thus we expect to see variations in return patterns when splitting up our data accordingly.

Sample Period $\mathcal{A}$ - Little Trading Activity

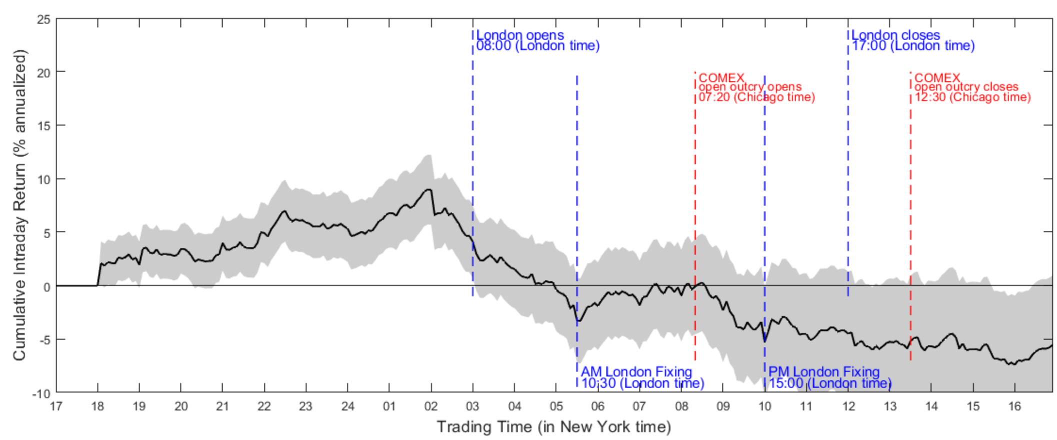
Between 2001 and 2006 gold returned a yearly average of 14.9% as shown in Figure 5.2, Panel (a). At Tokyo opening hours, returns jump up and keep rising until London takes over business at 3:00. From that time onwards, returns decline until open outcry at COMEX ends and rise up again for the remaining time of the day. We find a small downward swing around the London AM Fix, but unexpectedly, we cannot see a downward swing during London PM Fix. Also, the plot is comparably smooth as opposed to the baseline case. An explanation for both, missing London PM Fix and a smoother time series, could be the weak data quality in this first sample period. In fact, we had to forward fill many observations within that early sample, which leads to loss of information, because there are many small intervals with stale prices. Subperiod $\mathcal{A}$ is characterized by QE in Japan and



(a) Sample Period $\mathcal{A}$



(b) Sample Period $\mathcal{B}$



(c) Sample Period $\mathcal{C}$

Figure 5.2. Returns Around the Clock: Three Subsamples
The three panels in the figure show three subsamples each of six years length. T sample periods are denoted by $\mathcal{A}$ ranging from 2001 - 2006, $\mathcal{B}$ ranging from 2007 - 2012 and $\mathcal{C}$ ranging from 2013 - 2018.

the economic recovery from the dot-com bubble which can be a reason for increased gold demand from investors as a safe haven investment, which may explain high close-to-close returns.

Sample Period $\mathcal{B}$ - Global Financial Crisis

In this sample, there is no jump to see when Tokyo trading commences as shown in Figure 5.2, Panel (b). London AM and PM fixings are strongly pronounced and even stronger than in the baseline case, e.g during the PM Fix returns drop from 12.8% to 2.9% within half an hour of time. Despite all differences, returns show the same overall behavior we have found previously, i.e. returns increase during eastern trading hours and drop during western trading hours. Average annual close-to-close returns are the largest among the three subsamples with 16.3% and roughly twice as much compared to the baseline case of 8.3%. Even though the fixing scandal of these years was related only to the PM London Fix, we can observe that gold prices around the AM London Fix show the same behaviour. During 2007 and 2012, gold prices skyrocketed reaching an all-time high in August 2011 which may explain large close-to-close returns in sample $\mathcal{B}$. This subsample captures the global financial crisis and the recovery phase until 2012. During that period, along with the Bank of England and the Bank of Japan, the U.S. FED launched three quantitative easing programmes. The USD monetary base has more than threefold during that period, posing a threat to the dollar to devalue in the future. This may be a reason for increased gold demand by investors, which may explain the high returns earned during that time.

Sample Period $\mathcal{C}$ - London Gold Fix under Scrutiny

Taking a look at Figure 5.2, Panel (c), commencement of trading in Tokyo shows a strong jump at 20:00 and a small jump at 19:00. Again, when Shanghai starts trading returns do not show any reaction. Also, we find much smaller swings around the two London fixings. Another striking observation is the low close-to-close return of -5.2% earned during that sample period. Overall though, the return pattern follows the structure of the baseline case, in which returns increase during eastern trading hours and decrease during western trading hours. According to the Class Action Complaint (2015) of the lawsuit against gold manipulation, the year 2013 has been the first year in over a decade, in which prices during the PM Fix were going up or down equally likely. In previous years from 2001 to 2012, prices were on average dropping in 70% of cases and increasing in the remaining cases. Subsample $\mathcal{C}$ covers the time right after the LIBOR scandal in 2012. Due to that scandal, also benchmark prices for gold caught attention of official authorities and the gold price fixing process came under scrutiny starting from 2013, which may explain the reduced magnitude of the spikes around London fixing. As for the low close-to-close return, we can reasonably argue that investors learned that QE does not lead to high inflation, and confidence in the FED and US economy grew, which lead to decreasing gold prices.

Discussion

Overall, the main characteristics of the return pattern prevail in all three subsamples $\mathcal{A}$, $\mathcal{B}$ and $\mathcal{C}$, i.e. increasing returns during eastern trading hours, decreasing returns during western trading hours and two distinct downward spikes around the London fixings, this predominantly is the case in sample $\mathcal{B}$. During period $\mathcal{A}$ and $\mathcal{B}$, gold shows close-to-close returns of 14.9% and 16.3% respectively and in period $\mathcal{C}$ -5.2%. Interestingly, during the first two time periods the global economy went through an economic and a financial crisis. During these times, investors usually buy gold to store wealth and central banks had to back their currencies with gold to ensure trust while issuing their QE programmes.

5.2.2. Year by Year

Second, we want to zoom in further to understand whether the baseline pattern prevails on a yearly basis. Figure 5.3 shows average cumulative returns, sampled year by year. First off, the pronounced hat-shape has disappeared in half of the years, only 2001, 2003, 2006, 2007, 2010, 2011, 2012, 2013 and 2015 resembles the main structure of it. In contrast, in some years returns fluctuate very little during the average trading day or very much, anyhow, they evolve in a rather unsystematic way. For example, in 2017 and 2018 returns never cross ±10%, and in some other years they fluctuate a lot, for example in 2013, where returns are hitting the +18% mark at 2:00 and start slipping from that time onwards to -34% at 5:30, which in total is a return variation of 52% within an average day during that year. Regarding the London fixing, only years between 2007 and 2011 show clear downward spikes. From visual inspection, year by year returns do not seem to obviously mirror in every subperiod the three main characteristics from the baseline case.

In order to test the economic and statistical robustness of our results, we use daily returns that

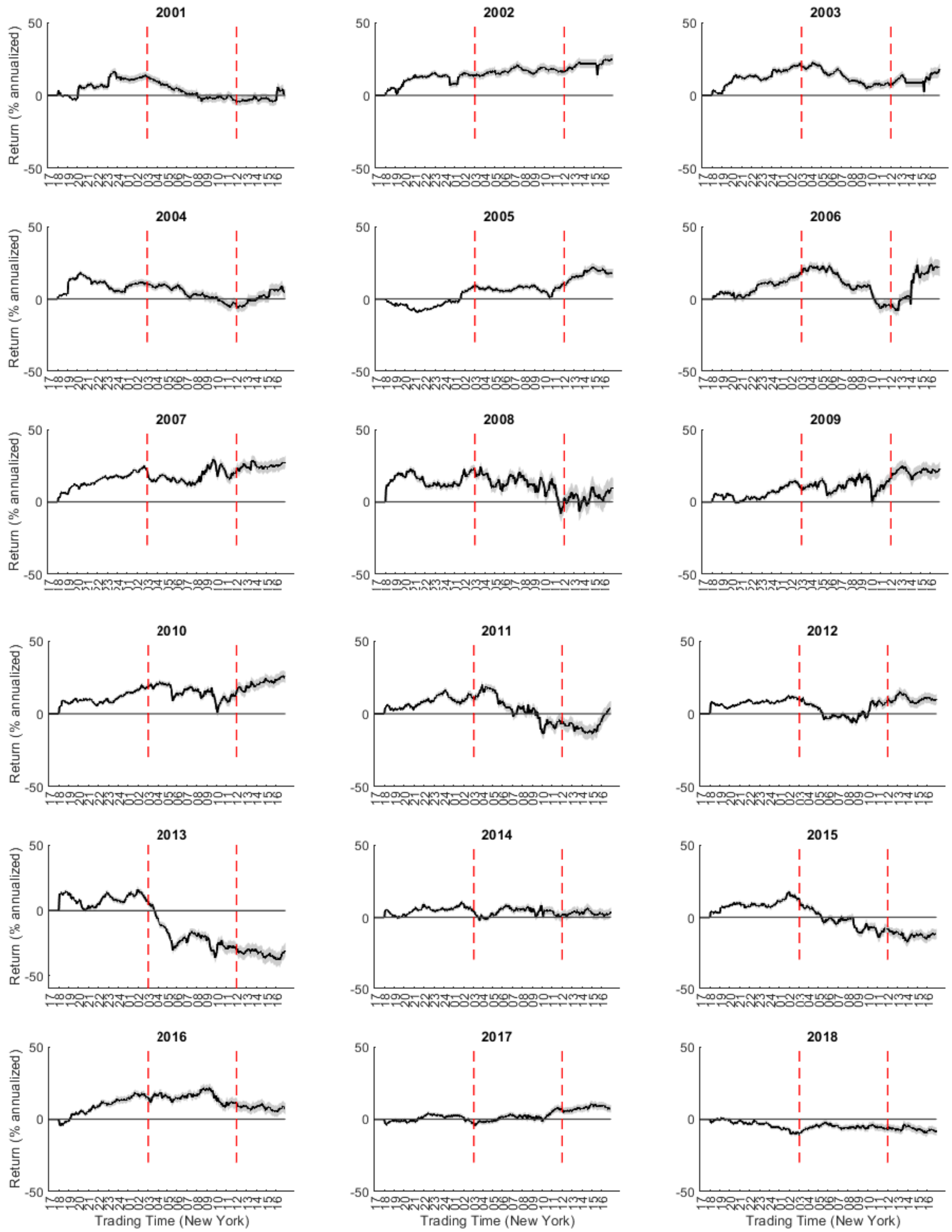


Figure 5.3. Returns Around the Clock: Year-by-Year
The figure shows cumulative returns sorted year by year, ranging from 2001 until 2018. Three grey zone around the return series is the estimated standard error. The two red lines mark opening and closing of the London OTC market.

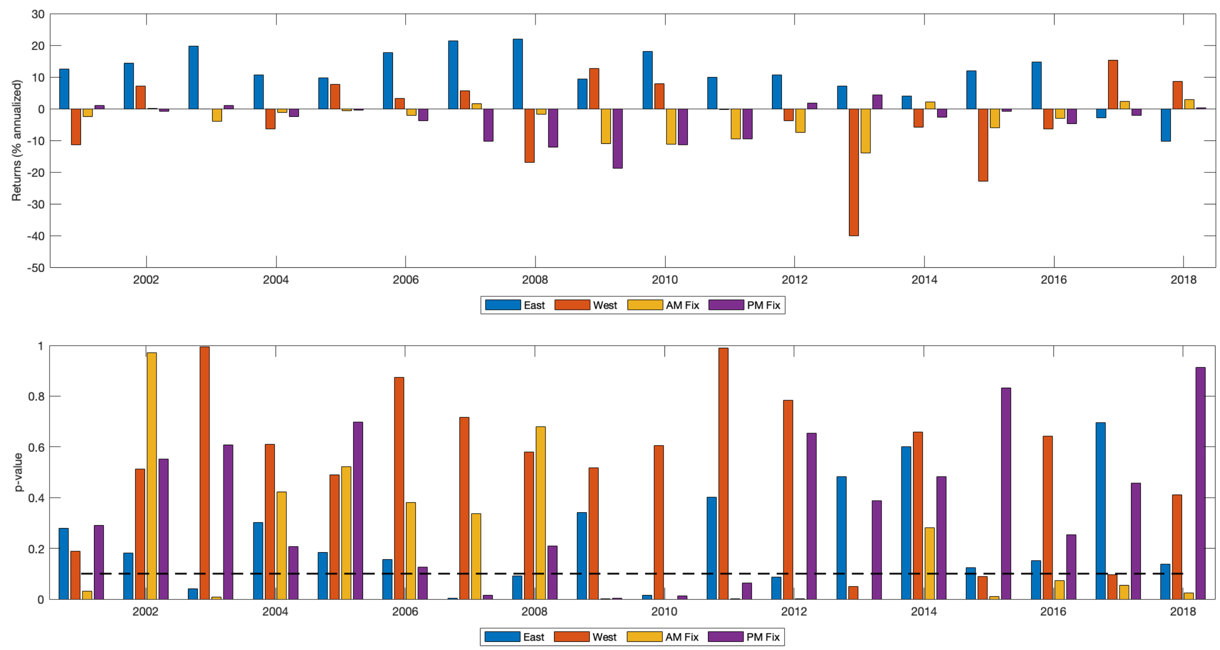


Figure 5.4. Year by Year Average Returns

The top panel of this figure shows average daily returns earned during eastern and western trading hours as well as during AM and PM fixings on a year by year basis from 2001 until 2018. The four time samples are (*i*) EAST (17:00 of one day to 3:00 the other day), (*ii*) WEST (3:00 to 17:00 the same day), (*iii*) AM FIX (30 minutes around the AM fixing) and (*iv*) PM FIX (30 minutes around the PM fixing). The bottom panel shows p-values from a t-test with the null hypothesis H_0: *daily average returns are being zero*. Precise values can be found in Table A.10.

can be earned during trading hours mainly associated with the eastern world (East) and the western world (West) as well as around the London fixings (AM Fix, PM Fix). "East" refers to Shanghai and Tokyo traders mainly trading between 17:00 to 3:00 and we expect East-estimates to be positive. "West" refers to London and New York traders mainly trading between 3:00 and 17:00 and we expect West-estimates to be negative. AM Fix & PM Fix refers to trading between 30 minutes prior to the fixing and the fixing and we expect the two Fix-estimates also to be negative. To do so, we construct average daily returns for East, West, AM Fix and PM Fix and their corresponding p-values for a t-test against the null of H_0: *daily average returns being zero.*[4]

The top panel of Figure 5.4 shows average return estimates, year by year, and the bottom panel shows their corresponding p-values. We consider first the blue bars which correspond to returns from East and are associated with the rising leg of the hat. Especially in early years until 2010,

[4]In fact, we regress daily returns (r^{East}, r^{West}, r^{AMFix}, r^{PMFix}) on a constant and obtain an estimate for the mean as well as related test statistics.

these returns are comparably high, exceeding +10% almost every year. In four out of ten years, these returns were significantly different from zero at the 10% level. In all years onwards, except of 2018, all returns remain positive but less consistent in magnitude and all of them except of 2012 are insignificant. Considering second the returns from West, represented by the orange bars, which correspond to the falling leg of the hat. There is no clear pattern to see and returns are in eight out of 18 years even positive, which is the opposite of what we would expect. In 2013 there is a very large negative return of -40%. Across the whole sample, West-returns are significantly different from zero only in 2013, 2015 and 2017. Considering lastly the returns from AM Fix and PM Fix, represented by yellow and purple bars, which correspond to the London fixings. From the yellow bars, in 13 out of 18 years AM Fix-returns are negative of which 9 are significant at the 10% level. Focusing on purple bars, the most striking result is that especially between 2007 and 2011 returns are strong in magnitude and in four cases they are statistically significant - before and after that time they are small and insignificant.

From these results, we conclude that the rising leg (East) is more consistently present and statistically significant than the falling leg. (West) Statistical evidence suggests, that the hat-shape is more robust over time than the fixing. This result is in line with what we observed from the visual inspection. As for the London fixings, it sticks out that between 2007 and 2012 (sample $\mathcal{B}$) they are particularly strong and significant.

5.3. Calendar Effects

In this section we address problem (*ii*): environmental changes. We want to investigate if there are some calendar effects (e.g. specific months of the year, or specific days of the week) driving the hat-shape and the fixing spikes.

5.3.1. Month of the Year

For a more detailed perspective as to whether a specific month of the year is driving the hat-shape of the baseline case, we compute average cumulative returns for every month of the year and report them in Figure 5.5. From visual inspection, hardly any month except of April and August show both downward swings during London fixing, but it is difficult to assess this based on visual evidence only, which is the reason why we turn to statistical evidence later. There is a strong close-to-close return pattern in January, meaning that returns cumulate to 49.6% throughout the day on average. Generally speaking, during winter months returns are varying stronger and reach higher levels than during summer months. In fact, during the summer months May, June and July, returns are notably flat throughout the day. These results coincide perfectly with what we find in Section 5.1 in which returns during summer months cumulate to -5.2% throughout the day and during winter months to +17.8%. In addition to the visual inspection we are testing average returns for their statistical and economic robustness. Figure 5.6 reports average annualized daily return estimates for each month of the year in the top panel and their corresponding p-values in the bottom panel. The blue bars correspond to eastern returns and except of May to August, the rest of the year they are at least as high as 10% in magnitude. In five out of 12 months, returns are insignificant and for the rest of the year they are at least borderline significant at the 10% level. The orange bars correspond to western returns and five out of 12 months show positive returns, which is the opposite of what we would expect. Only in January West-returns are positive, which coincides with the strong positive return of 49.6%. Finally, the yellow and purple bars, which correspond to London fixings, are all negative as expected, except the PM Fix in January. The PM Fix is only in three months statistically significant, whereas the AM Fix is seven times significant, which is unexpected.[5]

For monthly dissections of returns, we conclude that the rising leg (East) of the hat shows economic and statistical robustness, yet the falling leg less (West). London fixings show rather insignificant returns, especially the PM fixing. Noteworthy is that the time span in which eastern returns are insignificant are exactly those which coincide with daylight savings time, in which on average returns are lower.

[5]In fact fixing banks were accused of manipulating the PM fixing, but it seems also the AM fixing has very pronounced downward spikes.

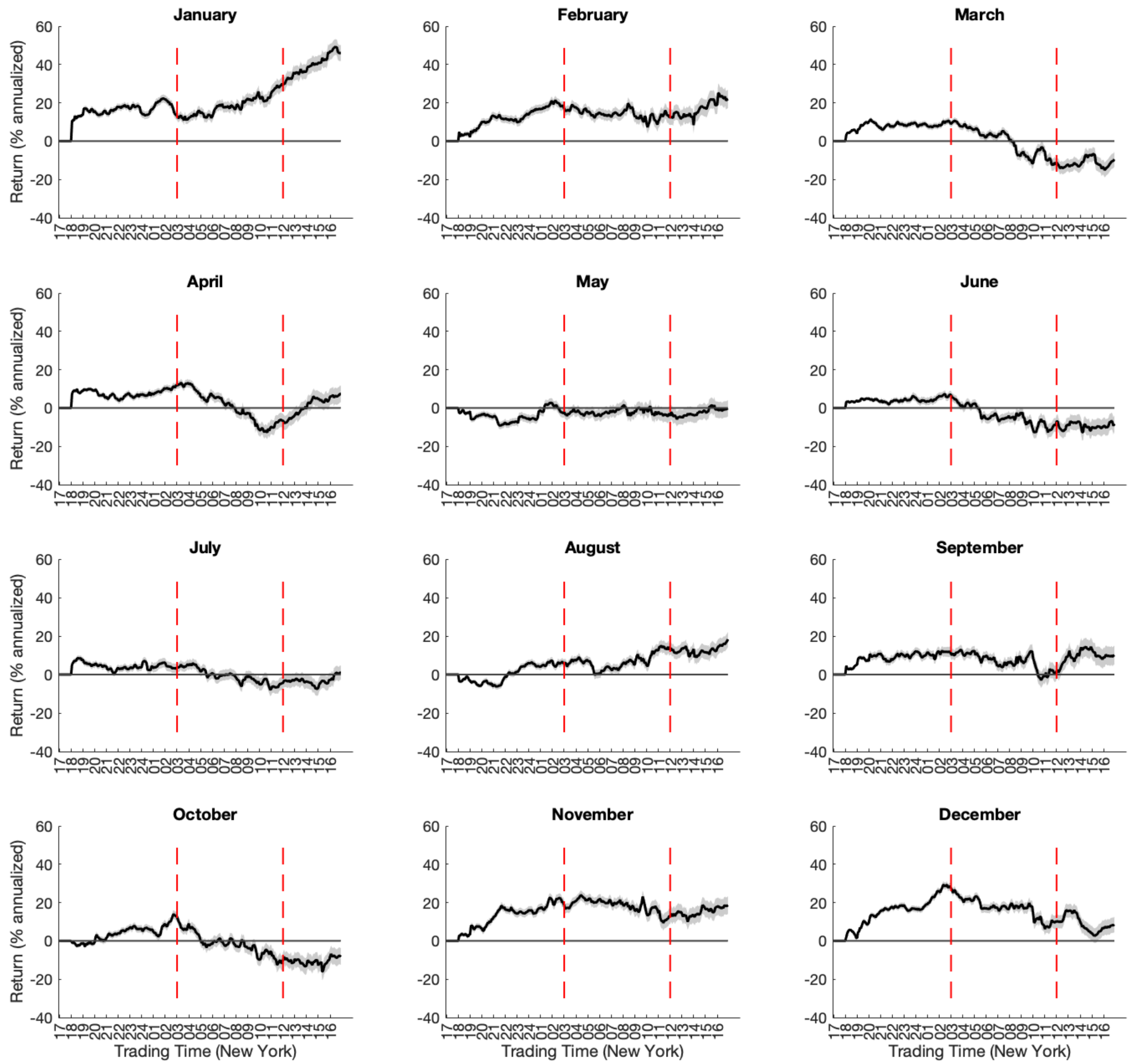


Figure 5.5. Month of the Year Returns
This figure shows average cumulative 5-minute log returns for each specific month of the year. The sample comprises of all months between Jan 2001 and Dec 2018. The two red lines mark opening and closing of the London OTC market.

