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Arbitrage Opportunities in the Bitcoin Market

Author: S.S.F.J. Heijmans
Student number: 457851
Thesis supervisor: Dr. J.J.G. Lemmen
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PREFACE AND ACKNOWLEDGEMENTS

I would personally like to thank the Rotterdam Erasmus University for enabling me to be part of the Financial Economics Master's program in the year 2017/2018. A year in which I gained a lot of knowledge which will support me not only during the year itself but also in the years to come. Also, would I like to thank my supervisor J.J.G. Lemmen and my friends and family for the support they have shown me throughout the process of writing my thesis. Writing the thesis was a very interesting project where I have learned to properly structure an analysis and include all the necessary facets. I hope the reader enjoys reading the thesis and the results may be useful to them it may concern.

ABSTRACT

The Bitcoin, a topic which has experienced a high level of scrutiny over the last couple of years. Consumers which were unknown with the concept before, now know the basics of its use and functionalities. This article provides an in-depth analysis with regards to one aspect in the Bitcoin market, arbitrage opportunities. This is done by examining whether the Law of One Price upholds in the world of cryptocurrencies. Here, three different arbitrage techniques are used to test for violations of the LOP. The three techniques used are: Multiple Fiat Currency Triangular Arbitrage, Multiple Crypto Currency Triangular Arbitrage and Inter-Exchange Arbitrage. By implementing three different techniques, multiple facets of the Bitcoin market are tackled and a comparison between the three techniques is made. The timeline of the sample reaches from July 1st 2017 till July 1st 2018. Within this timeline the closing prices of the variables are obtained using an hourly frequency. The results show that for all three techniques arbitrage opportunities are present in the according sample. Opportunities are most likely to emerge in an active market which could be described with a bull status accompanied by a volatile nature. In such market conditions there is an increased chance of discrepancies to emerge in numerous ways. These discrepancies are of different values for all three techniques. The second technique, described by Multiple Crypto Currency Triangular Arbitrage, shows arbitrage opportunities only in the beginning of the sample in month November 2017 with discrepancies ranging from +8.00% to -9.50%. After this month these opportunities disappear. The first and third technique follow roughly the same pattern. Nevertheless, with discrepancies up to 13.34%, the first technique shows the most significant arbitrage opportunities of all both techniques, compared to 9.13% for the third technique. This makes the first technique the most profitable arbitrage technique of all three techniques. Here, a triangular arbitrage is performed using the Bitcoin, the US dollar and the Euro as variables. I also find that just prior to the largest discrepancies found in the sample, the volume of trades on the exchanges increased significantly. Events such as banning the use of the Bitcoin or a significant drop in the price create incentives for people to trade their Bitcoin which has varying effect on the different exchanges creating these discrepancies. Altogether, in times of high demand for the Bitcoin during a bull market, numerous arbitrage opportunities emerge by the volatile nature of the market. These opportunities exist for a long enough period such that not only trading robots can take advantage of them but also institutional and private traders. The Bitcoin is currently in a bear market with low activity by traders but history has shown that these conditions can rapidly change and new arbitrage opportunities could present themselves again using the techniques described by this article.

Keywords: Bitcoin, cryptocurrency, arbitrage, electronic money, law of one price
JEL Classifications: E42, F31, G11

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Chapter 1. Introduction

Although Bitcoin has been around since 2011, the year 2017 has proven itself to be a very moving year for the cryptocurrency. In fact, according to Google Trends[1], Bitcoin was the second most discussed topic in the global news of the year 2017. All around us we hear the great success stories of people becoming so called 'crypto millionaires' (Stanley, 2018). Partly due to these stories, it is reasonable to assume that the vast majority of the public by now has a general idea of what the Bitcoin is and what main purpose it serves, namely a decentralized currency. By creating a digital currency, money can now be transferred from one side of the world to the other within a matter of seconds, with almost no transactions costs. This all can be done without the interference of any bank, government or other third party. Naturally, this kind of technology has a significant upside potential to increase the efficiency of the market. But how efficient is the Bitcoin market really? The efficient market hypothesis (EMH) states that in an efficient market, the prices "fully reflect" available information and thus the asset's price is an accurate reflection of that asset's true value (Fama, 1970). A research done by A. Urquhart (2016) shows that over the full sample used in his examination, the Bitcoin returns are significantly inefficient. However, when the sample is split up into two sub samples, the Bitcoin indicates signs of efficiency in the latter period. The results of the Bitcoin market being an inefficient one is supported by a study performed by Al-Yahyaee et al. (2018) who compared the efficiency of four markets: The Bitcoin-, gold-, stock- and currency market. Their results show that the long-memory feature and multifractality of the Bitcoin market was stronger than those of the other three markets, making the Bitcoin the most inefficient market amongst the four markets. Such inefficiencies implicate opportunities for investors to forecast future prices and generate abnormal returns. This article focusses on the latter by comparing three different possible arbitrage techniques in the cryptocurrency market and their potential pay-outs.