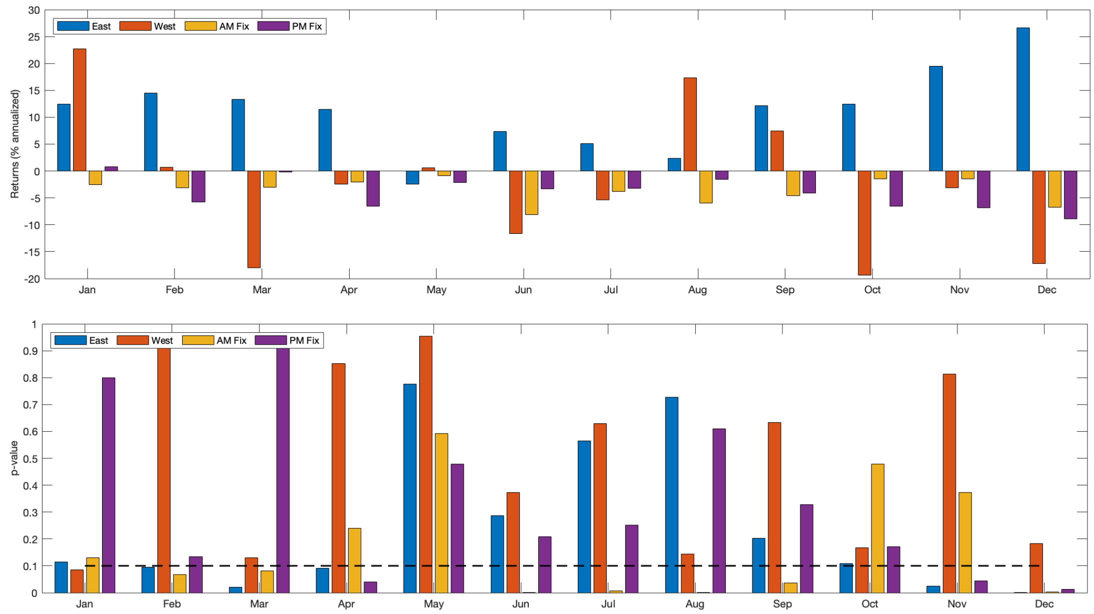


Figure 5.6. Month of the Year Returns
The top panel of this figure shows average daily returns earned during eastern and western trading hours as well as during AM and PM fixings, for each month of the year starting from 2001 until 2018. The four time samples are (*i*) East (17:00 of one day to 3:00 the other day), (*ii*) West (3:00 to 17:00 the same day), (*iii*) AM Fix (30 minutes around the AM fixing) and (*iv*) PM Fix (30 minutes around the PM fixing). The bottom panel shows p-values from a t-test with the null hypothesis H_0: *daily average returns are being zero*. Precise values can be found in Table A.11.

5.3.2. Day of the Week

We finally want to understand if there are specific days within a week, which are driving our main findings. Figure 5.7 shows intraday average cumulative 5-minute returns for each day between Monday and Friday. Except of Tuesday, all other days earn a positive close-to-close return during the day. Friday reaches the highest level of 36.8%. London AM and PM fixings are visually notable in all days, however the overall hat-shape is not clearly present in some days, in particular on Friday. Figure 5.8 provides test results for statistical and economic robustness. Considering first the blue bars, which correspond to eastern returns. Monday shows the largest average return and Tuesday the lowest throughout the week. Wednesday, Thursday and Friday are all in the same ballpark of 10% ±2%. Except of Tuesday all East returns are highly significant. Considering second the orange bars, which correspond to western trading hours, we find that Monday, Tuesday and Thursday show the largest negative returns and Friday shows a large positive return. However, only Monday and Friday returns are highly significant at the 5% level. Finally, turning to returns

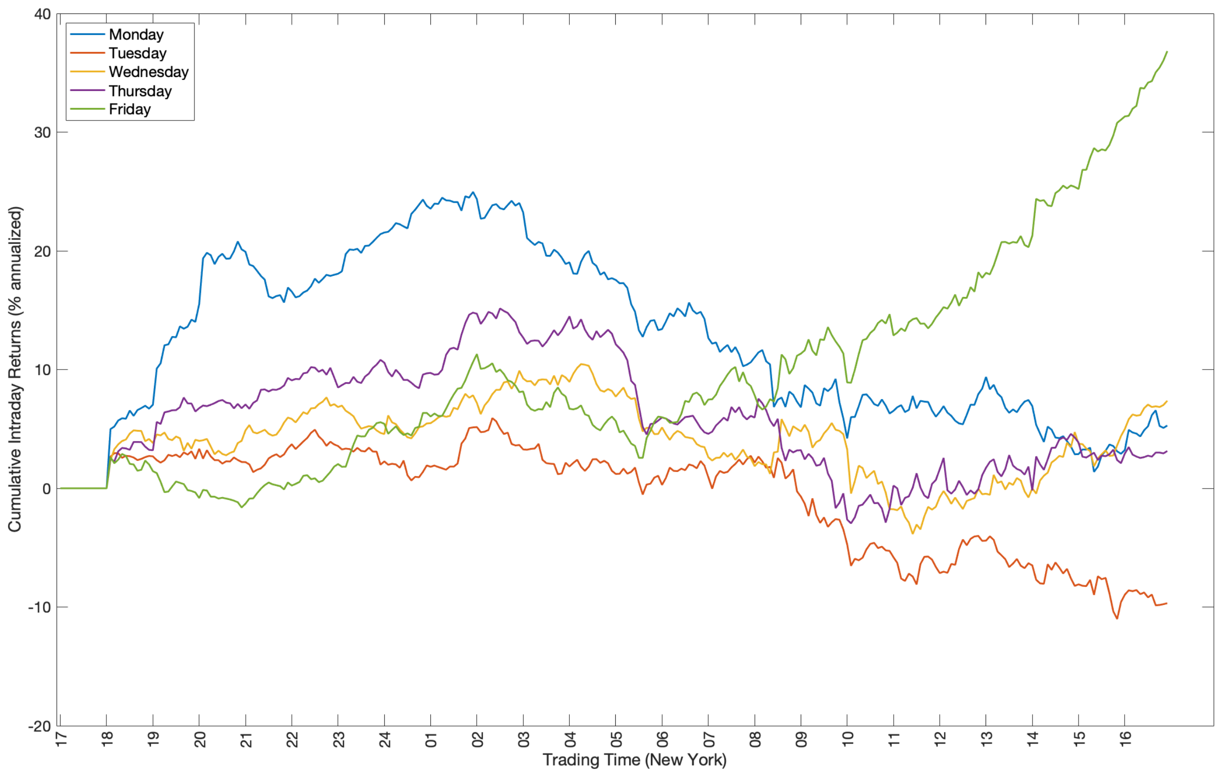


Figure 5.7. Day of the Week
This figure shows average cumulative 5-minute returns sampled for each day of the week. Returns depicted are in annualized percentage units. The horizontal axis shows the 24 hours time span from 17:00 to 17:00 in New York time. The sample comprises of all trading days between January 2001 and December 2018.

during the London fixings, represented by the yellow and purple bars, all days show negative and highly significant returns, which goes hand in hand with our visual inspection. An exception to that observation is Tuesday, where AM Fix returns are only borderline significant and Monday where PM Fix returns are insignificant. In conclusion, the last three days of the week support a strong rising leg and Monday, Tuesday, Thursday support a strong falling leg, while the London fixings are clearly present throughout the whole week. Also, there seems to be a Monday effect for East returns and a Friday effect for West returns.

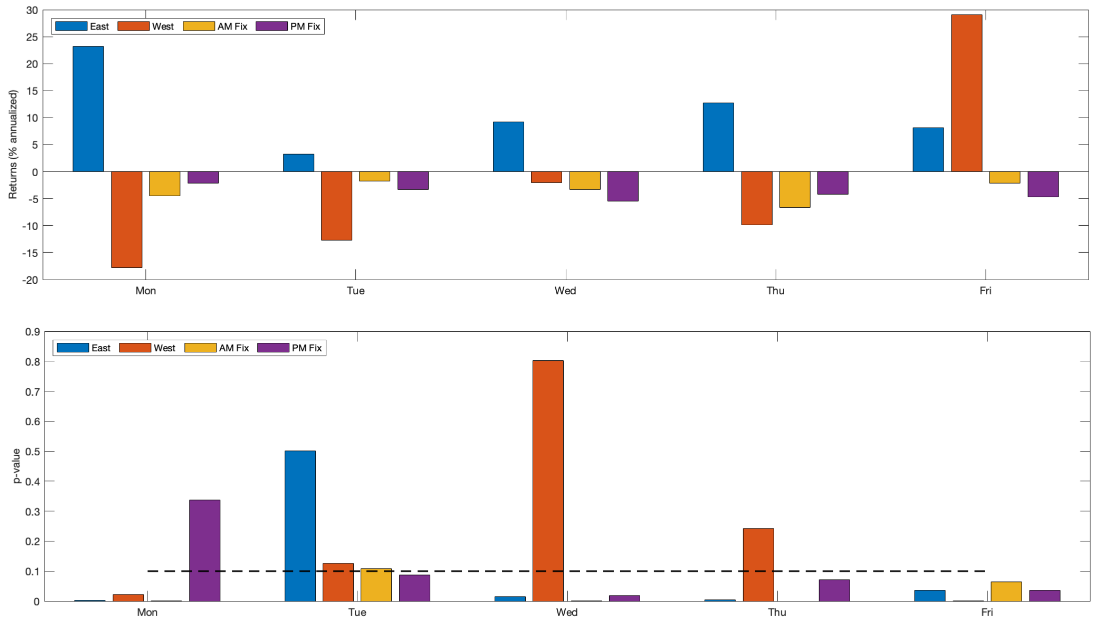


Figure 5.8. Day of the Week Average Returns
The top panel of this figure shows average daily returns earned during eastern and western trading hours as well as during AM and PM fixings, for every day of the week (Monday - Friday) starting from 2001 until 2018. The four time samples are (*i*) East (17:00 of one day to 3:00 the other day), (*ii*) West (3:00 to 17:00 the same day), (*iii*) AM Fix (30 minutes around the AM fixing) and (*iv*) PM Fix (30 minutes around the PM fixing). The bottom panel shows p-values from a t-test with the null hypothesis H_0: *daily average returns are being zero.* Precise values can be found in Table A.12.

5.4. Summary of Results

We wanted to address and better understand two problems which are affecting our return pattern: (*i*) the timing of daylight savings within each year and (*ii*) environmental changes. Problem (*i*) has been addressed by splitting up the sample into DST and ST. When sorted by DST/ST, we find only one instead of two upward jumps when Tokyo trading starts, which means Shanghai trading does not move prices at all. Also, the return pattern shows the hat and the spikes at London fixing. Problem (*ii*) has been addressed by splitting up the data into different samples and calendar effects. We find statistical and economic stable evidence for the rising leg of the hat, which is related to trading activity in the eastern world. As for the falling leg, related to trading activity in the western world, we find no clear-cut statistical or economical evidence whether prices move up or down. This means, we find stable evidence that eastern clientele is driving up prices, though, we cannot infer that the western world is bringing them down in a robust way. Regarding the fixing spikes, we find them economically and statistically stable only in sample period $\mathcal{B}$, but not in the other ones. This leads to the conclusion that the overall return pattern is *not* fully time-independent. Though, these insights guide us into two directions: (i) do economic dynamics explain the time variation in gold returns and (ii) we want to understand if it is still possible to profitably exploit the pattern?

Chapter 6

Macroeconomic Relationships

In Chapter 4 we observed that during some hours of the day gold on average appreciates while during others it depreciates. In Chapter 5 we dissected this result and observed that the pattern is time-varying, meaning that it is more pronounced in some subsamples and less pronounced in others. In this chapter, we want to complement our understanding of the return pattern by measuring the relationship between monetary and macroeconomic variables and returns earned during different time intervals of the day. More specifically, we aim to understand if returns during eastern and western trading hours can be explained by variables of those specific geographical regions.

To do so, we proceed as follows: (*i*) we present well established relationships between gold and macroeconomic and monetary factors, (*ii*) we relate these established factors and additional ones to our intraday returns and validate those relationships in a correlation analysis, (*iii*) we construct appropriate contemporaneous multivariate regression models that allow a comparison between all three gold returns (East, West and CTC). Results from this analysis give an understanding of how gold returns are explainable by economic fluctuations along the time dimension of our data.

6.1. Established Relationships

In this section we complement the literature review done in Chapter 1 and present macroeconomic and monetary variables that are known to be correlated with gold. For each variable we present different view regarding causality.

6.1.1. Gold, Inflation and Interest Rates

The relationship between these three variables is by far the most widely discussed in the literature, and to a large degree, the most controversial.

Gold and Inflation

Gold is scarce and its yearly mining production small and inelastic, meaning that gold is expected to be relatively scarce forever. Because of its scarcity and its ability to perpetually retain its natural shine, gold is believed to be a safe-haven asset, maintaining its intrinsic value no matter what. The same cannot be said for fiat currencies, whose value can be affected by a wider range of external factors, such as policy-makers' choices and macroeconomic conditions. For these reasons, when inflation is high and unstable, gold is seen as an hedge against it, meaning that investors are reportedly more willing to hold gold as opposed to other assets.

Feldstein (1980) was the first to provide a theoretical explanation of why gold and expected inflation are positively correlated. He argued that real assets, such as gold or land, have a limited supply which grows slowly, as opposed to the money supply of fiat currencies which grows at a higher rate. Therefore, while nominal assets lose their real value whenever there is a sudden increase of money supply, real assets maintain their real value.

Along these lines, Fortune (1987) argues that gold and expected inflation are positively correlated because of a "substitution effect". Inflation expectations encourage individuals to sell assets with a fixed nominal return and buy gold instead, which drives its price up.

Interestingly, Rockoff (1984) support the same view that inflation drives gold prices, but he suggests that this happens through a different long-term channel. In fact, he argues, inflation drives up the extraction cost of gold. Since gold mining companies are price taker and cannot charge the final customers for the higher cost, this reduces gold mining margins, which leads to a long-term reduction of the supply of gold, which in turn drives its price up immediately.

Taylor (1998) found a cointegration relationship between gold and US CPI, in two periods: 1914-1937 and 1968-1996. This implies that in these periods gold was an excellent hedge against inflation. Furthermore the author points out that in 1933-1974 it was illegal for US citizens to hold gold and therefore the behaviour of gold prices during this period should be disregarded.

Interestingly, Batten et al. (2014) point out that "the gold-inflation relationship is very sensitive to the timespan chosen", with time periods in which their correlation is higher and periods in which is lower. The authors find that when excluding the high volatile period of early 1980s, and considering the 1985-2012, no cointegration relationship can be found between US CPI and gold price. Also, they suggest that "gold's sensitivity to inflation is related to interest rate changes".

Gold and Interest Rates

Despite the large amount of literature in favour, the gold-inflation relationship is somewhat controversial. On the one hand, gold definitely provides an hedge against inflation, because its scarcity is unaffected by the level of prices and therefore gold retains its real value. On the other hand, when inflation is high, also nominal interest rates are generally high and thus the cost opportunity of investing in non-yielding assets like gold is high as well.

Fortune (1987) outlined this view by arguing that there is a "substitution effect" also between interest rates and gold: when expected interest rates rise, investors are encouraged to sell their gold an buy interest bearing assets instead. On a different view is Abken (1980), which suggests that the gold-inflation link is the main driver of the gold-interest rate link. In fact, he argues, changes in interest rates and changes in gold prices are both driven by changes in expected inflation. When using monthly data between 1973 and 1979 he finds that correlation between changes in the 1-month T-bill rate and changes in the gold price is positive and statistically significant. Despite the fact that the 1970s had very unusual inflation rates, this is a very fascinating finding.

Discussion

To sum up, the relationship between gold and inflation should not be analysed without considering interest rates and the relationship between gold and interest rates should not be analysed without considering inflation. Ultimately the literature agrees that other things equal, a higher inflation drives gold prices up, and that other things equal, a higher interest rate drives gold prices down. However, it's not clear which of the two effects dominates.

Historically, in periods of high and unstable inflation (e.g. 1970s and early 1980s), gold demand (and prices) increased because the alternative of investing in fixed-income assets, and therefore committing to a fixed nominal rate for several years, represented a risk. Therefore in this period the gold-inflation relationship was dominating over the gold-interest rate one.

On the other hand, in the last three decades, with the diffusion of inflation-linked bonds and less volatile inflation rates, incentives to hold gold as a hedge against inflation seemed to diminish and in most subperiods the gold-interest rate relationship dominated over the gold-inflation one.

6.1.2. Gold and Currencies

The most robust and acknowledged relationship between gold and other variables can be found in foreign exchange: gold price is negatively correlated with USD. In fact, gold prices are primarily denominated in USD and a weakening USD makes gold cheaper from the point of view of non-US investors, who are thus increasing their gold consumption.

However Pukthuanthong & Roll (2011) cast doubts against the above mentioned interpretation, by arguing that actually USD is no different than any other currency. They suggest that the gold-USD negative relationship is not casual but mainly statistical. Intuitively, gold can be viewed as a currency-like asset, and when a currency, such as USD, is depreciating on average against all major currencies, it is also usually losing value against gold. Moreover, they show empirically that when denominating the price of gold in Euro (Pound, Yen), a depreciation of Euro (Pound, Yen) against other major currencies is associated with an increase of the price of gold. These results imply that increases of gold USD-price, when USD is depreciating, cannot be solely attributed to an increased gold consumption of non-US investors.

Other than USD, currencies known to be related to gold are “safe-haven currencies” and “commodity currencies”. Surprisingly, literature on relationships between gold and gold importing countries, such as Chinese Yuan (CHY) and Indian Rupee (INR), is scarce. This is probably due to the fact that these countries have been massively importing gold only in the last few decades.

Safe-haven currencies are those currencies that tend to appreciate during periods of economic uncertainty or market instability. Most established safe-haven currencies are Japanese Yen (JPY) and Swiss Franc (SFR). Intuitively, since gold has safe-haven proprieties as well, it can be argued that these currencies and gold are driven by the same factors: they both appreciate in periods of uncertainty/instability. Sjaastad (2008) shows how in the 1991-2004 period JPY was the currency with highest absolute correlation with gold, after USD.

As for commodity currencies, these are merely the currencies of commodity-exporting countries. The idea here is that the price of a commodity is generally found to drive exchange rate fluctuations of countries whose economies heavily rely on the export of that commodity. When it comes to gold, commodity currencies are Australian Dollar (AUD), Canadian Dollar (CAD) and South African Rand (SAR). In particular, Australia is the second world gold producer, with gold being Australia’s third main export.

Apergis (2014) uses prices of gold to forecast the USD/AUD rate, finding that gold prices significantly improve AUD predictability. Additionally, they put the 2 variables in a VAR model and find that the causality relationship is bidirectional, with both directions highly statistically significant.

To sum up, in terms of causality, some currencies drive gold prices (e.g. USD), other currencies are driven by gold prices (e.g. AUD), and other again are driven by the same factors that also drive gold prices (e.g. JPY). However these relationships remain, to some degree, controversial.

6.1.3. Gold and Other Commodities

When it comes to commodities, the most important mention goes to oil. In fact oil prices are possibly the main driver of world inflation. Narayan et al. (2010) examine the long-run relationship between gold and oil, both in the spot and futures markets, and find that they are cointegrated at all maturities in the sample 1963-2008. They argue that "when oil price rises, it creates inflationary pressures, which instigate investments in gold as a hedge against inflation". However, as previously discussed, the relationship between gold and inflation weakens when considering only the last decades.

Other than oil, it should be noted that gold and other precious metals (silver mainly) show high correlations among each other, suggesting that to a large degree they are driven by the same factors. However, Ciner (2001) finds that no long run cointegrating relationship exist between gold and silver futures in the 1992-1998 sample, which contradicts what found in the literature when using previous samples. The authors argue that this may be attributed to the increasing importance of silver as an industrial metal in electronics, while gold role in it remained marginal.

6.2. Contemporaneous Correlations

In this section we consider 48 macroeconomic variables and check their correlation with close-to-close returns r^{CTC}, with returns earned during eastern hours r^{East} and with returns earned during western hours r^{West}. The 48 macro variables are quarterly returns and we correlate them with quarterly East, West and CTC returns.

To narrow down potential candidates, we preselect variables that are sufficiently high correlated with gold returns. In Table 6.1 we present a subset of these variables, selected when the correlation is larger than 20% in absolute terms, $|\rho(r^{Gold}, x^i)| \geq 20$. For transparency, the full correlation matrix is shown in Table A.13 in Appendix A.

Table 6.1. Correlations between Macro Variables and Returns

This table shows correlations between gold returns during different time periods of the day (East, West, Close-to-Close) and the percentage change of macroeconomic variables. We only report correlations above 20% on absolute terms. For variables originally available in daily frequency, we construct their returns r from first to last day of the quarter. All other variables are originally in quarterly frequency. Inflation rates are kept in levels. GDP growth is shown both with respect to previous year g_y^{GDP} and previous quarter g_q^{GDP}.

x^i	$\rho(r^{East}, x^i)$	$\rho(r^{West}, x^i)$	$\rho(r^{CTC}, x^i)$
$r^{Libor-USD}$	-21.54	-	-
r^{Tbill}	-24.06	-	-
$r^{USD/AUD}$	-	-28.00	-41.17
$r^{USD/CHY}$	-	-	-26.17
$r^{USD/EUR}$	-	-	-30.30
$r^{USD/GBP}$	-	-23.15	-20.25
$r^{USD/INR}$	-31.83	-	-37.87
$r^{USD/JPY}$	-34.97	-33.22	-59.59
$r^{USD/SAR}$	-24.24	-	-27.84
$r^{USD/SFR}$	-33.38	-	-39.03
$r^{USD/CAD}$	-	-24.66	-27.15
$r^{USD/TW}$	-21.85	-29.51	-46.47
r^{Brent}	-	27.49	-
$Infl^{China}$	-	20.99	29.97
$g_y^{GDP_{China}}$	27.24	-	30.28
$g_y^{GDP_{India}}$	-	-	20.11
$g_q^{GDP_{Japan}}$	27.69	-	-

Both interest rate returns,[1] $r^{Libor_{USD}}$ and r^{Tbill} are negatively correlated with gold returns, meaning that gold returns are high when interest rates are low and vice versa. Baur (2011) finds the same relationship between gold returns and short term interest rates and Fortune (1987) argues this is due to the opportunity cost of holding gold when there is an interest paying bond available. All FX rates are vis-a-vis the USD and show strong negative correlations, especially CTC returns are correlated with all FX returns, meaning that when the dollar appreciates, gold becomes more expensive for non-US investors also in our data. Baur (2011) points out that gold prices are mainly driven by the price of the USD, which is the same what our correlations suggest. The only

[1]The return of an interest rate is constructed as follows $r_t^i = \frac{1+\hat{r}_t^i}{1+\hat{r}_{t-1}^i} - 1$, where $\hat{r}_t^i$ is the pure Libor or TBill rate.

strongly correlated inflation rate is $Infl^{China}$ and inflation-gold relations are rather controversial as mentioned above. Lastly, growth of real GDP $g_y^{GDP_{China}}$, $g_y^{GDP_{India}}$ and $g_q^{GDP_{Japan}}$ are correlated with East and CTC returns.

6.3. Contemporaneous Regressions

Considering the abundance of macroeconomic variables at hand, we proceed in three steps to reach a compelling regression model. We apply the method of forward selection to distil a set of variables for each gold return (East, West, CTC). That means, we construct three separate models, each geared towards explaining its respective gold returns as good as possible.

6.3.1. Econometric Method

We set up a regression model for each time period of the day (East, West and CTC). The general structure of those linear regression models looks as follows:

$$Y = X\beta + \epsilon \tag{6.1}$$

where Y is a $T \times 1$ vector containing gold returns (e.g. r_t^{East}, r_t^{West} or r_t^{CTC}) and T is the number of quarters, β is a $k \times 1$ vector of coefficients we estimate by ordinary least squares (OLS), X is a $T \times k$ matrix containing $k-1$ explanatory variables (e.g. $r_t^{USD/INR}$) plus a column of ones for the intercept, finally ϵ is a $T \times 1$ vector of residuals, one for each quarter. We assume $\epsilon \sim \mathcal{N}(0,1)$ to be standard normally distributed. This assumption allows standard inference of the estimation results. For the estimation method to produce reliable estimates, we need to take two major problems into account which may lurk in the data:

(i) *Multicollinearity*, which means that explanatory variables are a linear combination of each other, or in other words, they are correlated with each other, $\rho(x_{1,t}, x_{2,t}) \in (-1, 1)$. Multicollinearity happens often, especially with economic variables. As a consequence, the variance of the OLS estimator explodes as $\rho(x_{1,t}, x_{2,t})$ approaches ± 1, which leads to high standard errors and ultimately our regression coefficients becomes insignificant. This is because the OLS estimator cannot distinguish between the effect of $x_{1,t}$ on gold returns and $x_{2,t}$ on gold returns. Thus we aim for low correlation among explanatory variables in the selection process.

(*ii*) *Autocorrelation* in errors arises when one single variable $x_{j,t}$ is correlated with its previous values $x_{j,t-h}$, for $h \in \mathbb{N}$. This type of correlation is called autocorrelation and leads to an increased variance of the OLS estimator and thus to insignificant estimates. We account for that problem by making our explanatory variables stationary and by reporting Newey-West standard errors alongside the OLS standard errors, in case there is still some autocorrelation left in the error term of the fitted model. When the two standard errors are actually different from each other, then there was autocorrelation or heteroskedasticity in the error term.

Forward Selection

We use the method of forward selection, to find an appropriate model specification for each gold return (East, West, CTC). There are two reasons why we use forward instead of backward selection. First, any regression model faces a trade-off between overfitting (losing efficiency) and underfitting (risking biased estimates). Biased estimators are a problem in large samples, because we literally estimate a wrong number in the limit. However, since our sample is only 72 observations, the estimate itself is not very precise and thus a biased estimator is less of a problem than an inefficient estimator. For this reason we aim for a parsimonious model. Second, we have the correlation analysis as a starting point and we are therefore able to set-up an order of preferred explanatory variables, based on the strength of correlation.

The procedure of forward selection is an iterative process and starts by choosing one explanatory variable and estimating the model with it. When the estimates are significant at the 5%, level we continue to add another variable and estimate the model again. We keep on doing this until one or more variables become insignificant. The last model in which all estimates are significant is the final specification. Using this procedure, we are aware of the fact that we are working under the risk of omitting explanatory variables.[2] In total we selected five variables: two foreign exchange returns $r^{USD/JPY}$ and $r^{USD/INR}$. The r^{TBill} which is the return on the 3 months US-TBill rate and r^{Brent} which refers to returns in Brent crude oil. We also include the growth rate of real GDP in China, $g_y^{GDP_{China}}$.

[2]Addressing all econometric issues would be beyond the scope of our thesis and thus we leave that specific exercise for an econometric study in this field.

6.3.2. Empirical Results

Ideal Econometric Models

Strictly applying the forward selection procedure, yields one single model specification for each of the three returns. By construction all explanatory variables are highly significant at least at the 5% level, ignoring the intercept. However, since we want to compare the models for each of the three returns, we need to use the same set of explanatory variables in each model. For this reason, we abstain form a detailed interpretation of these ideal models for the moment, because we will do that in the section below. For transparency reasons however, we show the estimated models in Table 6.2 below.

Table 6.2. Estimation Results Ideal Specification

This table shows results from three different regression models. The first panel shows the model for Close-to-Close returns, the second for East returns and the third for West returns. The first row in each panel shows the estimated coefficient and we report OLS-standard errors in parenthesis as well as Newey-West standard errors in squared brackets.***,**,* denote significance at the 1%, 5% and 10% level.

	$\hat{\beta}_0$	$r^{USD/JPY}$	$r^{USD/INR}$	$g_y^{GDP_{China}}$	r^{Brent}	r^{Tbill}	R^2
r^{CTC}	-0.09	-3.09***	-1.76**	2.00**	0.32***		53.6%
	(0.10)	(0.45)	(0.67)	(1.09)	(0.12)		
	[0.10]	[0.48]	[0.93]	[1.06]	[0.13]		
r^{East}	-0.05	-1.09**	-1.30***	1.78**			23.8%
	(0.09)	(0.39)	(0.59)	(0.95)			
	[0.08]	[0.49]	[0.55]	[0.85]			
r^{West}	-0.03	-2.35 ***			0.47***	9.72**	24.7%
	(0.03)	(0.60)			(0.16)	(8.25)	
	[0.03]	[0.77]			[0.17]	[5.30]	

Comparable Econometric Models

For the model comparison to be valid we need to estimate the same set of explanatory variables on the three different returns (CTC, East and West). Table 6.3 shows those three models, each in one panel, and each panel shows the estimated coeffiencients and its standard errors (OLS) and [Newey-West]. Statistical significance was taken from Newey-West standard errors. First off, we realize that there are either insignificant or weakly significant estimates in all models, which is what we have expected when adding redundant variables. We also find, that exactly those variables which were not part of the ideal specification are weakly significant or insignificant.

Table 6.3. Estimation Results

This table shows results from three different regression models. The first panel shows the model for Close-to-Close returns, the second for East returns and the third for West returns. The first row in each panel shows the estimated coefficient and we report OLS-standard errors in parenthesis as well as Newey-West standard errors in squared brackets.***,**,* denote significance at the 1%, 5% and 10% level.

	$\hat{\beta}_0$	$r^{USD/JPY}$	$r^{USD/INR}$	$g_y^{GDP_{China}}$	r^{Brent}	r^{Tbill}	R^2
r^{CTC}	-0.10	-3.15***	-1.74**	2.09**	0.30**	3.77	53.9%
	(0.10)	(0.46)	(0.68)	(1.10)	(0.13)	(6.27)	
	[0.10]	[0.48]	[0.93]	[1.09]	[0.14]	[4.76]	
r^{East}	-0.07	-0.83**	-1.52***	2.02**	-0.16*	-5.93*	28.4%
	(0.09)	(0.40)	(0.59)	(0.96)	(0.11)	(5.48)	
	[0.09]	[0.47]	[0.58]	[1.01]	[0.10]	[3.86]	
r^{West}	-0.03	-2.32***	-0.22	0.08	0.46***	9.70**	24.8%
	(0.14)	(0.62)	(0.91)	(6.14)	(1.51)	(0.17)	
	[0.13]	[0.76]	[1.00]	[3.87]	[1.35]	[0.17]	

Close-to-Close Model

The top panel of Table 6.3 shows estimates and standard errors (OLS) and [Newey-West] of the Close-to-Close model, meaning that we regress CTC returns on the given set of five explanatory variables plus an intercept. All estimates except of r^{TBill} and the intercept are significant at least at the 5% level.

Starting with FX returns, both coefficients are negative with -3.15 on $r^{USD/JPY}$ and -1.74 on $r^{USD/INR}$, confirming that when the USD appreciates against other currencies, gold becomes more expensive for non-US investors. Therefore they decrease their demand, resulting in lower gold prices. For instance, an increase of 1 percentage point of $r^{USD/JPY}$ decreases the CTC return of gold by 3.15 percentage points on average. On the one side, both the $r^{USD/JPY}$ and $r^{USD/INR}$ share the same above mentioned intuition. On the other side, JPY holds an additional unique insight. The Yen is a safe-haven currency, and therefore a strengthening JPY against the USD is a sign of financial uncertainty, resulting in gold appreciating as well. As for $g_y^{GDP_{China}}$, when China's real GDP growth increases by 1 percentage point, then CTC gold returns increase by 2.09 percentage points on average. We can interpret this as an income effect, with Chinese people consuming more gold when they are getting richer.

r^{Brent} is an indicator for world inflation and has a statistically significant loading of +0.30. The magnitude is not very large, meaning that a change of 1 percentage point in r^{Brent} underproportionally moves CTC gold returns only by 0.30 percentage points. Yet its statistical significance shows that there exists a stable relationship between gold return movements and returns of crude oil prices. The common denominator in this relationship is that a positive change in oil price increases global inflation, which in turn increases demand for gold.

r^{TBill} is economically significant with a loading of +3.77. The positive sign means that when interest rates increase and opportunity cost for holding non-yield-paying gold increase, gold prices increase as well, which does not make sense. Nevertheless, it is statistically insignificant. The precise interpretation of the loading is different from others, because the r^{TBill} is an interest rate. When it increases from, say 2% to 2.5% this is not a 25% increase, but a $\frac{1+r^{TBill_t}}{1+r^{TBill_{t-1}}} - 1 = 0.0049\%$, which is 49 basis points (BP) or 0.49%. Accordingly, an increase of 10BP in r^{TBill} would move gold returns by 0.38 percentage points.

East Model

The East model is reported in the middle panel of Table 6.3. We abstain from repeating the whole interpretation again and rather focus on differences to the CTC model and their meaning for the overall context of our narrative. All variables except of the intercept are significant at least at the 10% level.

Starting with FX returns, the signs are the same, but the the loading on $r^{USD/JPY}$ has decreased by $\sim$ 75% whereas the loading on $r^{USD/INR}$ has only decreased by $\sim$ 15%. Also their role has swapped in terms of economic and statistical significance because the loading on $r^{USD/JPY}$ is half the size of the loading of $r^{USD/INR}$, meaning that INR plays a more significant role in explaining East returns than the JPY. This means that returns earned during eastern hours are more sensitive to appreciation of INR rather than JPY, which in turn means that improvements in the well-being of the Indian economy have a much stronger effect on East returns.

$g_y^{GDP_{China}}$ is statistically significant at the 5% level and has the largest loading with +2.02. The size of the loading and its statistical significance has remained almost the same compared to the CTC model. This is a sign for China's demand predominance in the gold market during Eastern trading hours. r^{Brent} has changed its economic and statistical significance, with a loading having swapped sign, halved in size to -0.16 and decreased in significance only at the 10% level. This means r^{Brent} has lost in economic relevance during Eastern trading hours and even changed its effect on gold returns. Increases in r^{Brent} decrease gold returns which indicates that Asian clientele is less concerned about inflation when making investment decisions about gold. r^{TBill} has swapped sign, increased in magnitude to -5.93 and became statistically significant at the 10% level. [3] The negative sign means that when short term rates increase, gold returns decrease. According to the literature, the decrease in gold returns is due to an increase in opportunity cost of holding non-yield paying gold. Put in context of our thesis, this means, that eastern clientele actually trades off interest vs non-interest paying investment opportunities when it comes to investment choices.

West Model

The West model is reported in the bottom panel of Table 6.3. We abstain from repeating the whole interpretation and rather focus on differences to the East model and to the CTC model, and their meaning for the overall context of our narrative. $r^{USD/INR}$ and $g_y^{GDP_{China}}$ are statistically insignificant, which tells us that the main drivers of East returns, play no role in explaining West returns.

Starting with FX returns, statistical and economic significance has swapped compared with the East model. $r^{USD/JPY}$ has a loading of -2.32 and is highly significant at the 1% level whereas $r^{USD/INR}$ has a loading of -0.22 which is not statistically significant. This time it is the save-haven currency JPY that actually plays a role in explaining gold returns earned during western trading hours. Most interestingly, the save-haven property of JPY and gold seem to play a role in investment choices of western clientele. $g_y^{GDP_{China}}$ is statistically insignificant and of low magnitude of +0.08. The Chinese GDP has no effect on western gold returns, which contrasts the results in the East and CTC model. This result means that China's demand for gold does not materialize in West gold returns, which makes sense because Chinese investors do not trade in western hours. r^{Brent} is statistically highly significant at the 1% level and has a loading of +0.46. Its magnitude has increased by roughly 50% compared to the CTC model, which means that western clientele is more concerned about inflation when making investment choices in gold, and they buy more of it when inflation rises. Again, the relationship is not very strong but very significant which indicates a

[3] Bear in mind the different interpretation of r^{TBill}.

stable relationship. r^{TBill} has increased in statistical significance to 5% and in economic significance as its loading has increase to 9.70. This means western gold returns are more sensitive to r^{TBill} and most interestingly gold returns move in the same direction as the short term $TBill$ rate which only makes sense if we assume a different underlying mechanism than before. Assuming that an increase in expected inflation also increases interest rates. Then the initial increase in inflation is actually drives gold prices up (Abken 1980).

6.4. Summary of Results

In this chapter we mainly wanted to understand if the variation in gold returns earned during eastern and western trading hours can be explained by monetary and macroeconomic variables. In fact, 53.9% of variation in close-to-close returns, 28.4% in East returns and 24.8% in West returns can be explained by five variables: $r^{USD/JPY}$, $r^{USD/INR}$, $g_y^{GDP_{China}}$, r^{Brent} and r^{TBill}.

We find that East returns are explained well by $r^{USD/INR}$ and $g_y^{GDP_{China}}$. In contrast, West returns are not explained by these variables at all. This makes sense because when Chinese GDP grows and INR appreciates, India and China increase their gold consumption, and of course they do it in eastern hours. Furthermore, we find that West returns are explained well by $r^{USD/JPY}$ and r^{Brent}, while East returns are not. This suggests that when JPY and Brent appreciate (signals of financial uncertainty and inflation), western investors buy more gold as a safe-haven investment, while eastern investors do not. This may be explained by a more culturally motivated gold demand from the eastern clientele, in which therefore inflation plays a smaller role in making investment choices.

Chapter 7

Trading Strategies

In Chapter 4 we derived the intraday return pattern of Figure 4.1. In Chapter 5 we observed that none of the sections of this pattern is so robust to be considered time-independent, meaning that we should expect days, months or years in which the pattern looks completely different.

Nevertheless, the intraday return pattern of Figure 4.1 recurred most of the time, so far. The current chapter investigates if this recurrence can be exploited with profit. In particular, we observe two main facts: (i) the hat shape and (ii) the two downward spikes. Even though we could not actually *accurately* know these facts back in time, we now use them to set up trading strategies with the purpose of backtesting how much the pattern could have been exploited in a *best* case scenario.

In particular we set up 4 active trading strategies and we compare their profitability and performance with those of 2 traditional passive investment strategies. We first assume no transaction costs and then extend our analysis by introducing transaction costs. We measure the performance of all strategies by the Sharpe Ratio, since this is the most used in literature. Additionally, we report the Sortino Ratio, which is widely used among practitioners. We conclude the chapter by relating our results to the Efficient Markets Hypothesis.

7.1. Active and Passive Strategies

From the pattern in Figure 4.1 we observe two main facts: (i) the hat shape and (ii) the downward spikes. In order to set up the trading strategies that exploit the hat the most, we identify the two points of the pattern in which the trend changes its up/down direction. Additionally, in order to set up the trading strategies that exploit the spikes the most, we focus on the steep decrease of prices in the half hours before the two fixings.

Thus, the 4 best[1] performing trading strategies are:

- Short strategy - holding a short position when gold on average depreciates (2:00-11:00).
- Long strategy - holding a long position when gold on average appreciates (11:00-2:00).
- Combo strategy - performing both Long and Short strategies.
- Fixing strategy - holding a short position in the 5:05-5:35 and in the 9:35-10:05 periods.