When a central bank provides the consumer with money, they either press and print it, where you can collect that money at a local ATM machine, or you obtain it through an online transaction. Either way, the bank controls how much money there is in circulation and to a certain extent, where it goes to. With cryptocurrencies this works differently. Cryptocurrencies are traded on so called online exchanges. These online exchanges are essentially start-ups and can be founded by anyone. By being relatively young, most of the exchanges are still in their development phase and learning to overcome the majority of their hurdles by trial and error. Common problems experienced by these exchanges are events such as but not limited to transaction delays, price manipulation or even the activity of cybercriminals by hacking into people's accounts. Ever since the emergence of the Bitcoin, and other cryptocurrencies, these hacks have occurred quite frequently. In fact, the five biggest hacks sum up to a total value of

[1] https://trends.google.com/trends/yis/2017/GLOBAL/

almost $1 billion[2], with the largest being Mt. Gox. With this hack, nearly 750,000 customers were affected as well as 100,000 Bitcoins that were stolen from the exchange itself[3]. But not only hacks have proven themselves to have a significant effect on the price of the Bitcoin. Another event which affected the price of the Bitcoin was the introduction of the futures market. This created the opportunity for investors to trade Bitcoin without actually owning one. The future market increased the liquidity but also opened up new arbitrage possibilities for investors. With the opening of this new future market, the CBOE Global Markets Inc.'s new contracts were priced 13 percent higher than the Bitcoin itself[4], creating a so called 'free lunch' for the attentive investor. A third and final series of events which has caused the Bitcoin price to fluctuate are regulations. After the online exchange Coinbase announced an internal investigation related to the addition of new crypto currencies on their platform, the Bitcoin lost almost half its value. A similar situation occurred when South Korean regulators announced that they would ban crypto trading entirely[5]. Logically, all these events such as hacks, regulations and price manipulations increase the volatility of the Bitcoin significantly. A twenty percent fluctuation in one day is not exceptional, which makes the Bitcoin extremely volatile. Such volatility makes holding the Bitcoin riskier, however it also creates opportunities for arbitrage. Especially when the prices of the Bitcoin between the exchanges themselves varies as well. Arbitrage can be executed in numerous ways, this article will interpret three different forms of arbitrage including several crypto currencies, fiat currencies and online exchanges. The three different forms used are: triangular arbitrage using Fiat currencies, triangular arbitrage using cryptocurrencies and lastly arbitrage between the exchanges themselves. How and when these different techniques exactly are executed will be explained into greater detail in the second chapter of this article.

The topic Bitcoin has experienced a high level of scrutiny the last couple of years and therefore the research done in this field is growing rapidly. It all started with a paper published by Satoshi Nakamoto in 2008 (Nakamoto, 2008) and afterwards other papers such as Grinberg (2012), Mittal (2012) and Maurer (2013) have been published in order to give better insights on various aspects of the Bitcoin such as its functionality and possible effects. Although the available literature regarding the Bitcoin in general is increasing, this is not representative for the specific topic of arbitrage possibilities using the cryptocurrency. To the best of my knowledge, the literature regarding this topic is relatively scarce and thus a lot of ground can still be won here. Nonetheless, an article written by Gandal and Halaburda (2014) does address this topic by analysing the changes over time in exchange rate data among cryptocurrencies. They do this by looking at two aspects: they firstly look at competition among different currencies and secondly at competition among exchanges where those currencies were traded. So, in a

[2] https://www.cso.com.au/article/635648/7-biggest-recent-hacks-crypto-exchanges/
[3] https://cointelegraph.com/news/the-mess-that-was-mt-gox-four-years-on
[4] https://www.bloomberg.com/news/articles/2017-12-11/bitcoin-futures-are-dangling-a-free-lunch-for-starving-arbs
[5] https://cointelegraph.com/news/regulations-and-their-influence-on-cryptocurrency-prices

greater sense, the article written by Gandal and Halaburda (2014) is relatively comparable to this research. However, this research differentiates itself in various manners.

First, Gandal and Halaburda (2014) divide their data into two sub samples with one timeframe reaching from May 2nd 2013 to September 30th 2013 and another one reaching from October 1st 2013 to February 28th 2014, respectively. This separation is made due to specific events that occurred between the two periods which could have affected the results of the examination. Regardless of the fact what potential effects dividing your sample into two subsamples could have on your results, the timeline used for their research could be considered relatively dated. The Bitcoin has been introduced in 2009, which made the Bitcoin approximately four years old at the time of their research. Now, 4 years later, the market capitalization of the Bitcoin has grown exponentially which increases the possible opportunities for arbitrage due to changed conditions such as a higher liquidity level. A study done by Dominik Rösch (2013) shows that arbitrageurs improve liquidity and financial market integration by trading against local net market demand. So, it is desirable to have a market which provides a minimum level of liquidity such that the arbitrageurs are able to enter the market and perform their trades and the arbitrageurs will then automatically increase the liquidity of the market as well. In order to capture such conditions, this article will use a timeline where the liquidity level is the highest as it has been so far reaching from July 1st 2017 to July 1st 2018.

A second way this article differentiates itself is likewise related to the data. Gandal and Halaburda (2014) made use of daily data. This means that they collected the price of the Bitcoin, and their other variables, on a day-to-day basis. In general, using daily data is an appropriate interval and should have no significant effects on the results of your examination. However, due the high volatile nature of the Bitcoin prices and the speed at which transactions can be made, the use of hourly data seems more appropriate. By using hourly data, the market has less chance to correct itself and thereby eliminating profitable arbitrage possibilities. Consequently, hourly data will be collected for this examination.

A third and last way manner which will diversify the two articles is the implementation of one of the arbitrage techniques. Gandal and Halaburda (2014) use a technique where a Bitcoin is bought on one exchange, sent to another, and this Bitcoin is then exchanged back to USD. A technique where a profit can be made when the Bitcoin is bought cheaper at the first exchange and then sold for a higher price at the second exchange. However, when trading a Bitcoin, a certain number of variables are introduced which could ultimately eliminate your profitable arbitrage strategy. One of these variables is the transaction time. Since the number of Bitcoin transactions has increased significantly, the transaction time has also increased. Where in 2013 or 2014 it would only take a couple of minutes to complete a transaction, this can now sometimes take up to a couple hours. Logically, when a possible arbitrage technique is executed, the trading should be completed within a matter of minutes or preferably seconds,

otherwise the price of the Bitcoin could have already changed significantly. In order to prevent such an event from happening, the arbitrage technique used in this article is one which needs funds in Bitcoin as well as a fiat currency on both exchanges. This way trades can be performed on both exchanges simultaneously without the restraint of waiting for a Bitcoin to be sent from one exchange to the other. This technique will be elaborated into greater detail in the methodology section of this article.

Altogether, a different arbitrage technique as well as changed market conditions will support this article to shed new light on the different arbitrage possibilities in the crypto currency market. According to the previously mentioned EMH, the prices of the assets should reflect all available information and thus no excessive returns can be made by either technical or fundamental analysis of those assets. Prices may deviate from their intrinsic value for a short period of time and prices may seem to follow a predictive pattern, but once discovered, these inefficiencies will be corrected for and most certainly not earn investors excess returns (Malkiel, 2003). However, what is the intrinsic value of a Bitcoin and when do we know it deviates from this value? In recent years, structural deviations from the EMH, or so-called anomalies, have been found by financial researchers. An example of such an anomaly is value- vs. growth stocks. Here, value stocks have proven themselves to outperform growth stocks on a fundamental basis with regards to yearly returns. The EMH states that these excess returns are offset by a higher volatility (Schleifer, 1997). If so, then should the Bitcoin also earn excess returns due to its volatile nature? A. Schleifer and R. Vishny (1997) find that in general professional arbitrageurs do contribute in reducing those market inefficiencies by trading against them. Nevertheless, in extreme circumstances, when prices diverge far from their fundamental value, there is the possibility that arbitrage becomes ineffective due to the risk of arbitrageurs having to liquidate their positions when the prices deviate any further. Again, the cryptocurrency market is a highly volatile market, which could possibly discourage arbitrageurs of entering the market. This is tested by examining the relationship between the degree of mispricing and the volume of trades that are executed at those specific moments in time. If arbitrageurs do take advantage of these mispricing's, the volume of trades should have a linear relationship with the degree of mispricing.

As mentioned before, this article will examine three different arbitrage techniques. In order to maintain a clear structure of the article as a whole, its methods and its findings, the article will henceforth be subdivided, where necessary, into three different sections. Here, each section will represent one arbitrage technique separately. The data regarding the Bitcoin prices will be obtained on the same manner for all sections. All prices are obtained from www.cryptodatadownload.com since this source is one of the few sources that provides hourly historical prices for the intended time frame. This time frame will be one calendar year reaching from July 1st 2017 to July 1st 2018. However, for each of the three techniques, additional data is required.