The above strategies require multiple transactions each and every day to be continuously implemented over time. We will compare profitability and performance of these 4 active trading strategies with those of 2 passive investment strategies:

- S&P500 strategy - continuously holding a long position in the S&P500 [2]
- Hold strategy - continuously holding a long position in gold

7.2. Performance Measures

In this chapter we measure profitability and performance of the 6 strategies. Performance is another way of saying "risk-adjusted profitability", and we measure it with the Sharpe Ratio and the Sortino Ratio. Intuitively, different portfolios yielding the same return may have different volatilities of returns and therefore a rational risk-adverse individual may prefer investing in those with smaller risk. The Sharpe/Sortino Ratio tells us how much excess return is obtained per unit of risk taken. Thus a high Sharpe/Sortino Ratio means that the portfolio has a good performance. For our purposes we calculate the annualized Sharpe Ratio ${}^{a}\mathcal{SR}$ and the annualized Sortino Ratio ${}^{a}\mathcal{SR}_{\ominus}$ using 18 sub-samples of one year each. In each one year sample they are calculated as follow:

$$ {}^{a}\mathcal{SR} = \frac{{}^{a}\mu - {}^{a}r_f}{{}^{a}\sigma} \qquad\qquad {}^{a}\mathcal{SR}_{\ominus} = \frac{{}^{a}\mu - {}^{a}r_{ma}}{{}^{a}\sigma_{\ominus}} $$

[1]On a side note, in Chapter 5 we observed that gold close-to-close returns are way higher in the Winter period than in the Summer, and therefore we would be very temped to include an additional "Winter strategy". However, we find no logical explanation for this fact other than random chance and therefore we disregard it.

[2]The S&P500 that we consider is actually the S&P500 Total Return Index, an index assuming that dividends are immediately reinvested whenever issued. As a result, its growth is steeper than the traditional S&P500 index and it gives a more accurate representation of the investment. Data is taken from Bloomberg.

Where:

$$r_d = \text{daily log return of the strategy on a specific day } d$$

$$N = \text{number of days in the year} \approx 252$$

$$\mu = \text{average daily return of the strategy in the year} = \frac{\sum_{d=1}^{N} r_d}{N}$$

$$\begin{aligned} {}^a\mu &= \text{annualized average daily return of the strategy in the year} = \mu \times N \\ &= \text{return of the strategy in the year} = \sum_{d=1}^{N} r_d \end{aligned}$$

$$\begin{aligned} {}^a r_f &= \text{annualized risk free rate} \\ &= \text{annualized average 3 months T-Bill rate in the year} \end{aligned}$$

$$\begin{aligned} {}^a r_{ma} &= \text{annualized minimum acceptable return} \\ &= \text{annualized average 3 months T-Bill rate in the year} \end{aligned}$$

$$r_{ma} = \text{daily minimum acceptable return} = \frac{{}^a r_{ma}}{N}$$

$$\begin{aligned} {}^a\sigma &= \text{annualized standard deviation of daily returns} \\ &= \sigma \times \sqrt{N} = \sqrt{\frac{\sum_{d=1}^{N}(r_d - \mu)^2}{N-1}} \times \sqrt{N} \end{aligned}$$

$$\begin{aligned} {}^a\sigma_\ominus &= \text{annualized downside deviation of daily returns} \\ &= \sigma_\ominus \times \sqrt{N} = \sqrt{\frac{\sum_{d=1}^{N}[min(r_d - r_{ma}, 0)]^2}{N-1}} \times \sqrt{N} \end{aligned}$$

Sharpe Ratio ${}^a\mathcal{SR}$ and Sortino Ratio ${}^a\mathcal{SR}_\ominus$ are very similar in the sense that both of them are ratios of excess return to returns' volatility. The main difference between the two is that the Sharpe Ratio has standard deviation ${}^a\sigma$ as denominator, while the Sortino Ratio has downside deviation ${}^a\sigma_\ominus$ as denominator. Both standard and downside deviations are measures of volatility of daily returns. However the standard deviation considers both upside and downside volatility of daily returns with respect to their mean μ, while the downside deviation considers only downside volatility of daily returns with respect to a minimum acceptable return r_{ma}. The economic argument for using the Sortino Ratio, rather than the Sharpe Ratio, is that portfolio managers and investors are mainly worried about downside volatility, meaning that the Sortino Ratio may give a more accurate idea of which portfolios have preferable return distributions. As for the ${}^{a}r_f$, we set this equal to the annualized 3 months T-Bill rate. As for the ${}^{a}r_{ma}$, practitioners often set this equal to zero or equal to the ${}^{a}r_f$, we choose the latter solution.

In the following sections we apply Sharpe Ratios and Sortino Ratios, as outlined above, to the 4 active strategies. Additionally, we do the same for the 2 passive strategies, which are often considered a benchmark.

7.3. Without Transaction Costs

In this section we assume no transaction costs, meaning that in any day d at any time hh:mm a gold futures contract can be bought or sold at the current mid price $M_d^{\text{hh:mm}}$. It follows that daily returns r_d of all the strategies are computed using mid prices. We denote $m_d^{\text{hh:mm}} = ln(M_d^{\text{hh:mm}})$. Daily returns of the 2 passive strategies are computed from close prices [3]. Therefore these can be seen as close-to-close returns:

$$r_d^{\text{S\&P500}} = m_d^{16:00} - m_{d-1}^{16:00}$$

$$r_d^{\text{Hold}} = m_d^{17:00} - m_{d-1}^{17:00}$$

Daily returns of the 4 active strategies are as follows:

$$r_d^{\text{Short}} = -m_d^{11:00} + m_d^{2:00}$$

$$r_d^{\text{Long}} = m_{d+1}^{2:00} - m_d^{11:00}$$

$$r_d^{\text{Combo}} = r_d^{\text{Long}} + r_d^{\text{Short}}$$

$$r_d^{\text{Fixing}} = -m_d^{5:35} + m_d^{5:05} - m_d^{10:05} + m_d^{9:35}$$

[3] COMEX closes at 17:00 and NYSE closes at 16:00

7.3.1. Profitability

Once daily returns are computed, we can aggregate them by month, by quarter and by year [4]. In our analysis we focus only on yearly returns. However, for transparency, we show monthly and quarterly returns (annualized) of the 6 strategies in Figures B.7 and B.8 in the Appendix.

Yearly returns of the 6 strategies are shown in Table 7.1. The first 18 rows show returns for each individual year. The following 3 rows show average yearly returns in the 3 subsamples $\mathcal{A}$, $\mathcal{B}$ and $\mathcal{C}$. The last row shows the average yearly returns in the full sample $\mathcal{ABC}$.

In particular, from the last row of Table 7.1, we observe that the 4 active strategies [Short (10.0%), Long (18.6%), Combo (28.6%), Fix (7.6%)] are more profitable than the 2 passive ones [S&P500 (5.5%), Hold (8.6%)] in the full sample. The returns of the active strategies are consistent with what we already saw in Figure 4.1 : in the 2-to-11 period gold prices go down, with an annualized return of -10%, while in the 11-to-2 period they go up, with an annualized return of 18.6%. Overall in the 24-hour day this translates in an annualized return of 8.6%. Also, this means that if we hold a short position in the 2-to-11 period and a long position in the 11-to-2 period each and every day, we obtain a return of 28.6% per year. As for the Fixing strategy, it is indeed surprising that a strategy with positions open only 1 hour per day, can return more than the S&P500.

Since the returns of the active strategies in Table 7.1 depend on the shape of the intraday return pattern, they can be seen as measures of how pronounced the different sections of the pattern are at each particular point in time in the 2001-2018 sample period.

We can notice that the profits of the Fixing strategy come almost entirely from a few years. These years correspond roughly to the $\mathcal{B}$ sub-sample, period in which Fixing returned 16.6% per year on average. As discussed in Chapter 5, these were the years in which gold fixing banks allegedly performed manipulation. The numbers are in line with the puzzling pattern seen in Figure 5.2, in which we see almost no downward spikes in $\mathcal{A}$ and $\mathcal{C}$ and big ones in $\mathcal{B}$.

As for the Combo strategy, excluding a few recent years (2014, 2017, 2018), yearly returns are always greater than 10%. This is in line with what we saw in Figure 5.3.

[4] Due to the properties of log returns, each annualized monthly return can be computed in two ways: by (a) taking the average of annualized daily returns in that month, or by (b) first obtaining the non-annualized monthly return as the sum of non-annualized daily returns in that month and then annualizing. Similar arguments apply to annualized quarterly returns and yearly returns.

Table 7.1. Yearly Returns, without Transaction Costs

This table shows yearly returns ${}^{a}\mu$ of the 6 strategies assuming no transaction costs. Each yearly return is the sum of daily log returns in that year. Values in the last 4 rows are averages of the above yearly returns in the $\mathcal{A}$ sub-sample (2001-2006), $\mathcal{B}$ sub-sample (2007-2012), $\mathcal{C}$ sub-sample (2013-2018) and $\mathcal{ABC}$ full sample (2001-2018). To give a more comprehensive understanding of the profitability, negative returns are in red and returns above 10% are in green.

	Passive Strategies		Active Strategies				${}^{a}r_f$
	S&P500	Hold	Short	Long	Combo	Fixing	
2001	-12.7%	1.1%	13.2%	14.4%	27.6%	1.4%	3.4%
2002	-25.0%	21.6%	-3.1%	19.0%	15.8%	0.8%	1.6%
2003	25.2%	19.5%	12.5%	31.5%	44.0%	3.1%	1.0%
2004	10.3%	4.3%	13.9%	18.0%	31.9%	3.8%	1.4%
2005	4.8%	17.5%	-1.7%	16.1%	14.4%	1.2%	3.2%
2006	14.7%	20.8%	22.2%	43.1%	65.3%	5.9%	4.7%
2007	5.3%	26.9%	3.2%	30.0%	33.2%	8.6%	4.4%
2008	-46.2%	5.2%	11.5%	15.8%	27.2%	13.9%	1.4%
2009	23.5%	21.9%	1.7%	24.9%	26.6%	29.8%	0.1%
2010	14.0%	25.9%	7.4%	32.7%	40.2%	22.6%	0.1%
2011	2.1%	9.7%	15.6%	26.9%	42.5%	19.2%	0.1%
2012	14.8%	6.7%	3.0%	8.6%	11.6%	5.7%	0.1%
2013	28.1%	-32.9%	45.1%	13.3%	58.4%	9.5%	0.1%
2014	12.8%	-1.8%	4.4%	1.4%	5.8%	0.5%	0.0%
2015	1.4%	-10.9%	30.6%	20.2%	50.7%	6.9%	0.1%
2016	11.3%	8.2%	5.5%	13.3%	18.8%	7.7%	0.3%
2017	19.7%	12.5%	-3.7%	8.7%	5.1%	-0.2%	0.9%
2018	-5.3%	-1.7%	-1.1%	-3.2%	-4.3%	-3.2%	1.9%
$\mathcal{A}$	2.9%	14.1%	9.5%	23.7%	33.2%	2.7%	2.5%
$\mathcal{B}$	2.3%	16.0%	7.1%	23.1%	30.2%	16.6%	1.0%
$\mathcal{C}$	11.3%	-4.4%	13.5%	8.9%	22.4%	3.5%	0.6%
$\mathcal{ABC}$	5.5%	8.6%	10.0%	18.6%	28.6%	7.6%	1.4%

More in general these numbers confirm that the hat shape is not coming only from a few years but it is somewhat robust over time, with 11 years with returns above 25%.

7.3.2. Performance

So far we analysed profitability ${}^{a}\mu$ of the 6 strategies with no transaction costs, and we observed that the 4 active strategies have overall been more profitable than the 2 passive ones. Now we keep the assumption of no transaction costs and we move our attention to performance. Sharpe Ratios ${}^{a}\mathcal{SR}$ of the 6 strategies are shown in Table A.14 in the Appendix. Sortino Ratios ${}^{a}\mathcal{SR}_{\ominus}$ of the 6 strategies are shown in Table A.15 in the Appendix. Both tables maintain the structure of Table 7.1. The first 18 rows show Sharpe/Sortino ratios for each individual year. The following 3 rows show averages of yearly Sharpe/Sortino ratios in the 3 subsamples $\mathcal{A}$, $\mathcal{B}$ and $\mathcal{C}$. The last row shows averages of yearly Sharpe/Sortino ratios in the full sample $\mathcal{ABC}$.

We are interested in seeing if the good returns of the 4 active strategies in Table 7.1 mainly represent compensation due to bigger risk exposure or due to smart investment. When looking at the last row of Table A.14, we see that the averages of yearly Sharpe Ratios are higher for the 4 active strategies [Short (0.69), Long (1.40), Combo (1.61), Fix (0.96)], and smaller for the 2 passive ones [S&P500 (0.58), Hold (0.45)]. When looking at the last row of Table A.15, we observe that averages of yearly Sortino ratios confirm the previous results: all the active strategies [Short (1.19), Long (2.19), Combo (2.63), Fix (1.65)] outperform the passive ones [S&P500 (0.88), Hold (0.67)].

From both tables we see once again that Fixing has excellent results only in the few years of sample $\mathcal{B}$, while the other 3 active strategies are more robust over time. If in terms of profitability the Fixing strategy was behind Hold and Short, in terms of performance it is now better. This is due to its lower volatility of returns, which makes intuitively sense since Fixing has open positions for only 60 minutes per day.

Turning to the Combo strategy, this can be seen as a portfolio of Long and Short and it is straightforward that its return is the sum of its components. What is not straightforward is its higher performance. This depends on the fact that Long and Short are not correlated (-0.05%, using daily returns), characteristics that makes Combo a well diversified portfolio. Hence, the highest ${}^{a}\mathcal{SR}$ and ${}^{a}\mathcal{SR}_{\ominus}$.

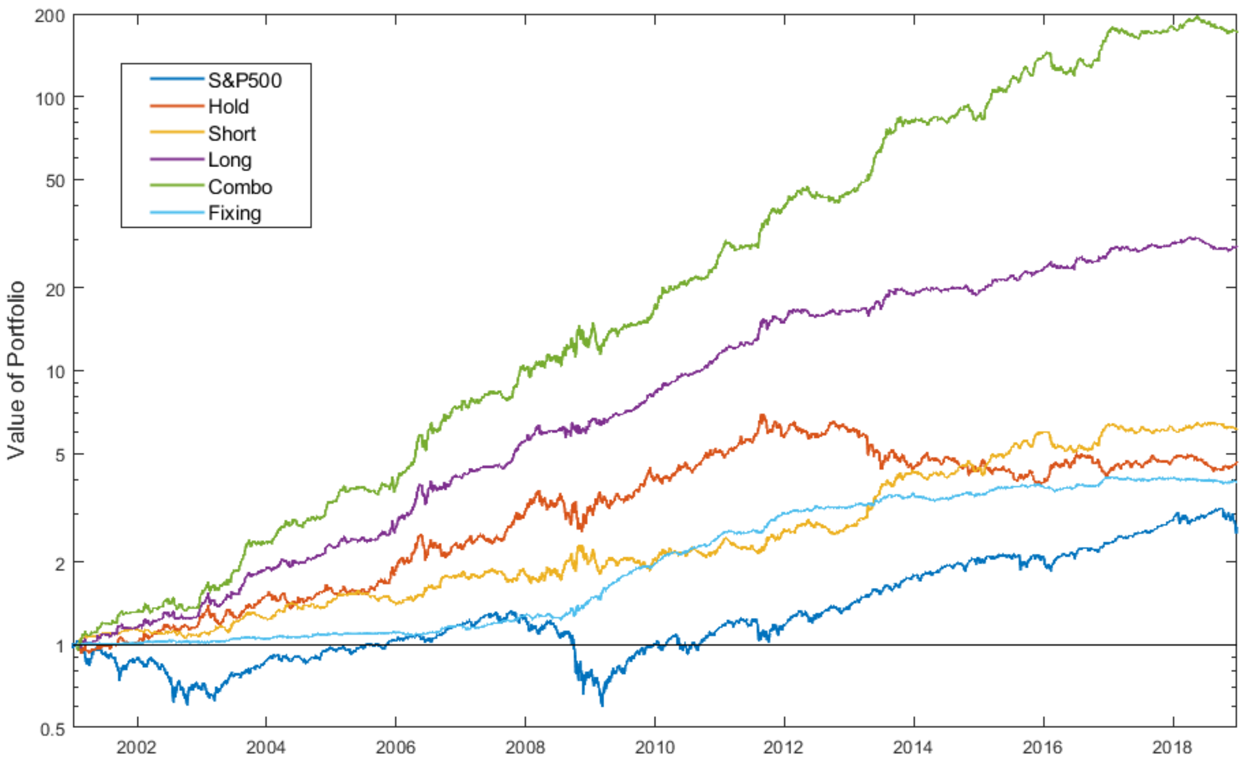


Figure 7.1. Portfolios' Values, without Transaction Costs
The figure shows the value of 6 portfolios employing the 6 different strategies, starting with an initial investment of 1 USD. The figure is in log scale.

7.3.3. Portfolios

We now provide an additional representation of an investment in the 6 strategies. We assume to be standing on the 1^{st} Jan 2001 and to invest 1 USD in 6 different portfolios, each portfolio focused on one of the 6 different strategies. Using daily returns r_d of the strategies we can calculate the value of the portfolio V_d in any day d as follows:

$$V_d = V_{d-1} \times e^{r_d}$$

Figure 7.1 shows in log scale 6 time series, each one representing the value over time of one of the 6 portfolios. As expected, all portfolios' values grow overall, with terminal values on the 31^{st} Dec 2018 higher for active portfolios [Short (6.06$), Long (28.37$), Combo (172.05$), Fix (3.94$)] and smaller for passive ones [S&P500 (2.69$), Hold (4.68$)].

Results encountered so far are really promising. Nevertheless, they belong to an imaginary world in which transaction costs do not exist. Since the active trading strategies considered require 2 to 4 transactions per day, we should expect these costs to wipe out most of the good profitability and performance. We check to which degree this is true in the next section.

7.4. With Transaction Costs

In this section we now drop the assumption of no transaction costs. We instead assume transaction costs to be 100% of bid-ask spread for all 4 active strategies. This means that at any time hh:mm in any day d we can enter a long position at the ask price $A_d^{\text{hh:mm}}$ and a short position at the bid price $B_d^{\text{hh:mm}}$. We compute bids and asks again, starting from mid prices $M_d^{\text{hh:mm}}$ and the cleaned spreads $\Delta_d^{\text{hh:mm}}$, from Chapter 3. Bids and asks are:

$$A_d^{\text{hh:mm}} = M_d^{\text{hh:mm}} + \frac{\Delta_d^{\text{hh:mm}}}{2}$$

$$B_d^{\text{hh:mm}} = M_d^{\text{hh:mm}} - \frac{\Delta_d^{\text{hh:mm}}}{2}$$

We denote $a_d^{\text{hh:mm}} = ln(A_d^{\text{hh:mm}})$, and $b_d^{\text{hh:mm}} = ln(B_d^{\text{hh:mm}})$.

Once we have bids and asks, we can compute daily returns r_d of the 4 active strategies:

$$r_d^{\text{Short}} = -a_d^{11:00} + b_d^{2:00}$$

$$r_d^{\text{Long}} = b_{d+1}^{2:00} - a_d^{11:00}$$

$$r_d^{\text{Combo}} = r_d^{\text{Long}} + r_d^{\text{Short}}$$

$$r_d^{\text{Fixing}} = -a_d^{5:35} + b_d^{5:05} - a_d^{10:05} + b_d^{9:35}$$

As for the 2 passive strategies, they do not require multiple transactions each and every day they are implemented, and therefore we compute $r_d^{\text{S\&P500}}$ and r_d^{Hold} as in the previous section:

$$r_d^{\text{S\&P500}} = m_d^{16:00} - m_{d-1}^{16:00}$$

$$r_d^{\text{Hold}} = m_d^{17:00} - m_{d-1}^{17:00}$$

The Hold strategy does actually have some transaction costs: implementing this strategy requires opening (and closing) a long position in a GC1/GC2 futures once every two months. However this cost is somewhat irrelevant [5] when compared to costs of active strategies: while Short (42), Long (42), Combo (84) and Fixing (84) require many trades per month, Hold only requires 1 on average. Same argument can be made for S&P500: investing in an ETF tracking an index requires a management fee, but this cost is really small when compared to the cost of implementing the 4 active strategies. For simplicity in this section we assume transaction costs of the 2 passive strategies to be null, as in the previous section.

7.4.1. Profitability

As for active strategies, since we are considering transaction costs now, we expect profitability to be particularly bad in those periods in which spreads were high. As shown in Figure 3.1, spreads were particularly wide in the early years of the full sample, and much tighter later on. This is certainly connected to the fact that trading volumes were smaller back in time.

Table 7.2 keeps the same structure of previous tables, and shows yearly returns of active and passive strategies when including transaction costs.