In the first section potential arbitrage possibilities are examined using Fiat currencies. This is tested as follows. In here the three different variables are: The Bitcoin, the US dollar, and the Euro. Although the Japanese Yen would be an interesting fiat currency to take into consideration due to the fact that they are, after the USD, one of the most used currencies to trade Bitcoins, there are few online exchanges which provide the option to exchange Bitcoins to US dollars as well as Japanese Yen. Contrarily, numerous exchanges do provide this option for US Dollars and the Euro. In this section, an examination will be conducted to check whether a profit can be made when exchanging a Bitcoin to US dollars, buying Euros from these US dollars and then buy back the Bitcoin with these Euros.

In the second section cryptocurrencies are used instead of Fiat currencies to test for arbitrage possibilities. In this equation, the three variables are: The Bitcoin, Ethereum and the US dollar. Ethereum is used as a variable because this is, with a market share of around 11.00%[6], the second most traded cryptocurrency at the moment. Here, opportunities for arbitrage are examined where one would buy x amount of Bitcoin with USD, trade this to Ethereum and then exchange this Ethereum back to USD. If an arbitrage opportunity indeed is possible, the amount of USD should be higher after the trade than before.

For the last section of this research, a different kind than triangular arbitrage is examined. Here, arbitrage opportunities between the exchanges themselves are tested. For this, two different exchanges are used: GDAX and Kraken. After Bitfinex, these are the most used exchanges to trade Bitcoin[7]. The reason why Bitfinex is not used for this examination is because no sufficient amount of data on hourly Bitcoin prices for this exchange is provided by cryptodatadownload.com. Perhaps, the hourly historical prices of the Bitcoin on Bitfinex could be found somewhere else but this can influence the results of the examination. Since different sites use different techniques, or so-called API's, to obtain their prices, this could have an impact on what they all provide as prices for the Bitcoin. Therefore, obtaining all Bitcoin prices from the same source, will increase the chance of these prices being obtained in the same manner and thus not influencing the results of the examination. All the other sources used for obtaining the required data such as the USD/EUR exchange rates and the hourly prices of Ethereum are covered in the data section of this article.

Dividing the article into three different sub sections results in not only having one main research question but also three different sub questions and accompanying hypotheses, one for each section. Here, the main research question (RQ) will provide an answer to the overall arbitrage conditions in the Bitcoin

[6] https://coinmarketcap.com/. Retrieved by dividing the market cap of Ethereum by the total market cap (on 16th September 2018)
[7] https://www.cryptocompare.com/coins/btc/analysis/USD

market whereas the three sub-questions (SQ) will give insights to each technique separately. The main research question of this article is as follows:

RQ: Can profitable arbitrage techniques, net of transaction costs and currency fees, be executed in the Bitcoin market by means of violations of the Law of One Price?

H1: The Bitcoin market provides profitable arbitrage opportunities due to violations of the Law of One Price
H0: The Law of One Price holds in the Bitcoin market and thus no profitable arbitrage opportunities can be found

In general, profitable arbitrage possibilities emerge if there is a mispricing somewhere in the transaction which still needs to be corrected for (Daniël, 2001). Such a mispricing is usually generated by two or more parties where information is not updated simultaneously or interpreted in a different way. In such a situation, a discrepancy between the prices or exchange rates of both parties is observed. If we take a closer look at the three different arbitrage techniques, we notice that technique one and three involve multiple parties whereas technique number two only involves one, namely the cryptocurrency exchange. Rationally, technique one and three are expected to have the most significant probability to experience profitable arbitrage due to an inefficiency as explained above. This leads to the following hypotheses:

SQ-1: Does multiple fiat currency triangular arbitrage result in excess returns?
H1: Exercising a triangular arbitrage using the Bitcoin, the US dollar and the Euro will result in excess return
H0: No 'risk-free' excess returns can be obtained when exercising a triangular arbitrage using the Bitcoin, the US dollar and the Euro

SQ-2: Does multiple crypto currency triangular arbitrage result in excess returns?
H2: No excess returns can be obtained when exercising a triangular arbitrage using the Bitcoin, Ethereum and the US dollar
H0: Exercising a triangular arbitrage using the Bitcoin, Ethereum and the US dollar will result in excess returns

SQ-3: Does inter-exchange triangular arbitrage result in excess returns?
H3: Exercising an inter-exchange arbitrage technique using the Bitcoin will result in excess returns
H0: No excess returns can be obtained when exercising an inter-exchange arbitrage technique using the Bitcoin

The results of the analyses show that for all three techniques arbitrage opportunities exist in the sample period used. However, differences between the techniques are also present. The majority of the opportunities present themselves in the months November 2017 until January 2018. A period in which the Bitcoin experiences a bull market characterised by high levels of volatility. The opportunities for the second arbitrage technique seem to diminish after the month November 2017 when the prices of both variables abruptly converge. This could be due to an amendment in the software used by the exchange. Technique one and three follow the same pattern and show roughly the same results. Significant deviations from their parities are found for a period of several months. Nevertheless, technique one shows considerable higher degrees of deviation with passing the 10% level multiple times, whereas technique three has a maximum deviation of 9.13%. These results suggest that arbitrage opportunities are most likely to be found in an active market with a volatile nature and that from the three techniques examined, technique one has the largest probability of finding profitable arbitrage opportunities.

In section 2, a theoretical framework provides in-depth knowledge regarding the Bitcoin itself and all three forms of arbitrage. Here, the rationale behind the different techniques will be elaborated, as well as their relation to the cryptocurrencies. Section 3 serves as a section where all information regarding the collection of the data used for this examination is elaborated. Section 4 will describe the different methods used for the examination followed by the results in section 5. A conclusion will be drawn in section 6 accompanied by remarks for possible future research.

Chapter 2. Theoretical Framework

Before diving into the different potential forms of arbitrage possible when using the Bitcoin, or any cryptocurrency, let us first take a step back and discuss what a Bitcoin is following with how arbitrage opportunities emerge, and how these two topics relate to each other.

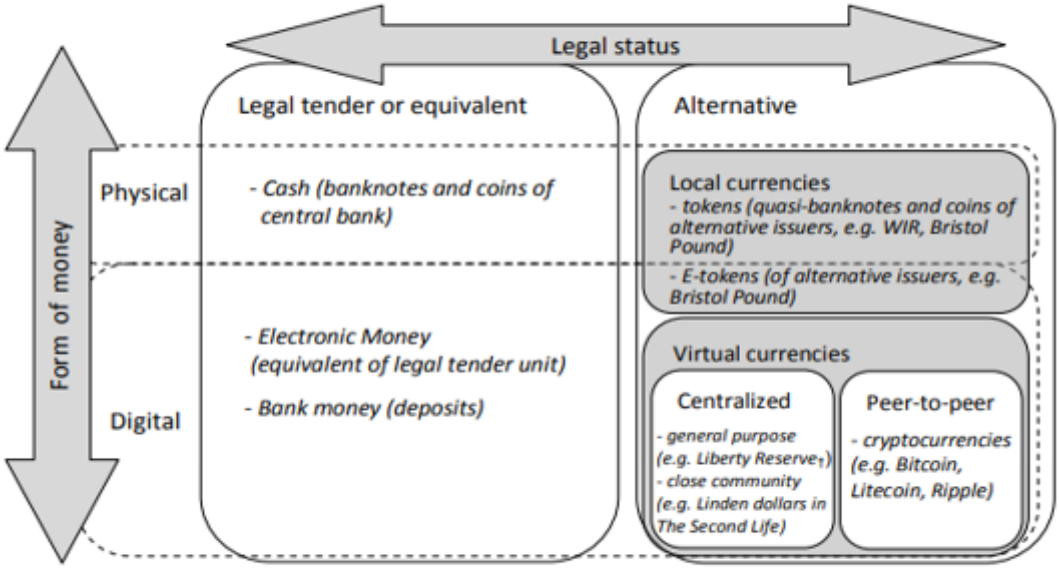
The Bitcoin

2.1 The technology behind the Bitcoin

The Bitcoin is a cryptographic virtual currency which can be exchanged peer-to-peer via an online exchange. The Bitcoin was first introduced in 2008 by Satoshi Nakamoto, whose identity up till today remains anonymous. The Bitcoin has similarities with currencies currently used. However, as can be seen in figure 1, it also distinguishes itself from these currencies in numerous ways.

Figure 1

Classification of Money



Source: Polasik, M., Piotrowska, A. I., Wisniewski, T. P., Kotkowski, R., & Lightfoot, G. (2015). Price fluctuations and the use of Bitcoin: An empirical inquiry. *International Journal of Electronic Commerce*, *20*(1), 9-49.