As expected, yearly returns of the 4 active trading strategies are remarkably bad in the first years, often below -50% for Long and Short, and often below -100% for Combo and Fixing. This makes sense since Combo and Fixing require twice as much transactions.

We can now observe the impact of transaction costs. For instance, Long strategy has yearly returns of -48.4%, 6.3% and 1.7% in subsamples $\mathcal{A}$, $\mathcal{B}$ and $\mathcal{C}$. When assuming no transaction costs, the same returns were 23.7%, 23.1% and 8.9%. This means that transaction costs reduce returns respectively of 72, 17 and 7 percentage points in $\mathcal{A}$, $\mathcal{B}$, and $\mathcal{C}$. This is due to the fact that spreads were very high in sample $\mathcal{A}$ (0.25% of mid prices, on average), way smaller in $\mathcal{B}$ (0.06% of mid prices, on average), and even smaller in $\mathcal{C}$ (0.03% of mid prices, on average). We observe similar results for for Short, Combo and Fixing. At any rate, we should point out that results in this section rely heavily on (i) data quality and (ii) assumptions made in the data cleaning process.

[5] Similar in size to the storage cost paid by owners of physical gold or to the management fee paid when investing in a the SPDR Gold Shares.

Table 7.2. Yearly Returns, with Transaction Costs

This table shows yearly returns ${}^{a}\mu$ of the 6 strategies assuming that transaction costs are 100% of spreads. Each yearly return is the sum of daily log returns in that year. Values in the last 4 rows are averages of the above yearly returns in the $\mathcal{A}$ sub-sample (2001-2006), $\mathcal{B}$ sub-sample (2007-2012), $\mathcal{C}$ sub-sample (2013-2018) and $\mathcal{ABC}$ full sample (2001-2018). To give a more comprehensive understanding of the profitability, negative returns are in red and returns above 10% are in green.

	Passive Strategies		Active Strategies				${}^{a}r_f$
	S&P500	Hold	Short	Long	Combo	Fixing	
2001	-12.7%	1.1%	-68.8%	-67.7%	-136.5%	-163.5%	3.4%
2002	-25.0%	21.6%	-85.4%	-63.4%	-148.8%	-152.4%	1.6%
2003	25.2%	19.5%	-58.9%	-39.8%	-98.7%	-124.4%	1.0%
2004	10.3%	4.3%	-52.4%	-48.4%	-100.8%	-115.1%	1.4%
2005	4.8%	17.5%	-68.7%	-50.8%	-119.5%	-104.4%	3.2%
2006	14.7%	20.8%	-41.0%	-20.2%	-61.2%	-95.2%	4.7%
2007	5.3%	26.9%	-33.9%	-7.1%	-41.0%	-45.0%	4.4%
2008	-46.2%	5.2%	-2.2%	2.2%	0.0%	-21.3%	1.4%
2009	23.5%	21.9%	-16.3%	6.9%	-9.5%	7.3%	0.1%
2010	14.0%	25.9%	-12.6%	12.7%	0.1%	8.1%	0.1%
2011	2.1%	9.7%	11.3%	22.6%	33.9%	8.4%	0.1%
2012	14.8%	6.7%	-5.1%	0.4%	-4.7%	-4.7%	0.1%
2013	28.1%	-32.9%	36.8%	5.0%	41.8%	-2.6%	0.1%
2014	12.8%	-1.8%	-2.5%	-5.6%	-8.1%	-11.8%	0.0%
2015	1.4%	-10.9%	26.0%	15.6%	41.5%	-7.0%	0.1%
2016	11.3%	8.2%	2.2%	10.1%	12.3%	-4.6%	0.3%
2017	19.7%	12.5%	-12.7%	-0.4%	-13.1%	-11.3%	0.9%
2018	-5.3%	-1.7%	-12.6%	-14.6%	-27.2%	-18.8%	1.9%
$\mathcal{A}$	2.9%	14.1%	-62.5%	-48.4%	-110.9%	-125.8%	2.5%
$\mathcal{B}$	2.3%	16.0%	-9.8%	6.3%	-3.5%	-7.9%	1.0%
$\mathcal{C}$	11.3%	-4.4%	6.2%	1.7%	7.9%	-9.3%	0.6%
$\mathcal{ABC}$	5.5%	8.6%	-22.0%	-13.5%	-35.5%	-47.7%	1.4%

Summing up, Fixing has only 3 profitable years. Interestingly, it is unprofitable even in sample $\mathcal{B}$. Long, Short and Combo are very unprofitable overall, but profitable when excluding the first half of the sample. Despite the promising fact that spreads are getting lower over time, there is no evidence of the 4 active strategies beating the 2 passive ones in profitability (except in some specific lucky years).

7.4.2. Performance

Turning now to performance, Sharpe Ratios ${}^{a}\mathcal{SR}$ of the 6 strategies are shown in Table A.16 in the Appendix. Sortino Ratios ${}^{a}\mathcal{SR}_{\ominus}$ of the 6 strategies are shown in Table A.17 in the Appendix. The two tables keep the same structure as before. Results are in line with what observed in profitability terms: the 4 active trading strategies underperform the 2 passive investment strategies. We see that at least Short, Long and Combo have some very positive Sharpe/Sortino ratios in a few years (2011, 2013 and 2015) and decent Sharpe/Sortino ratios in $\mathcal{B}$ and $\mathcal{C}$. As for Fixing, despite the good performance in 2009, 2010, 2011, Sharpe/Sortino Ratios are negative even in $\mathcal{B}$ (and way worse in $\mathcal{A}$ and $\mathcal{C}$).

7.4.3. Portfolios

Just like we did before, we assume to be standing on the 1^{st} Jan 2001 and to invest 1 USD in 6 different portfolios, each portfolio focused on one of the 6 strategies. Using daily returns of the strategies we can calculate the value of the portfolio V_d in any day d. Figure 7.2 shows in log scale the value over time of the 6 portfolios, when transaction costs are considered. As expected, the 4 active portfolios perform terribly in the first 5 years: all of them burning more than 90% of their capital. As discussed, this is because of high spreads. More interestingly, after 2008 all the active trading strategies (except Fixing) recover some of their value and are actually profitable.

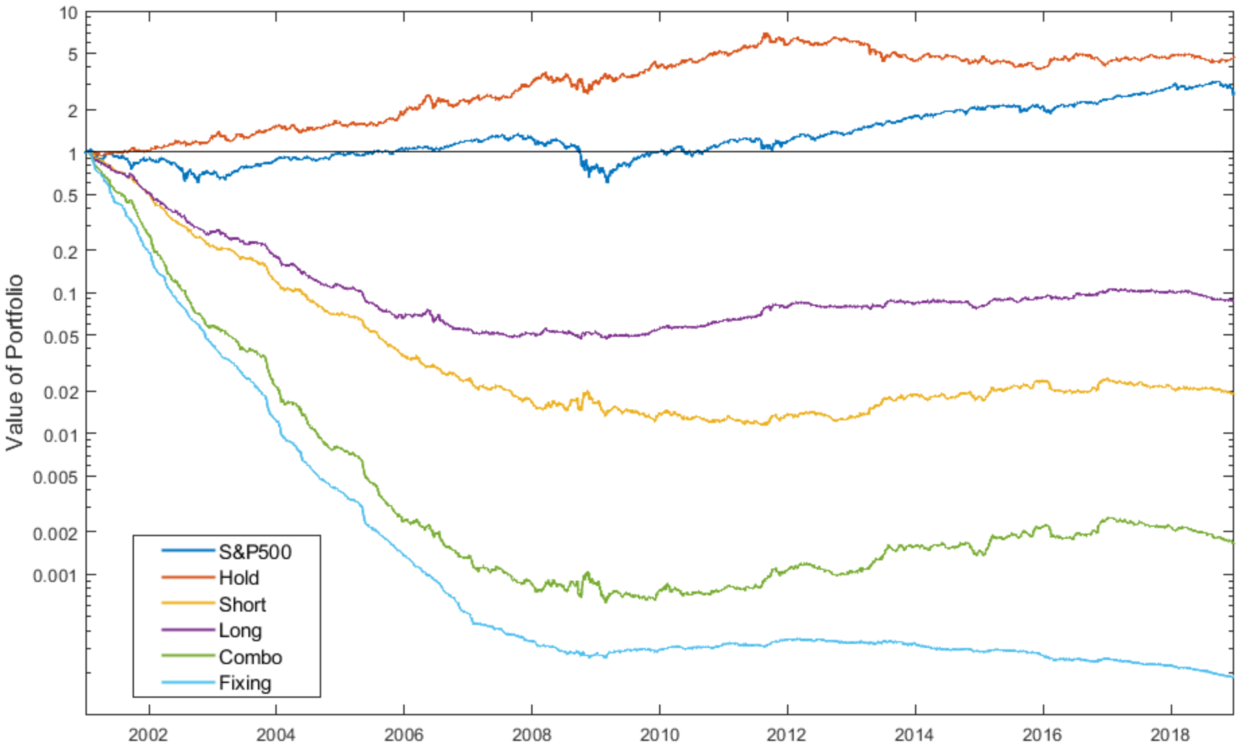


Figure 7.2. Portfolios' Values, with Transaction Costs
The figure shows the value of 6 portfolios employing the 6 different strategies, starting with an initial investment of 1 USD. The figure is in log scale.

7.5. The Efficient Market Hypothesis

The current analysis of trading performance can be related to the Efficient Market Hypothesis (EMH). As defined by (Fama 1970), the EMH states that current asset prices "fully reflect" all the available information regarding the assets[6]. There are 3 forms of market efficiency:

- **Weak**: current asset prices reflect all historical price information. It follows that historical return sequences do not provide any additional information regarding future returns (i.e. returns are not serially correlated: prices move in a random walk). The weak form of EMH implies that technical analysis is useless for predicting future returns.

[6]The EMH is mainly concerned with stock prices but the argument can be extended to asset prices in general.

- **Strong**: current asset prices reflect all public and private available information.
- **Semi-strong**: current asset prices reflect all publicly available information. This implies that both technical and fundamental analysis are useless for predicting future returns.

In the literature there is a wide range of different tests of the EMH (e.g. RWH tests, event studies). However a formal test of the EMH requires the assumption of a theoretical asset pricing model. In such a test, observing abnormal returns α is a rejection of the "joint hypothesis" of the EMH and of the assumed pricing model [7] , meaning that you don't know what to reject: the EMH, the pricing model or both [8] . In the current thesis we do not provide a formal test of market efficiency. In fact the traditional equity asset pricing models are not suited to our non-equity strategies.

For our purposes, the most important implication of the EMH is that the expected excess return of an asset is just a function of its risk factors, and therefore active asset managers should not be able to consistently "beat the market" in terms of risk-adjusted excess returns. In the current chapter, we used Sharpe Ratio and Sortino Ratio - measures of risk-adjusted excess returns - to compare the performance of the 6 strategies, with fascinating results.

All in all, we conclude that the overperformance of the active strategies in the no transaction costs scenario may be seen as a violation of the EMH. However, when including spreads, evidence against the EMH seems to vanish. Abstracting away from our particular performance results, we may argue that intraday return patterns (of gold and of other different assets), if enough pronounced and robust, may be considered violations of the EMH. Being examples of how irrational behaviours affect the valuation that different investors around the globe attribute to assets. In our case, we may reasonably claim that gold price is on average higher at the end of the Asian session because Chinese and Indian investors attribute a higher valuation to gold than what western investors do, due to diverse cultural and economic backgrounds.

[7]For example *value* is a rejection of the joint hypothesis when assuming the CAPM as asset pricing model. This means that *value* is an asset pricing "anomaly" in the framework of the EMH-CAPM, however it is not an anomaly when you assume the Fama French 3-factor model as your pricing model. Likewise *momentum* is an anomaly in the framework of the EMH-CAPM and also in the framework of the EMH-FF3FM. However it is not when assuming your pricing model is the Carhart 4-factor model.

[8]Supporters of the EMH argue that anomalies such as *value* are risk factors and therefore investors rationally want to be compensated for them (i.e. they should be included in the asset pricing model). On the other hand, behaviourists argue that these anomalies are actually behavioural biases that cause assets to be mispriced (i.e. markets are not efficient).

7.6. Future Profitability of Active Strategies

Assuming that the downward fixing spikes were caused by manipulation, we expect this specific behaviour of gold prices around the clock not to present itself any more in the future. Consequently we expect the Fixing strategy not to be particularly profitable from now on. On the other hand, Short, Long and Combo's returns seemed more robust over time so far. Also, assuming that the hat shape is caused by geographical clienteles, economic intuition suggests that this behaviour will persist. Consequently we expect Short, Long and Combo to keep their profitability, at least to some degree. As for bid-ask spreads, we expect them not to be as wide as the first years of the sample, meaning that the negative effect of trading costs will be small and the overall return may be positive again.

In any case, we should note that the 4 active trading strategies presented in this chapter were set up using *ex post* information. For instance, way back in the past we could not actually know that gold has on average its highest and lowest prices respectively at 2am and 11am. We indeed conclude that using ex post information cause backtested returns to be upward biased estimators of future returns. Furthermore, no economic argument can be made on why gold contracts should have their highest price *exactly* at 2am and their lowest price *exactly* at 11am. It follows that out of sample the intraday return pattern may be very different from Figure 4.1.

In conclusion, the results of this chapter, rather than suggest to actively engage in these specific strategies, should more in general suggest that intraday return patterns can be very pronounced for some assets and that when these assets are very liquid (like GC futures in recent years), intraday return patterns may be profitably exploited.

7.7. Summary of Results

In this chapter we wanted to try to exploit the return pattern of Figure 4.1, despite the fact that neither the hat nor the two downward spikes are fully robust over time. When assuming no transaction costs, all the active strategies beat the market, which implies a rejection of the EMH. However, when transaction costs are implemented, all the active strategies underperform the market, which implies no rejection of the EMH. Nevertheless, in the second half of the sample period the tight spreads of the GC futures allow 3 active strategies out of 4 to be profitable.

Chapter 8

Conclusion

In this thesis we aim to understand how gold prices behave within the course of 24 hours of a day and in particular we test three hypotheses.

H_0^1 : There is intraday seasonality in gold prices driven by a West-East gold demand shifts.

H_0^2 : There are downward price movements around the London fixing times.

H_0^3 : If H_0^1 or H_0^2 or both prove to be true, then there exist trading strategies which profitably exploit these patterns.

Ad H_0^1 : We find intraday seasonality in gold prices. This seasonality follows a hat-shaped pattern. However, this pattern is *not* fully robust over time. In particular, the rising leg of the hat (East returns) is statistically and economically more stable than the falling leg (West returns). Which suggests that prices during eastern trading hours rise rather systematically but they do not fall systematically during western trading hours. Nevertheless, rising prices in eastern hours are consistent with the economic argument that China and India are the two largest importers of gold. The hat pattern cannot be explained by means of a liquidity or volatility premium. Regressing these East and West returns on monetary and macroeconomic variables we find a distinct set of relationships. GDP growth in China and appreciation of INR lead to increased East returns but not to increased West returns. To some degree this means that the hat shape is more pronounced when these two economies are doing well. On the other hand, an appreciation of JPY and of Brent leads to increased West returns but not increased East returns. More in general, East and West returns react differently to the same shock, which means eastern and western clienteles react asymmetrically to the same shock in their gold consumption choices.

Ad H_0^2 : We find two strong downward spikes around the London fixing times. However, this pattern is less robust than the hat pattern. The downward spikes are mainly driven by the years between 2007 and 2011, years in which this pattern is robust. These are the years in which the fixing banks allegedly performed manipulation of the London Gold Fix. This means that the fixing spikes were a temporary phenomenon and not a systematic return pattern.

Ad H_0^3 : Despite H_0^1 and H_0^2 not being time-independent, these patterns recur on average and therefore we try to exploit this recurrence. Without transaction costs we could profitably exploit the hat and the downward spikes and all the four strategies constructed would outperform the market, both in terms of Sharpe and Sortino ratios. This may be seen as a violation of the EMH. However, when including transaction costs none of the four strategies beat the market, despite three of them being profitable in the second half of the sample. This means that when transaction costs are taken into account the EMH is not violated.

To sum up, we find a compelling statistical explanation for the spikes during a time period which coincides with alleged manipulation of the London Gold Fix. However we could not find a convincing statistical explanation for the recurrence of the hat, even though there is a number of qualitative reasons that may serve as explanation. The hat seems to occur due to asymmetric demand between eastern and western clientele. Eastern clientele is willing to pay more than western clientele due to their different cultural or economic backgrounds. Gold plays a central role in wedding traditions as well as Hinduistic and Buddhistic rituals which explains the strong culturally rooted bond of Chinese and Indian population with gold. Both countries are in a state of economic development and therefore in rural areas access to banking services, financial education and trust in financial markets are yet to be established which is the reason why gold is high in demand as a store of wealth in those areas.

Further research could extend this study in two main directions. We may think of running a panel data or panel VAR model on the market microstructure characteristics to better understand how illiquidity, return volatility and volume relate to the return pattern, an in particular to formally understand if the hat pattern is driven by a liquidity or volatility premium. Lastly, we think it is an interesting exercise to make the same analysis with different commodities, to understand if also for them it is true that net-importing geographical areas face rising prices during their trading hours.

Appendix A

Additional Tables

Table A.1. Global Gold Stock

This table shows the total gold stock that has been mined sorted by utilization based on information provided by the World Gold Council, 2019.

Sector	Distribution (in t)	Distribution (in %)
Jewellery	92,043.2	47.57
Offical Holdings	33,229.6	17.18
Private Investment	41,278.6	21.34
Bars & Coins	38,838.3	20.07
ETFs	2,440.2	1.26
Other Fabrication and Unaccounted	26,921.1	13.91
Σ	193,472.4	100

Table A.2. Global Gold Demand by Sector

This table shows the demand of gold in 2018 by sector based on information provided by the World Gold Council, 2019.

Sector	Distribution (in t)	Distribution (in %)
Jewellery	2,241.8	50.96
Offical Holdings	656.9	14.93
Private Investment	1,165.3	26.49
Bars & Coins	1096.0	24.92
ETFs	69.3	1.58
Technology	334.8	7.61
Σ	4,398.7	100

Table A.3. Global Gold Supply

This table shows the total gold supply by primary and secondary sources for the year 2018. Data is provided by the World Gold Council, 2019.

Country	Distribution (in t)	Distribution (in %)
Mine Production	3,502.8	75.19
Net Producer Hedging	-12.4	-0.27
Recycled Gold	1,168.1	25.08
Σ	4658.5	100

Table A.4. Global Gold Reserve by Country

This table shows the total central bank reserves of gold by country and we chose to show only the largest six holders. The relative distribution uses total gold reserves of 33,869.2 tonnes as reference quantity. Data is provided by the IMF, 2019.

Country	Distribution (in t)	Distribution (in %)
United States	8,133.5	24.01
Germany	3,369.7	9.95
Italy	2,451.8	7.24
France	2,436.0	7.19
Russia	2,119.2	6.26
China	1,864.3	5.50
Σ	20,374.5	60.16

Table A.5. Global Gold Mining Supply by Region

This table shows the suppy of gold in 2018 by region based on information provided by the World Gold Council, 2019. Africa includes South Africa, Ghana, Tanzania, Mali, Congo, Bukina Faso, Sudan, Zimbabew, Guinea, Ivory Coast, Egypt, Ethopia, Maritania, Senegal, Namibia, Others. Asia includes China, Indonesia, Philippines, Mongolia, Turkey, Iran, Others. Central & South America includes Peru, Brazil, Argentina, Colombia, Chile, Domenican Republic, Venezuela, Suriname, Guyana, Ecuador, Nicaragua, Others. North America includes United States, Canada, Mexico. Commonwealth of Independent States include Russia, Uzbekistan, Kasakhstan, Kyrgyzstan, Others. Oceania includes Australia, Papua New Guinea, New Zealand, Others. Europe includes Finland, Sweden, Others.

Region	Share (in t)	Share (in %)
Africa	821.0	23.44
Asia	667.1	19.30
Central & South America	558.0	15.93
North America	526.1	15.02
Commonwealth of Independet States	498.5	14.23
Oceania	394.8	11.27
Europe	27.9	0.8
Σ	3,502.6	100

Table A.6. Global Gold Mining Supply by Country

This table shows the mining supply of gold in 2018 by country based on information provided by the World Gold Council, 2019.

Country	Share (in t)	Share (in %)
China	404.1	11.54
Australia	314.9	8.99
Russia	297.3	8.49
USA	221.7	6.33
Canada	189.0	5.40
Peru	158.4	4.52
Ghana	130.5	3.73
Σ	1,716.0	48.99%

Table A.7. Gold Trading volumes, Average Daily

This table shows average daily trading volumes (in tonnes and in Billion USD) for each of the 4 main gold markets. Data is referred to a particular week in which LBM published its own data. Data source is Bullion Vault (2018), which in turn gathered the official data published by the exchanges and by LBM.

City	Market	Tonnes	Billion USD	of which
London	LBM	939.3	36.9	spot (63%), forwards and swaps (31%), options (3%), leases (3%)
Chicago	COMEX	1062.5	41.7	futures (80%) and options (20%)
Shanghai	SHFE	80.7	3.2	futures (100%)
Shanghai	SGE	46.7	1.8	spot (100%)

Table A.8. Gold Trading Volumes, yearly (Exchange Only)

This table shows yearly trading volumes (in tonnes) for each exchange. The table does not include LBM, which is an OTC market. Data source is Refinitiv (2019)

City	Exchange	2016	2017	2018
Chicago	COMEX	179,047	226,467	249,794
Shanghai	SHFE	34,760	19,478	16,124
Shanghai	SGE	15,492	15,710	10,931
Tokyo	TOCOM	8,541	6,398	8,091
London	LME	0	1,989	2,276
Mumbai	MCX	4,094	2,297	2,256
Dubai	DGCX	453	359	314
New York	ICE Futures US	294	152	73
Istanbul	Borsa Istanbul	243	457	265
Σ		242,924	273,307	290,124

Table A.9. Macro Variables

This table shows a list of all 48 macroeconomic variables and their corresponding mnemonic for retreival from FRED database. CPI inflation and GDP growth data was downloaded from the OECD website and does not have a mnemonic.

ID	Variable	Source	Mnemonic	ID	Variable	Source	-
1	$Libor - UDS$	FRED	USD3MTD156N	25	CPI^{OECD}	OECD	-
2	$Libor - EUR$	FRED	EUR3MTD156N	26	CPI^{Russia}	OECD	-
3	$TBill$	FRED	TB3MS	27	GDP_y^{AU}	OECD	-
4	$USD - AUD$	FRED	DEXCAUS	28	GDP_y^{China}	OECD	-
5	$USD - CHY$	FRED	DEXCHUS	29	GDP_y^{EU19}	OECD	-
6	$USD - EUR$	FRED	DEXUSEU	30	GDP_y^{EU28}	OECD	-
7	$USD - GBP$	FRED	DEXUSUK	31	GDP_y^{G20}	OECD	-
8	$USD - INR$	FRED	DEXINUS	32	GDP_y^{G7}	OECD	-
9	$USD - JPY$	FRED	DEXJPUS	33	GDP_y^{India}	OECD	-
10	$USD - SAR$	FRED	DEXSFUS	34	GDP_y^{Japan}	OECD	-
11	$USD - SFR$	FRED	DEXSZUS	35	GDP_y^{OECD}	OECD	-
12	$USD - CAD$	FRED	DEXCAUS	36	GDP_y^{UK}	OECD	-
13	$USD - TW$	FRED	DTWEXB	37	GDP_y^{US}	OECD	-
14	REI	FRED	WILLREITIND	38	GDP_q^{AU}	OECD	-
15	$Crude^{Brent}$	FRED	DCOILBRENTEU	39	GDP_q^{China}	OECD	-
16	$Unempl^{AU}$	FRED	LRHUTTTTAUM156S	40	GDP_q^{EU19}	OECD	-
17	$Unempl^{US}$	FRED	LRHUTTTTUSM156S	41	GDP_q^{EU28}	OECD	-
18	$Unempl^{EU}$	FRED	LRHUTTTTEUM156S	42	GDP_q^{G20}	OECD	-
19	CPI^{China}	OECD	-	43	GDP_q^{G7}	OECD	-
20	CPI^{US}	OECD	-	44	GDP_q^{India}	OECD	-
21	CPI^{EU}	OECD	-	45	GDP_q^{Japan}	OECD	-
22	CPI^{G20}	OECD	-	46	GDP_q^{OECD}	OECD	-
23	CPI^{G7}	OECD	-	47	GDP_q^{UK}	OECD	-
24	CPI^{India}	OECD	-	48	GDP_q^{US}	OECD	-

Table A.10. Year by Year Average Returns

This table shows average daily returns $\hat{\mu}$ earned during Eastern and Western trading hours as well as during AM and PM Fixing on a year by year basis from 2001 until 2018 and their corresponding standard errors, $se(\hat{\mu}$. The four time samples are (*i*) EAST (17:00 of one day to 3:00 the other day), (*ii*) WEST (3:00 to 17:00 the same day), (*iii*) AM FIX (30 minutes around the AM Fixing) and (*iv*) PM FIX (30 minutes around the PM Fixing). From annualized daily returns, we compute their mean $\hat{\mu}$ and standard errors $se(\hat{\mu})$. We test against the null hypothesis H_0: *daily average returns being zero.* ***,**,* denote significance at the 1%, 5% and 10% level.

	EAST		WEST		AM FIX		PM FIX	
Year	$\hat{\mu}$	se($\hat{\mu}$)	$\hat{\mu}$	se($\hat{\mu}$)	$\hat{\mu}$	se($\hat{\mu}$)	$\hat{\mu}$	se($\hat{\mu}$)
2001	12.48	(11.51)	-11.33	(8.59)	-2.50**	(1.16)	1.06	(1.00)
2002	14.36	(10.70)	7.20	(10.99)	0.07	(1.87)	-0.83	(1.40)
2003	19.63**	(9.52)	-0.09	(13.92)	-4.04***	(1.51)	0.93	(1.80)
2004	10.66	(10.30)	-6.36	(12.50)	-1.18	(1.46)	-2.58	(2.04)
2005	9.71	(7.28)	7.76	(11.22)	-0.71	(1.11)	-0.53	(1.37)
2006	17.72	(12.46)	3.18	(19.97)	-2.14	(2.44)	-3.81	(2.48)
2007	21.30***	(7.02)	5.71	(15.74)	1.66	(1.73)	-10.27***	(4.23)
2008	22.04*	(13.05)	-16.87	(30.38)	-1.73	(4.18)	-12.12	(9.64)
2009	9.31	(9.77)	12.61	(19.39)	-11.09***	(3.29)	-18.76***	(6.20)
2010	18.00***	(7.36)	7.87	(15.23)	-11.20***	(2.13)	-11.39***	(4.52)
2011	9.98	(11.87)	-0.25	(18.83)	-9.55***	(2.82)	-9.63*	(5.15)
2012	10.56*	(6.13)	-3.83	(13.99)	-7.52***	(1.68)	1.79	(4.00)
2013	7.07	(10.05)	-40.02**	(20.40)	-13.91***	(2.34)	4.39	(5.06)
2014	3.92	(7.48)	-5.77	(13.06)	2.13	(1.97)	-2.59	(3.70)
2015	11.89	(7.68)	-22.79*	(13.31)	-6.09***	(2.36)	-0.85	(4.05)
2016	14.65	(10.16)	-6.45	(13.84)	-3.04*	(1.69)	-4.63	(4.05)
2017	-2.78	(7.13)	15.34*	(9.18)	2.24*	(1.16)	-2.04	(2.74)
2018	-10.36	(6.96)	8.67	(10.53)	2.95**	(1.31)	0.24	(2.20)

Table A.11. Month of the Year Average Returns

This table shows average daily returns $\hat{\mu}$ earned during Eastern and Western trading hours as well as during AM and PM Fixing for every month of the year from 2001 until 2018 and their corresponding standard errors, $se(\hat{\mu}$. The four time samples are (*i*) East (17:00 of one day to 3:00 the other day), (*ii*) West (3:00 to 17:00 the same day), (*iii*) AM Fix (30 minutes around the AM Fixing) and (*iv*) PM Fix (30 minutes around the PM Fixing). From annualized daily returns, we compute their mean $\hat{\mu}$ and standard errors $se(\hat{\mu})$. We test against the null hypothesis H_0: *daily average returns being zero.* ***,**,* denote significance at the 1%, 5% and 10% level.

	East		West		AM Fix		PM Fix	
Month	$\hat{\mu}$	se($\hat{\mu}$)	$\hat{\mu}$	se($\hat{\mu}$)	$\hat{\mu}$	se($\hat{\mu}$)	$\hat{\mu}$	se($\hat{\mu}$)
Jan	12.46	(7.86)	22.74*	(13.13)	-2.56	(1.69)	0.81	(3.17)
Feb	14.46*	(8.66)	0.67	(15.25)	-3.14*	(1.71)	-5.75	(3.83)
Mar	13.33***	(5.73)	-17.97	(11.83)	-2.98*	(1.70)	-0.15	(3.20)
Apr	11.44*	(6.74)	-2.44	(13.06)	-2.06	(1.75)	-6.56**	(3.19)
May	-2.47	(8.68)	0.63	(10.92)	0.84	(1.56)	-2.13	(3.00)
Jun	7.36	(6.89)	-11.67	(13.06)	-8.15***	(1.77)	-3.29	(2.60)
Jul	5.06	(8.76)	-5.32	(11.00)	-3.80***	(1.42)	-3.23	(2.81)
Aug	2.39	(6.81)	-17.30	(11.80)	-5.94***	(1.41)	-1.52	(2.97)
Sep	12.12	(9.48)	7.44	(15.56)	-4.55**	(2.16)	-4.11	(4.19)
Oct	12.47	(7.77)	-19.39	(14.00)	-1.46	(2.06)	-6.51	(4.76)
Nov	19.51**	(8.60)	-3.12	(13.17)	-1.42	(1.59)	-6.80**	(3.35)
Dec	26.58***	(6.44)	-17.21	(12.91)	-6.74***	(2.29)	-8.80***	(3.53)

Table A.12. Day of the Week Average Returns

This table shows average daily returns $\hat{\mu}$ earned during Eastern and Western trading hours as well as during AM and PM Fixing for every day of the week (Monday until Friday) from 2001 until 2018 and their corresponding standard errors, $se(\hat{\mu})$. The four time samples are (*i*) East (17:00 of one day to 3:00 the other day), (*ii*) West (3:00 to 17:00 the same day), (*iii*) AM Fix (30 minutes around the AM Fixing) and (*iv*) PM Fix (30 minutes around the PM Fixing). From annualized daily returns, we compute their mean $\hat{\mu}$ and standard errors $se(\hat{\mu})$. We test against the null hypothesis H_0: *daily average returns being zero.* ***,**,* denote significance at the 1%, 5% and 10% level.

	East		West		AM Fix		PM Fix	
Day	$\hat{\mu}$	se($\hat{\mu}$)	$\hat{\mu}$	se($\hat{\mu}$)	$\hat{\mu}$	se($\hat{\mu}$)	$\hat{\mu}$	se($\hat{\mu}$)
Mon	23.23***	(7.51)	-17.81**	(7.80)	-4.51***	(1.24)	-2.19	(2.28)
Tue	3.27	(4.87)	-12.73	(8.31)	-1.75	(1.08)	-3.29*	(1.93)
Wed	9.24***	(3.77)	-2.06	(8.22)	-3.31***	(1.05)	-5.43***	(2.30)
Thu	12.69***	(4.44)	-9.85	(8.40)	-6.63***	(1.21)	-4.21*	(2.33)
Fri	8.16**	(3.87)	29.06***	(9.00)	-2.14*	(1.16)	-4.69**	(2.33)

Table A.13. Correlation Matrix

This table shows correlations between strategies and 50 macro variables. For variables originally available in daily frequency, we construct their returns r from first to last day of the quarter. All other variables are originally in quarterly frequency. Unemployment rates and inflation rates are kept in levels. GDP growth is shown both with respect to previous year g_y^{GDP} and quarter g_q^{GDP}.

		Correlations (in%)					Correlations (in%)		
ID	X_i	r^{East}	r^{West}	r^{CTC}	ID	X_i	r^{East}	r^{West}	r^{CTC}
1	$r^{Libor-UDS}$	-21.54	8.35	-6.29	25	$Infl^{OECD}$	-1.29	16.17	16.16
2	$r^{Libor-EUR}$	-5.81	5.39	1.61	26	$Infl^{Russia}$	13.01	-4.89	3.97
3	r^{TBill}	-24.06	8.60	16.18	27	$g_y^{GDP_{AU}}$	8.00	5.61	11.54
4	$r^{USD-AUD}$	-16.55	-28.00	-41.17	28	$g_y^{GDP_{China}}$	27.24	10.59	30.28
5	$r^{USD-CHY}$	-17.27	-13.32	-26.17	29	$g_y^{GDP_{EU19}}$	-0.25	6.20	6.37
6	$r^{USD-EUR}$	-16.26	-17.90	-30.30	30	$g_y^{GDP_{EU28}}$	-0.14	6.09	6.33
7	$r^{USD-GBP}$	5.98	-23.15	-20.25	31	$g_y^{GDP_{G20}}$	2.86	8.28	10.75
8	$r^{USD-INR}$	-31.83	-14.73	-37.87	32	$g_y^{GDP_{G7}}$	-6.93	5.62	1.07
9	$r^{USD-JPY}$	-34.97	-33.22	-59.59	33	$g_y^{GDP_{India}}$	9.77	12.56	20.11
10	$r^{USD-SAR}$	-24.24	-10.27	-27.84	34	$g_y^{GDP_{Japan}}$	2.53	-2.37	-0.73
11	$r^{USD-SFR}$	-33.38	-14.80	-39.03	35	$g_y^{GDP_{OECD}}$	-5.33	-5.91	2.50
12	$r^{USD-CAD}$	-1.60	-24.66	-27.15	36	$g_y^{GDP_{UK}}$	1.60	3.35	4.67
13	r^{USD-TW}	-21.85	-29.51	-46.47	37	$g_y^{GDP_{US}}$	-14.34	8.50	-1.08
14	r^{REI}	16.24	-5.94	5.11	38	$g_q^{GD_{AU}}$	12.33	7.21	16.27
15	r^{Brent}	-14.29	27.49	19.00	39	$g_q^{GDP_{China}}$	-	-	-
16	$Unempl^{AU}$	-8.36	-8.94	-15.29	40	$g_q^{GDP_{EU19}}$	12.40	1.57	10.36
17	$Unempl^{US}$	11.83	-3.28	4.83	41	$g_q^{GDP_{EU28}}$	10.89	3.75	11.59
18	$Unempl^{EU}$	4.59	18.80	-16.63	42	$g_q^{GDP_{G20}}$	17.00	6.17	18.43
19	$Infl^{China}$	11.14	20.99	29.97	43	$g_q^{GDP_{G7}}$	5.28	7.63	11.76
20	$Infl^{US}$	-7.12	19.87	15.98	44	$g_q^{GDP_{India}}$	18.40	-5.70	6.88
21	$Infl^{EU}$	14.82	2.07	12.58	45	$g_q^{GDP_{Japan}}$	27.69	-8.16	10.80
22	$Infl^{G20}$	3.64	15.75	19.18	46	$g_q^{GDP_{OECD}}$	11.47	4.38	12.67
23	$Infl^{G7}$	-2.86	15.71	14.58	47	$g_q^{GDP_{UK}}$	1.73	9.73	11.48
24	$Infl^{India}$	1.49	1.21	2.32	48	$g_q^{GDP_{US}}$	-9.66	15.11	9.17

Table A.14. Sharpe Ratios, without Transaction Costs

This table shows annualized Sharpe ratios ${}^{a}\mathcal{SR}$ of the 6 strategies assuming no transaction costs. All Sharpe Ratios are calculated using samples of one year. Values in the last 4 rows are averages of the above yearly Sharpe ratios in the $\mathcal{A}$ sub-sample (2001-2006), $\mathcal{B}$ sub-sample (2007-2012), $\mathcal{C}$ sub-sample (2013-2018) and $\mathcal{ABC}$ full sample (2001-2018). To give a more comprehensive understanding of the performances, Sharpe ratios above 1 are in green and those below 0 are in red.

	Passive Strategies		Active Strategies			
	S&P500	Hold	Short	Long	Combo	Fixing
2001	-0.75	-0.17	1.75	0.91	1.88	-1.23
2002	-1.02	1.29	-0.77	1.33	0.99	-0.38
2003	1.42	1.14	1.47	2.07	2.61	0.90
2004	0.81	0.17	1.42	1.33	2.12	0.94
2005	0.16	1.09	-0.65	1.16	0.83	-1.06
2006	0.99	0.69	1.52	1.98	2.88	0.33
2007	0.06	1.27	-0.09	2.76	1.80	0.91
2008	-1.16	0.12	0.41	0.72	0.81	1.14
2009	0.86	1.04	0.10	2.01	1.33	4.22
2010	0.77	1.52	0.62	3.37	2.67	4.46
2011	0.09	0.46	1.13	1.77	2.38	3.11
2012	1.16	0.43	0.26	0.84	0.77	1.36
2013	2.53	-1.38	2.75	1.01	2.94	1.77
2014	1.12	-0.13	0.41	0.16	0.46	0.10
2015	0.09	-0.71	2.59	2.54	3.50	1.43
2016	0.84	0.47	0.46	1.17	1.16	1.69
2017	2.82	1.01	-0.66	0.99	0.40	-0.37
2018	-0.43	-0.28	-0.38	-0.88	-0.60	-1.98
$\mathcal{A}$	0.27	0.70	0.79	1.46	1.89	-0.08
$\mathcal{B}$	0.30	0.81	0.40	1.91	1.63	2.53
$\mathcal{C}$	1.16	-0.17	0.86	0.83	1.31	0.44
$\mathcal{ABC}$	0.58	0.45	0.69	1.40	1.61	0.96

Table A.15. Sortino Ratios, without Transaction Costs

This table shows annualized Sortino ratios ${}^{a}\mathcal{SR}_{\ominus}$ of the 6 strategies assuming no transaction costs. All Sortino Ratios are calculated using samples of one year. Values in the last 4 rows are averages of the above yearly Sortino ratios in the $\mathcal{A}$ sub-sample (2001-2006), $\mathcal{B}$ sub-sample (2007-2012), $\mathcal{C}$ sub-sample (2013-2018) and $\mathcal{ABC}$ full sample (2001-2018). To give a more comprehensive understanding of the performances, Sharpe ratios above 1 are in green and those below 0 are in red.

	Passive Strategies		Active Strategies			
	S&P500	Hold	Short	Long	Combo	Fixing
2001	-1.02	-0.26	3.16	1.59	3.48	-1.77
2002	-1.44	1.89	-1.02	1.92	1.39	-0.47
2003	2.17	1.71	2.25	3.30	4.20	1.25
2004	1.16	0.24	2.59	2.07	3.61	1.48
2005	0.22	1.67	-0.83	1.66	1.16	-1.50
2006	1.49	0.93	2.52	2.92	4.61	0.58
2007	0.08	1.82	-0.13	4.48	2.96	1.37
2008	-1.54	0.17	0.58	1.01	1.23	1.80
2009	1.23	1.52	0.14	3.30	2.02	7.06
2010	1.09	2.19	0.91	5.38	4.43	7.81
2011	0.12	0.64	1.89	2.53	4.07	5.38
2012	1.76	0.62	0.37	1.30	1.21	2.16
2013	3.83	-1.69	5.10	1.60	5.29	2.66
2014	1.57	-0.18	0.56	0.22	0.65	0.14
2015	0.12	-1.00	4.02	4.03	5.63	1.98
2016	1.18	0.69	0.65	1.85	1.72	2.82
2017	4.43	1.54	-0.90	1.52	0.59	-0.56
2018	-0.55	-0.39	-0.53	-1.21	-0.82	-2.45
$\mathcal{A}$	0.43	1.03	1.45	2.24	3.07	-0.07
$\mathcal{B}$	0.46	1.16	0.63	3.00	2.65	4.26
$\mathcal{C}$	1.76	-0.17	1.48	1.33	2.18	0.76
$\mathcal{ABC}$	0.88	0.67	1.19	2.19	2.63	1.65

Table A.16. Sharpe Ratios, with Transaction Costs

This table shows annualized Sharpe ratios ${}^{a}\mathcal{SR}$ of the 6 strategies assuming transaction costs are 100% of spreads. All Sharpe Ratios are calculated using samples of one year. Values in the last 4 rows are averages of the above yearly Sharpe ratios in the $\mathcal{A}$ sub-sample (2001-2006), $\mathcal{B}$ sub-sample (2007-2012), $\mathcal{C}$ sub-sample (2013-2018) and $\mathcal{ABC}$ full sample (2001-2018). To give a more comprehensive understanding of the performances, Sharpe ratios above 1 are in green and those below 0 are in red.