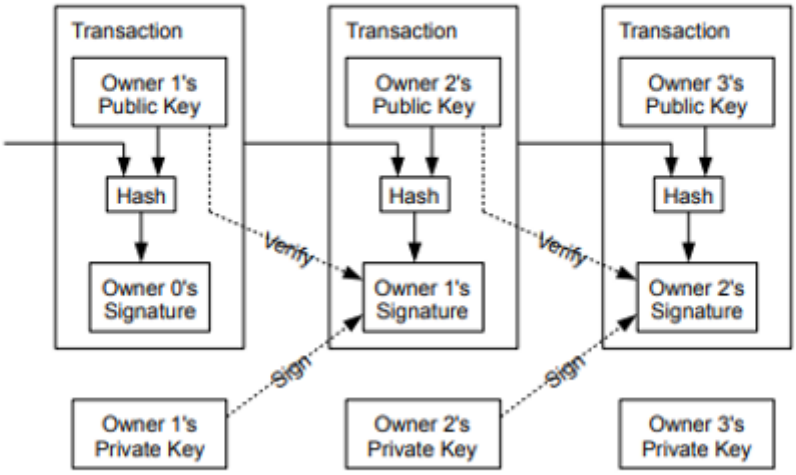
By being a digital currency, it is related to the money used by consumers deposited on their bank accounts. However, in contrast to electronic money, Bitcoin does not represent a pre-existing legal tender (Polasik, 2015). This means that the value of the Bitcoin is not related any other currency or value holding identity but instead has its own unique value, respectively. Another way the Bitcoin differentiates itself from other previous digital currencies is by being a peer-to-peer currency. A decentralized currency offers the users the possibility to transfer money to each other without the

interference of any third party. This significantly reduces the transaction costs, retains the anonymity of the user, and reduces the transaction time greatly.

As we have seen by now, the Bitcoin differentiates itself from former used currencies in various ways. Nonetheless, the aspect in which the Bitcoin differentiates itself the most is undoubtedly the technology behind it. By understanding its technology, one can comprehend the full spectrum of functionalities and possibilities the Bitcoin entails. However, this technology has the tendency to become relatively complex and challenging to fully understand. This article does not aim to discuss and describe every aspect of the Bitcoin's technology but instead analyses the possibilities with regards to one feature, namely arbitrage. For this, a general knowledge of the Bitcoin's technology will suffice and therefore this section will uphold such a level of complexity[8]. As stated by S. Nakamoto (2008): 'We define an electronic coin as a chain of digital signatures. Each owner transfers the coin to the next by digitally signing a hash of the previous transaction and the public key of the next owner and adding these to the end of the coin.' So basically, a Bitcoin is a chain of signed transactions done by previous owners, as can be seen in figure 2. The more transactions this Bitcoin undergoes, the longer the chain gets.

Figure 2

Transaction of a Bitcoin



Source: Nakamoto, S. (2008) Bitcoin: A Peer-to-Peer Electronic Cash System. http://bitcoin.org/bitcoin.pdf

This chain of transactions as a whole is called the Blockchain. For a transaction to become valid both the owner and the receiver of the Bitcoin have to agree with this transaction by means of signing with their private key and signature. When a transaction is defined as valid, this transaction is added to the

[8] If a deeper understanding of the Technology behind the Bitcoin is preferred, a reference is made to: Bitcoin, A Peer-to-Peer Electronic Cash System, S. Nakamoto (2008). In this original, nine-page, white paper S. Nakamoto introduces the reader to the Bitcoin for the first time by explaining the reasoning and technology behind this so-called crypto currency.

Blockchain and becomes irreversible. In order to prevent an owner of a Bitcoin to sell its coin multiple times to different receivers, a time-stamp is added to every transaction.

A ledger of all these transactions made by the users of Bitcoin is not held at one centralized place, like a bank or government would. Instead, a copy of this ledger is sent online to all computers which form the network and these copies are constantly updated when a new transaction is done. If someone would try to alter any of the Bitcoins they own, they would not only have to change their own transaction but also all the transactions previously done on the Blockchain, and this for all computers on the network. This makes it practically impossible for any individual to hack the Bitcoin itself.

According to Kroll et al. (2013) and what also can be translated from the information given above, the success of the Bitcoin relies on three types of consensus. These three types are consensus about the rules, the state and that the Bitcoins are valuable. With the consensus about the rules is meant that the users of the Bitcoin must agree on the criteria which define the transaction valid and that only valid transactions will be included in the ledger. The consensus about the state says that users of Bitcoin must agree on the transaction history of the Bitcoin. So, everybody knows or can retrieve which transactions were done and when. The third and last consensus is one that applies to all value-holding currencies, which is that all users must agree that the Bitcoin has a value such that users are willing to pay and be paid by the cryptocurrency (Kroll, 2013).