	Passive Strategies		Active Strategies			
	S&P500	Hold	Short	Long	Combo	Fixing
2001	-0.75	-0.17	-9.17	-6.00	-9.43	-19.48
2002	-1.02	1.29	-10.73	-5.08	-9.54	-20.58
2003	1.42	1.14	-5.90	-3.09	-6.11	-18.85
2004	0.81	0.17	-4.96	-3.95	-6.03	-14.73
2005	0.16	1.09	-7.72	-4.93	-7.99	-15.05
2006	0.99	0.69	-3.40	-1.43	-3.28	-16.07
2007	0.06	1.27	-2.58	-1.65	-2.69	-8.18
2008	-1.16	0.12	-0.12	0.06	-0.04	-2.05
2009	0.86	1.04	-0.92	0.67	-0.45	1.00
2010	0.77	1.52	-0.89	1.63	0.00	1.59
2011	0.09	0.46	0.65	1.96	1.86	1.36
2012	1.16	0.43	-0.38	0.06	-0.32	-1.15
2013	2.53	-1.38	1.99	0.42	1.94	-0.49
2014	1.12	-0.13	-0.20	-0.85	-0.55	-2.83
2015	0.09	-0.71	2.06	2.12	2.72	-1.32
2016	0.84	0.47	0.15	0.98	0.70	-1.13
2017	2.82	1.01	-1.68	-0.20	-1.36	-3.97
2018	-0.43	-0.28	-1.62	-3.09	-2.55	-7.74
$\mathcal{A}$	0.27	0.70	-6.98	-4.08	-7.06	-17.46
$\mathcal{B}$	0.30	0.81	-0.71	0.46	-0.27	-1.24
$\mathcal{C}$	1.16	-0.17	0.12	-0.10	0.15	-2.91
$\mathcal{ABC}$	0.58	0.45	-2.52	-1.24	-2.40	-7.20

Table A.17. Sortino Ratios, with Transaction Costs

This table shows annualized Sortino ratios ${}^{a}\mathcal{SR}_{\ominus}$ of the 6 strategies assuming transaction costs are 100% of spreads. All Sortino Ratios are calculated using samples of one year. Values in the last 4 rows are averages of the above yearly Sortino ratios in the $\mathcal{A}$ sub-sample (2001-2006), $\mathcal{B}$ sub-sample (2007-2012), $\mathcal{C}$ sub-sample (2013-2018) and $\mathcal{ABC}$ full sample (2001-2018). To give a more comprehensive understanding of the performances, Sharpe ratios above 1 are in green and those below 0 are in red.

	Passive Strategies		Active Strategies			
	S&P500	Hold	Short	Long	Combo	Fixing
2001	-1.02	-0.26	-8.75	-7.07	-9.10	-12.23
2002	-1.44	1.89	-9.30	-5.72	-8.77	-12.55
2003	2.17	1.71	-6.47	-4.05	-6.64	-12.13
2004	1.16	0.24	-5.95	-4.82	-6.61	-10.79
2005	0.22	1.67	-7.33	-5.59	-7.68	-10.91
2006	1.49	0.93	-4.27	-1.83	-4.04	-11.36
2007	0.08	1.82	-3.32	-2.15	-3.34	-7.72
2008	-1.54	0.17	-0.17	0.09	-0.06	-2.72
2009	1.23	1.52	-1.26	1.04	-0.63	1.46
2010	1.09	2.19	-1.28	2.37	0.00	2.40
2011	0.12	0.64	1.13	2.96	3.57	2.13
2012	1.76	0.62	-0.54	0.08	-0.47	-1.62
2013	3.83	-1.69	3.23	0.61	2.92	-0.67
2014	1.57	-0.18	-0.25	-1.10	-0.70	-3.37
2015	0.12	-1.00	3.15	3.56	4.59	-1.56
2016	1.18	0.69	0.21	1.67	1.06	-1.61
2017	4.43	1.54	-2.14	-0.29	-1.78	-4.88
2018	-0.55	-0.39	-2.07	-3.65	-3.06	-7.53
$\mathcal{A}$	0.43	1.03	-7.01	-4.85	-7.14	-11.66
$\mathcal{B}$	0.46	1.16	-0.91	0.73	-0.15	-1.01
$\mathcal{C}$	1.76	-0.17	0.36	0.13	0.50	-3.27
$\mathcal{ABC}$	0.88	0.67	-2.52	-1.33	-2.26	-5.32

Appendix B

Additional Figures

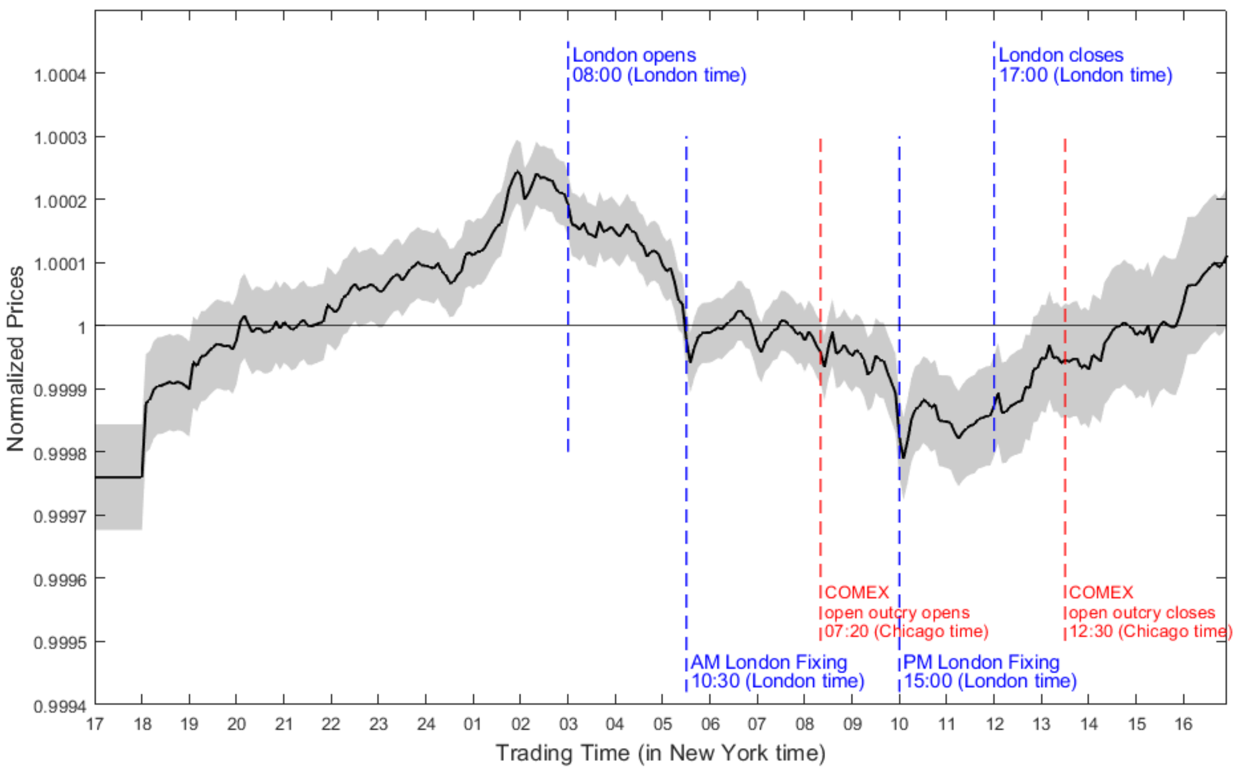
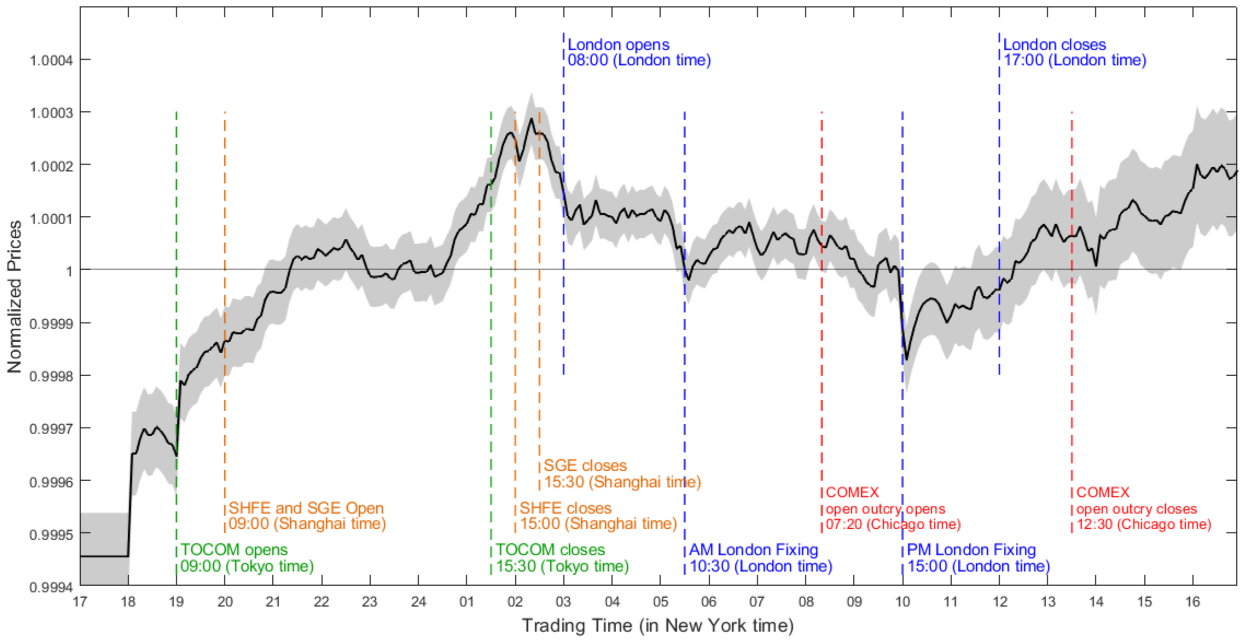
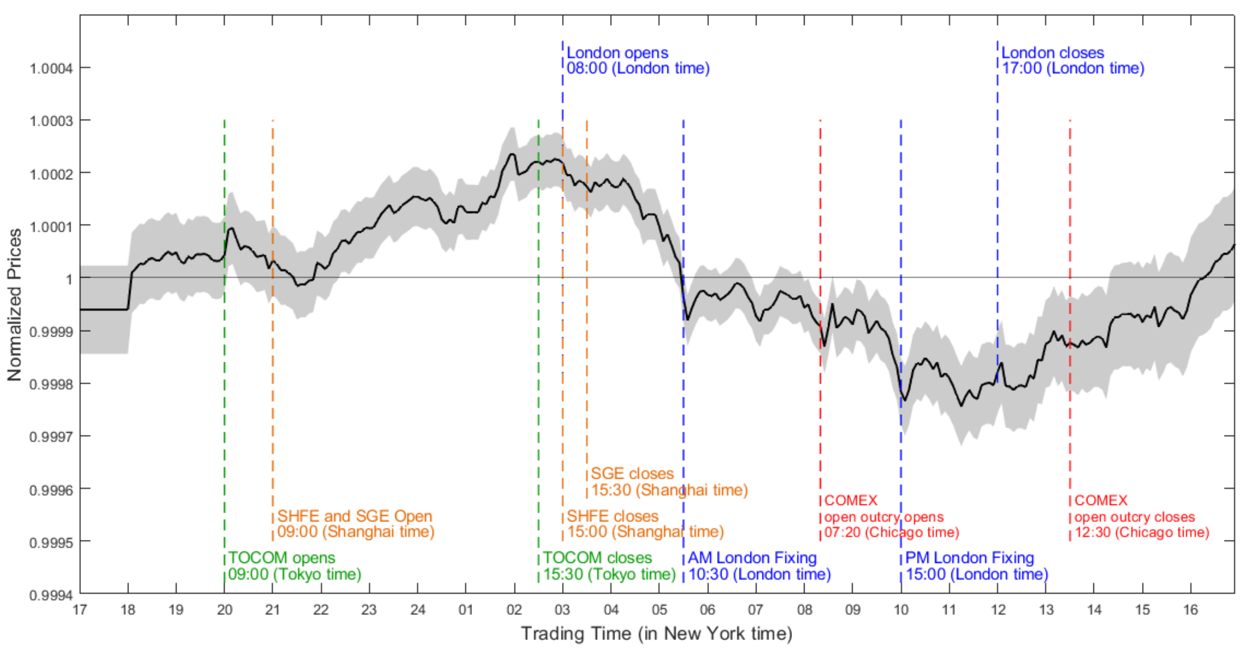


Figure B.1. Prices Around the Clock: Full Sample
The figure shows the full sample (2001-2018)



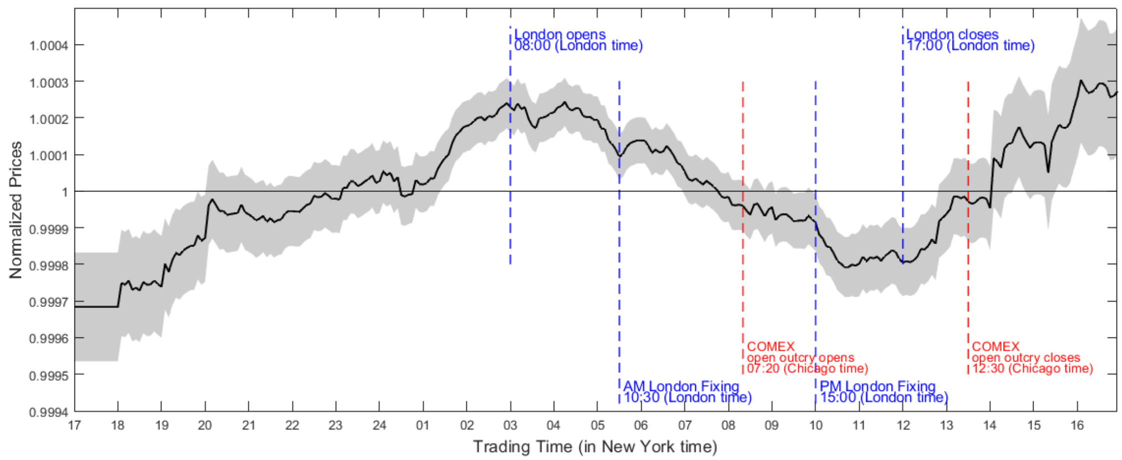
(a) No Daylight Saving Time



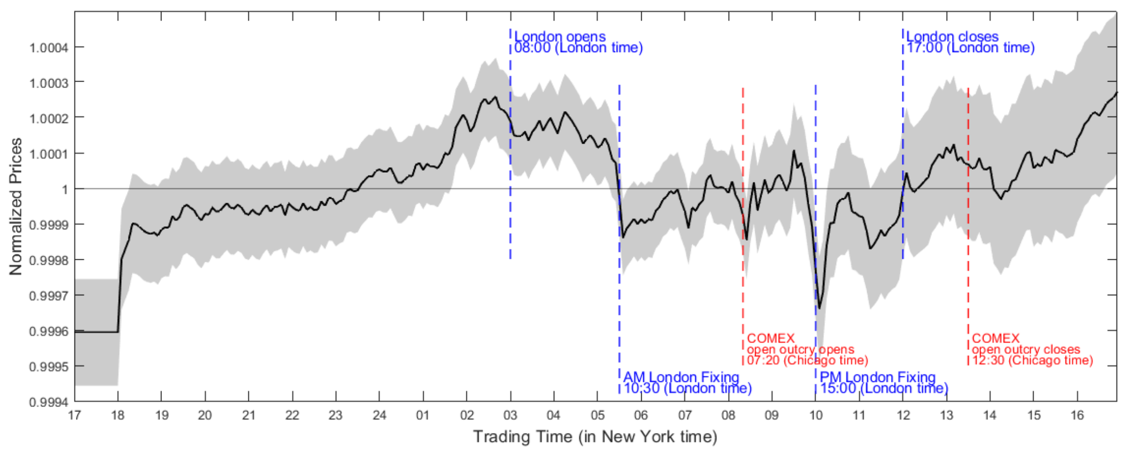
(b) Daylight Saving Time

Figure B.2. Prices Around the Clock: ST vs DST

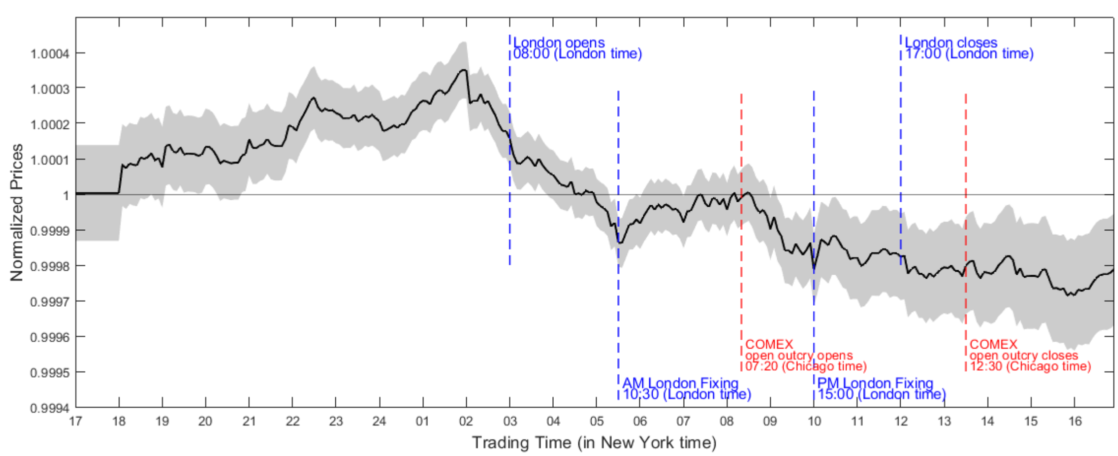
The two panels in the figure show two subsamples: one in which New York is in ST (between November and March) and one in which it is in DST (between March to October).



(a) First Sample Period: $\mathcal{A}$

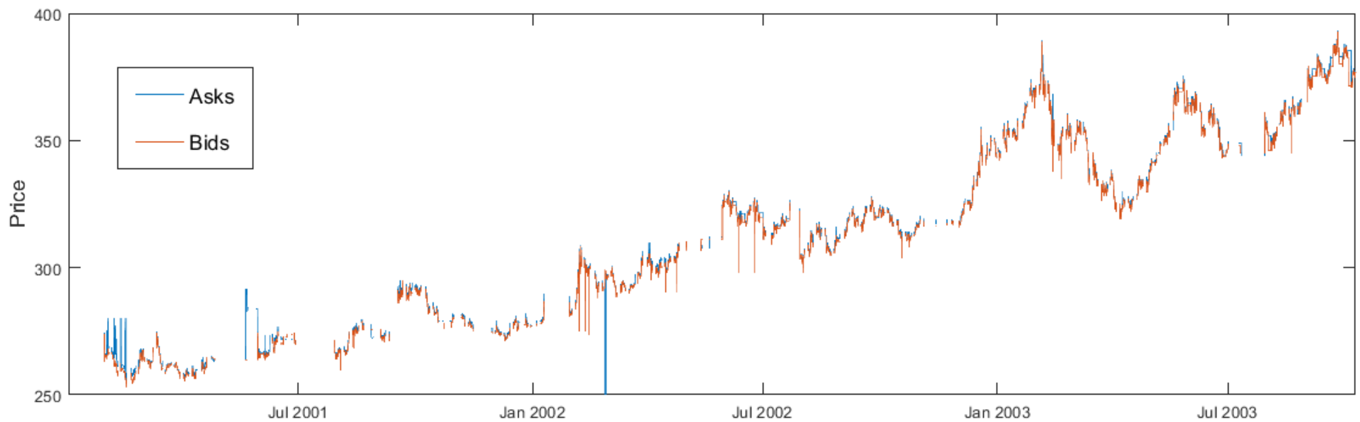


(b) Second Sample Period: $\mathcal{B}$

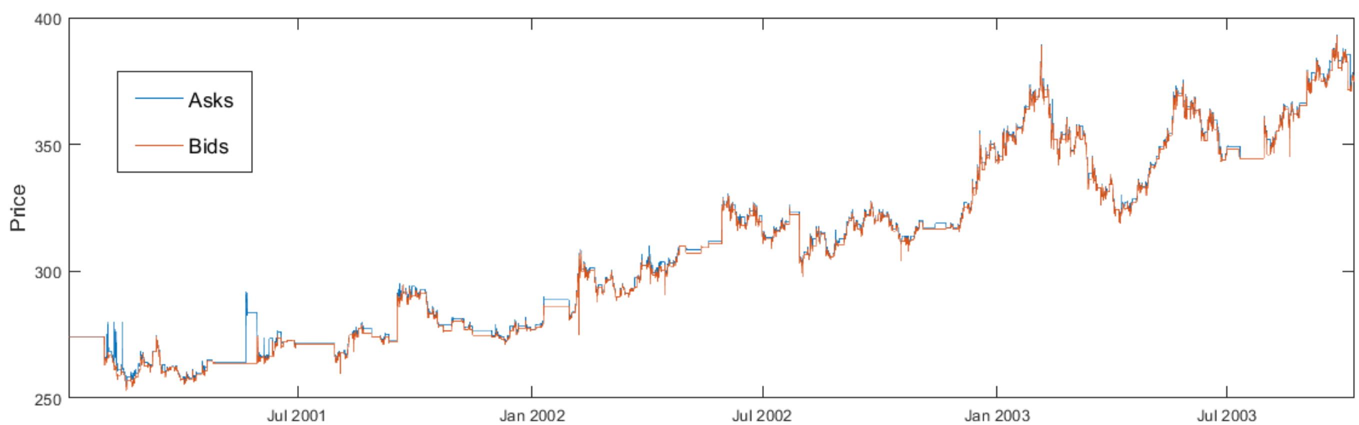


(c) Third Sample Period: $\mathcal{C}$

Figure B.3. Prices Around the Clock: Three Subsamples
The three panels in the figure show three sub-samples of 6 years each.

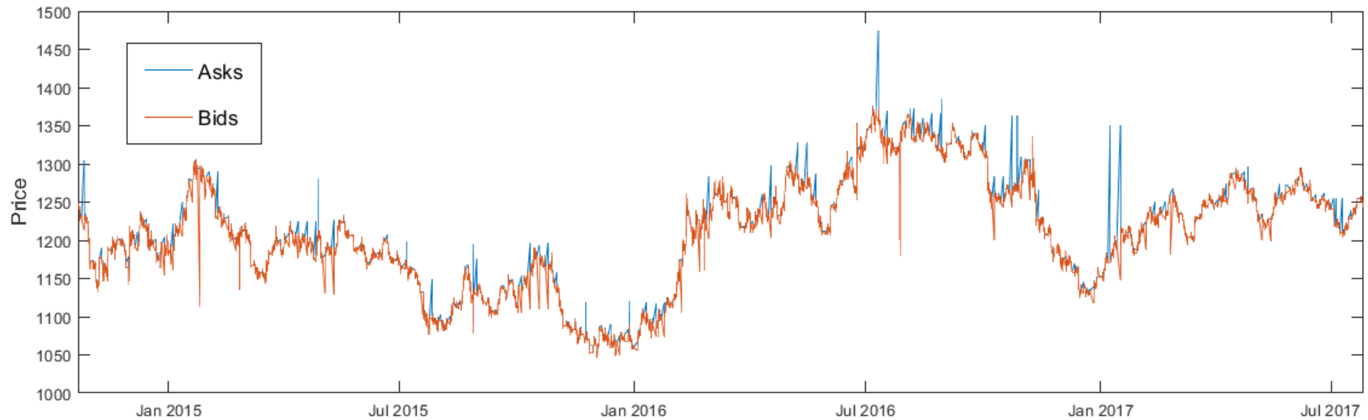


(a) Quotes before Cleaning and Filling

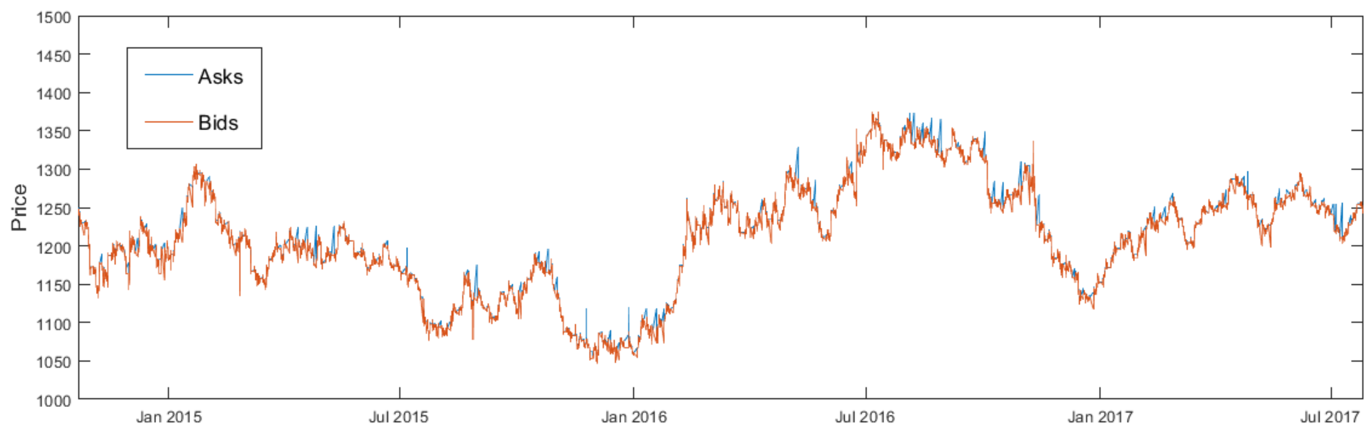


(b) Quotes after Cleaning and Filling

Figure B.4. Data Quality, Example 1
Figures show quotes before and after the cleaning and filling procedure for a early part of the 2001-2018 sample. Data in the early part of the sample has bad quality, due to the high percentage of intervals with missing quotes.



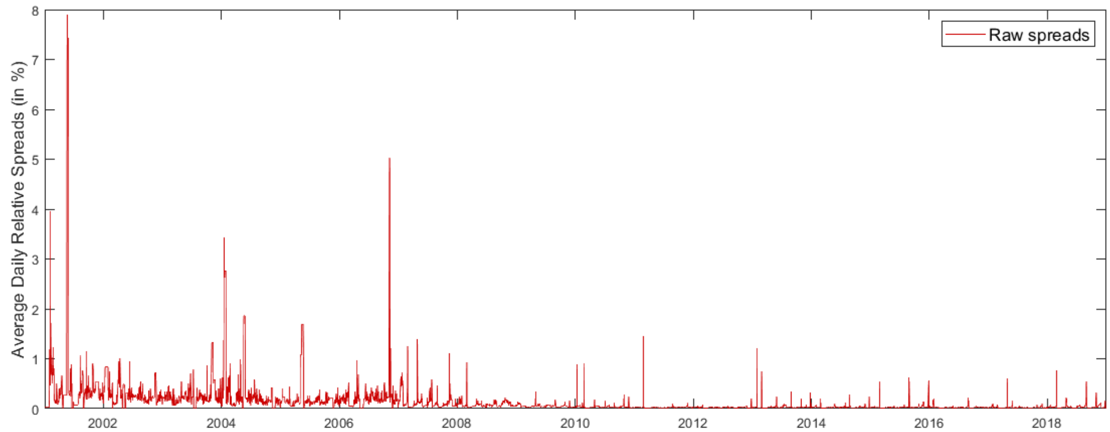
(a) Quotes before Cleaning and Filling



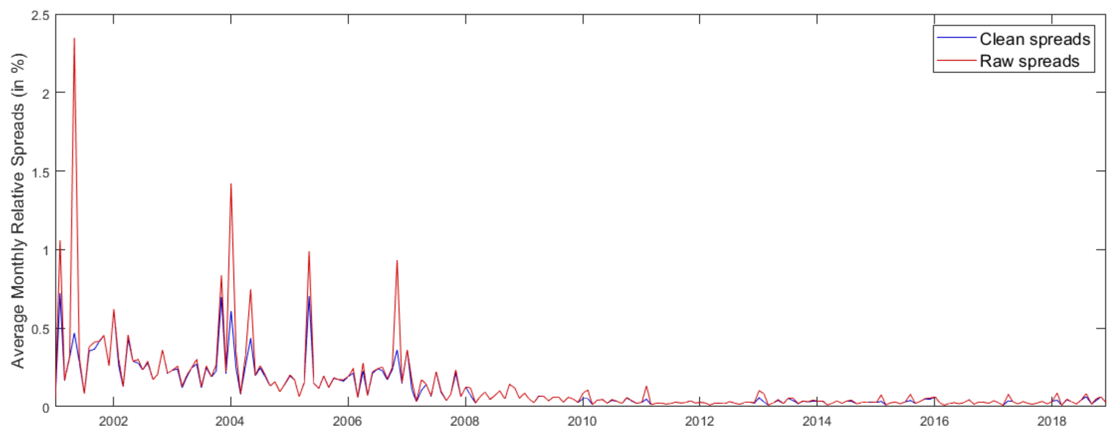
(b) Quotes after Cleaning and Filling

Figure B.5. Data Quality, Example 2

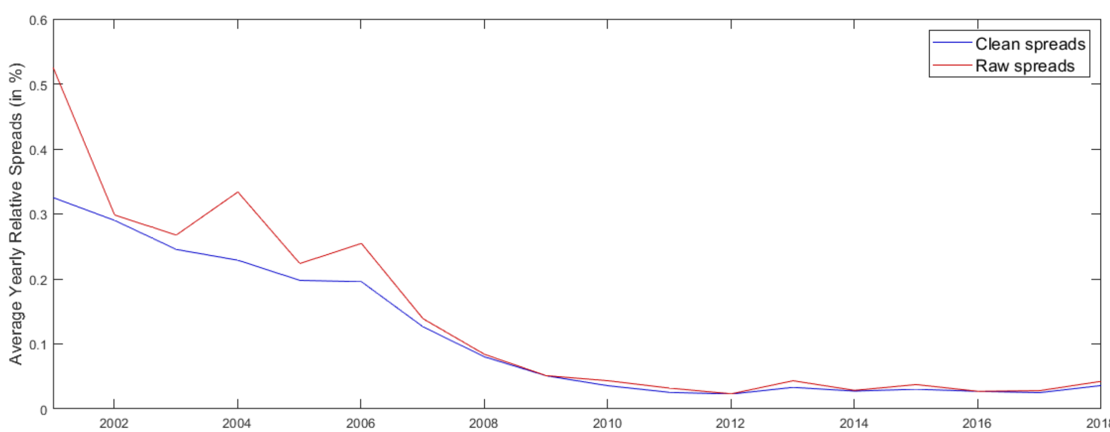
Figures show quotes before and after the cleaning and filling procedure for a late part of the 2001-2018 sample. Data in the late part of the sample has relatively good quality, due to the low percentage of intervals with missing quotes



(a) Daily Averages



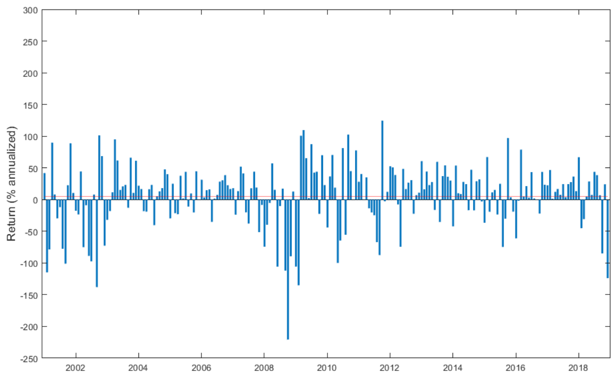
(b) Monthly Averages



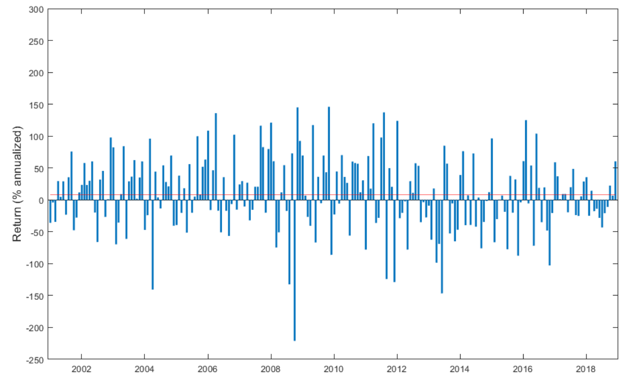
(c) Yearly Averages

Figure B.6. Average Spreads

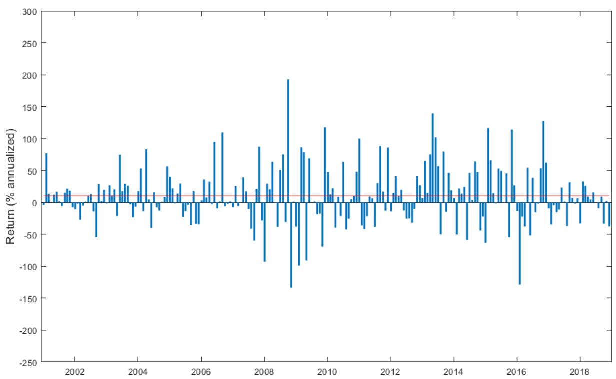
The 3 panels shows respectively daily, monthly and yearly averages of relative spreads. All the 3 panels show averages before cleaning outliers, the last 2 panels show also averages after.



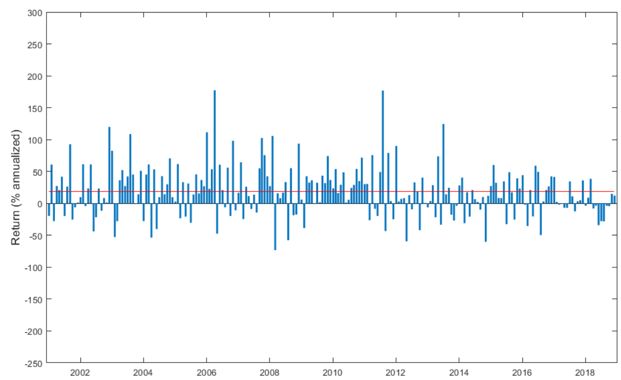
(a) S&P500 Strategy



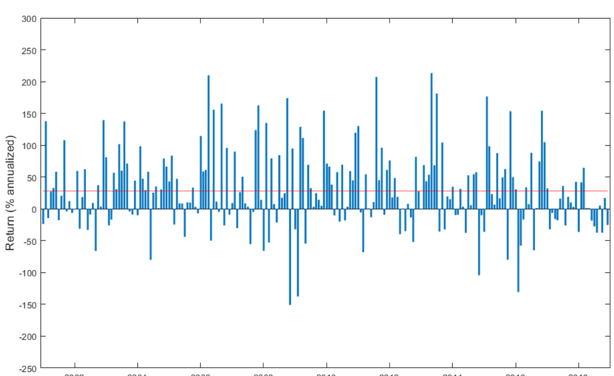
(b) Hold Strategy



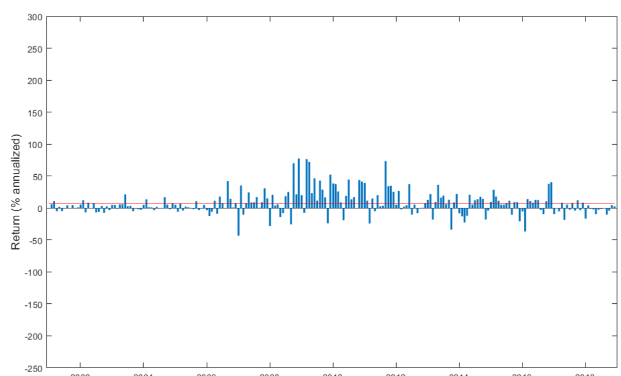
(c) Short Strategy



(d) Long Strategy



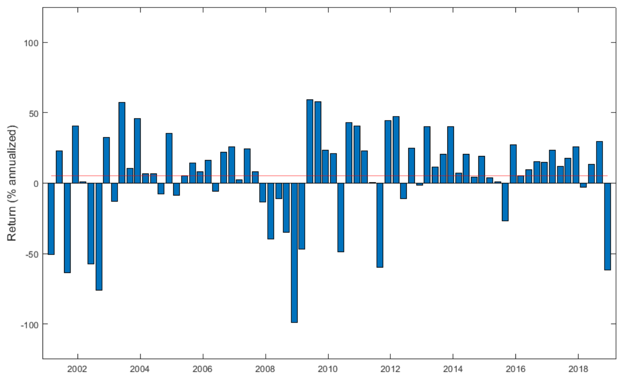
(e) Combo Strategy



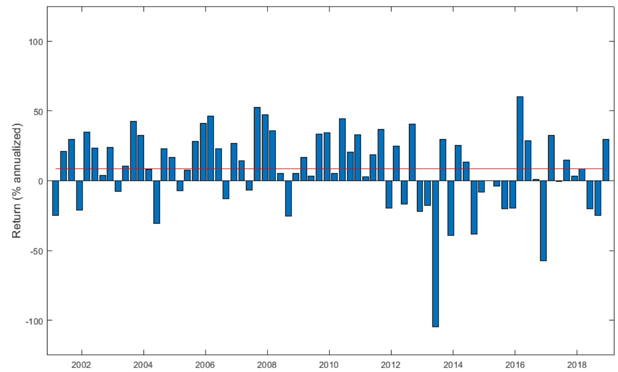
(f) Fixing Strategy

Figure B.7. Monthly Returns of Strategies

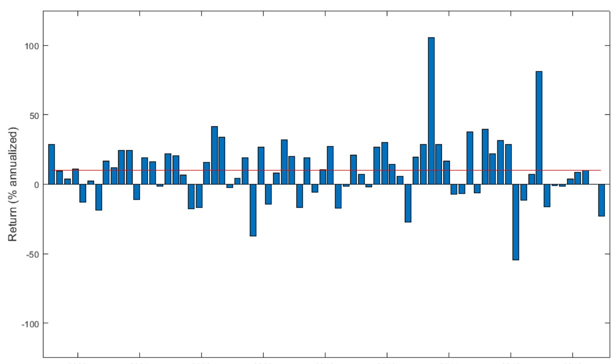
This figure shows for each of the 6 strategies annualized monthly returns. The red lines show the average return of the strategies throughout the whole sample period.



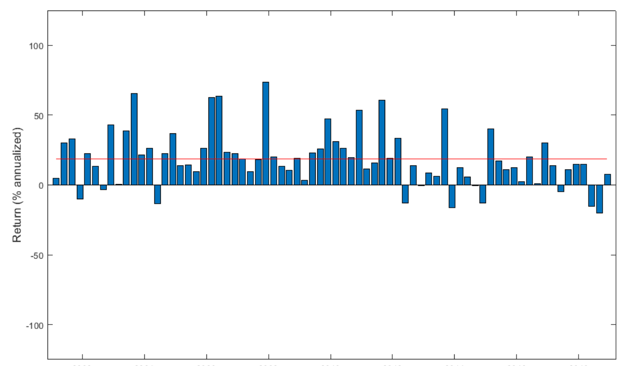
(a) S&P500 Strategy



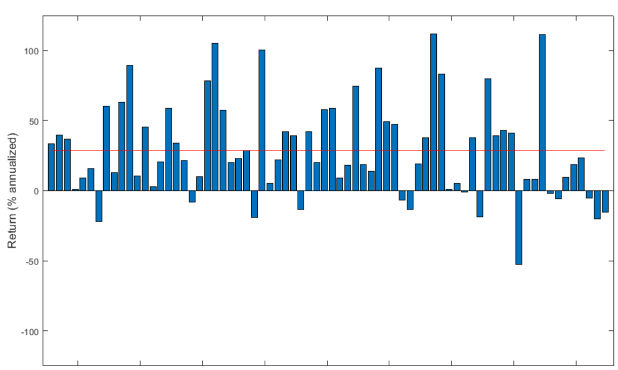
(b) Hold Strategy



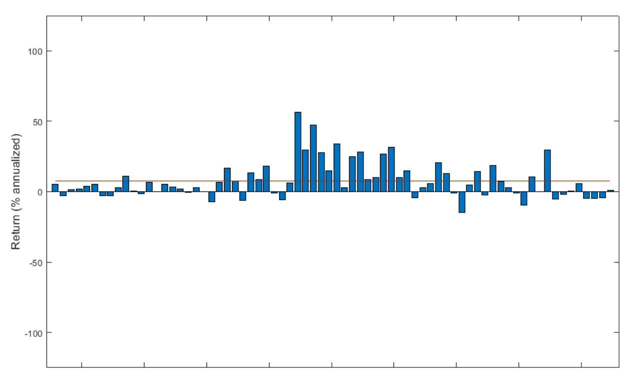
(c) Short Strategy



(d) Long Strategy



(e) Combo Strategy



(f) Fixing Strategy

Figure B.8. Quarterly Returns of Strategies

This figure shows for each of the 6 strategies annualized quarterly returns. The red lines show the average return of the strategies throughout the whole sample period.

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