Arbitrage and the Bitcoin

2.2 The law of one price (LOP) and the Purchasing Power Parity (PPP)

Consider two countries x and y which both sell a commodity such as rice. The exchange rate between these two countries' currencies is 1:1.5, respectively. The law of one price states that all homogenous primary goods, so goods which have not yet experienced any form of manufacturing, should be traded at the same price (Ardeni, 1989). If this holds, the price of good a in Country x can be equated by the following formula:

$$Pa, Country\ x = Pa, Country\ y * Ex, y \qquad (2.1)$$

This means, that in our example, the price of one kilo rice in Country x should be traded at a price that is 1.5 times higher compared to Country y, when both prices are stated in their own currency. If this equation does not hold, and thus prices are not equal, then arbitrage opportunities will present themselves. Traders will try to buy rice in the country where it is relatively cheaper and sell it in the more expensive country. By doing so, a 'riskless' profit can be made. Consequently, the prices of rice in

the relatively cheaper country will go up due to a higher demand and the prices of the more expensive country will go down. This process will continue until the prices of both countries are equalized, and the law of one price is restored. However, history has shown that the LOP does not always hold and a distinction should be made between the short run and the long run perspective. Short-run prices have shown to occasionally differ from each other whereas the long-run prices generally are pushed to long-run equilibrium. In fact, short run price deviations will be corrected by a supposedly efficient market in order to obtain the long run equilibrium. These corrections in the short-run are also known as arbitrage. A study performed by Akram et al. (2008), analysing arbitrage in the foreign exchange market, shows that, when using the right data frequency, numerous short-lived violations of the covered interest rate parity (CIP) and the LOP arise where the size and the duration, on average, is high enough to allow agents to exploit them. This shows that even for well-matured markets such as the foreign exchange market arbitrage possibilities still emerge.

As shown by formula 2.1, the law of one price could be used to test whether homogenous goods in different countries are priced correctly according to their exchange rates. However, when rewriting the equation, one could also test for any inefficiencies in the exchange rates. If the price of good a in Country x is equal to the price of the same good in Country y times the exchange rate between those two countries, then it must also hold that dividing the prices of both goods should equal the exchange rate between both countries. This leads to following equation:

$$Ex, y = \frac{Pa,Country\ x}{Pa,Country\ y} \qquad (2.2)$$

This equation is also called the purchasing power parity (PPP). The PPP states that the exchange rate between Country x and y should equal the price of a kilo rice in country x divided by the price of a kilo rice in Country y. In essence, the PPP creates the possibility to compare different standards in quality of life across the world. If, for example, the Country x's currency would depreciate by 10% this would decrease the buying power of that country's residents. Nonetheless, if Country y 's currency would depreciate even more, by 20%, then the purchasing power of Country x would ultimately increase even though their currency depreciated by 10%.

2.3 How is the Bitcoin, or any crypto, related to this LOP? And does this create arbitrage opportunities?

A bitcoin may not be a commodity like rice in the previous stated example, nevertheless Bitcoin can be defined as a homogeneous good or asset. A bitcoin in the US is exactly the same as a Bitcoin in South-Korea. It has the same technology and the same functionalities. It has not experienced any branding or

other types of adjustments which could change the value of a Bitcoin in different places in the world. For this reason, the Bitcoin should have the same prices in all countries, when adjusted for the exchange rates. Therefore, the LOP and the PPP should also hold for the Bitcoin. And thus, dividing the Bitcoin prices off two different countries should also reflect their exchange rate. Assuming these relations hold, this will lead to the following equations for each separate arbitrage technique, respectively:

LOP 1. Multi Fiat Currency Triangular Arbitrage: $P(btc, usd) = P(btc, eur) * \frac{USD}{EUR}$

LOP 2. Multi Crypto Currency Triangular Arbitrage: $P(btc, usd) = P(btc, eth) * \frac{ETH}{USD}$

LOP 3. Inter-Exchange Arbitrage: $P(btc, usd, Gdax) = P(btc, usd, Kraken)$

In an efficient market these LOP's should hold and no significant differences between Bitcoin prices should be observed. However, in practice we often do find discrepancies between the global prices of Bitcoin, when corrected for their exchange rate. Moreover, there is one country which is known to have a premium in the Bitcoin compared to those of other countries in the world, and that is South Korea. South Korea has, for a period of months, showed such a significant discrepancy for the price of a Bitcoin compared to those of other countries, that it has even obtained his own name, the Kimchi premium. When looking at figure 3, The Kimchi premium, in relation to the US dollar, reached as high as 50% on the first of January 2018 (Nagy, 2018). Here, the red line is the Korean Bitcoin price and the blue line is the US Bitcoin priced, both given in Korean Won (KRW). This suggests that the cryptocurrency market is inefficient and thus the LOP and PPP do not hold, making arbitrage possible.

Figure 3

The Kimchi Premium

Source: Nagy, M. (2018). Arbitraging the Kimchi premium with Bitcoin. Haaga-Helia ammattikorkeakoulu Oy

2.4 Conditions and violations of the LOP and PPP

So, according to the LOP and the PPP, all homogeneous goods and assets should always have the same price, corrected for their exchange rates. However, we have seen that these economic laws can be violated and thus do not always hold. This section will provide a deeper insight in the conditions which need to be present in order for the LOP to withhold and how these conditions can be violated. Here, only the LOP will be discussed since the PPP is a derivation from the LOP, hence violating the LOP will automatically also violate the PPP. This will then be linked to the Bitcoin to see whether this potentially can be a market where arbitrage possibilities will present themselves by means of violations of the LOP. The general assumption of the LOP is for the market to be efficient. In order to reach this state, the market should not be heavily restricted and is desired to meet the follow criteria: no restrictions on the transportation of the goods, no tariffs are imposed by the countries using the goods, and there should be no or low transportation costs charged when trading the goods. 'Discriminating monopolies and tariffs, subsidies, or other trade restrictions create disparities between export and wholesale prices' (Isard, 1977).

2.4.1. No restrictions on the transportation of goods

A good example of a restriction on the transportation of a good would be a quota or even a ban on the export or import of that particular good. If a good would receive a quota on the maximum amount which is allowed to be imported in a country x, the price of that good in country x will automatically increase. The demand for that good will remain the same but the supply will decrease due to the quota, causing the price to increase. The magnitude of the impact of this quota can, however, depend on the other already implemented measures. If, for example, a tariff is already in place, the effect of the quota will be significantly less as when a quota would be the only restriction implemented (Dean et al., 2008). When looking at the Bitcoin market, we see some interesting developments in the field of regulations. The Bitcoin market is a relatively young and underdeveloped market. This created a market where the first couple of years few to none regulations were in place and Bitcoin traders could buy and sell goods using Bitcoin without any form of control. Due to the anonymous nature of Bitcoin and this unregulated market, the Bitcoin was soon to be used for the buying and selling of illegal goods through online websites. A well-known example of such a market place is Silk Road. Silk Road is, just like eBay, an online market place where an infrastructure is provided for buyer and sellers to connect online. This way transactions can be done between buyers and sellers where anonymity is ensured (Christin, 2013). Figure 4 shows a list of the top 20 items that were available on Silk Road. As you can see, the list is mostly dominated by items with an illegal nature. After the discovery of Silk Road, the US government shut down the site and realized that intervention in the cryptocurrency market was necessary.

Figure 4

Top 20 Categories Silk Road

Category	#. items	Pct.
Weed	3338	13.7%
Drugs	2194	9.0%
Prescription	1784	7.3%
Benzos	1193	4.9%
Books	955	3.9%
Cannabis	877	3.6%
Hash	820	3.4%
Cocaine	630	2.6%
Pills	473	1.9%
Blotter (LSD)	440	1.8%
Money	405	1.7%
MDMA (ecstasy)	393	1.6%
Erotica	385	1.6%
Steroids, PEDs	376	1.5%
Seeds	374	1.5%
Heroin	370	1.5%
DMT	343	1.4%
Opioids	342	1.4%
Stimulants	291	1.2%
Digital goods	260	1.1%

Source: Christin, N. (2013, May). Traveling the Silk Road: A measurement analysis of a large anonymous online marketplace. In *Proceedings of the 22nd international conference on World Wide Web* (pp. 213-224). ACM.

In recent years, and in particular 2017, governments have been implementing different regulations as regards to the Bitcoin where some countries have even banned the use of Bitcoin in general. The announcement of South Korean regulators to ban, or at least implement significant control to the crypto market caused the Bitcoin to decrease more than 15% in value[9]. But even companies can have an impact on the price of the Bitcoin. When Google announced that they would ban all cryptocurrency advertising, the price of Bitcoin also dropped by more than 10%[10]. Conclusively, the Bitcoin market is experiencing significant regulation among which restrictions on the use of Bitcoin is a prominent one. These regulations have a substantial effect on the price of the Bitcoin which makes it increasingly volatile. Nevertheless, due to the fact that these regulations are generally only locally applied, often only in one country or continent, this increases the chances of discrepancies between Bitcoin prices globally which will have a positive effect on the arbitrage possibilities.

2.4.2. No tariffs are imposed by the countries using the goods

When a tariff is implemented, the goods that are imported become more expensive for the consumers in that particular country. Let's say a computer costs \$450 when it is bought in Country x but only \$400

[9] https://cointelegraph.com/news/regulations-and-their-influence-on-cryptocurrency-prices
[10] https://www.reuters.com/article/us-crypto-currencies-google/google-bans-cryptocurrency-advertising-bitcoin-price-slumps-idUSKCN1GQ0GD

when the same computer is bought in Country y. Country x can then decide to impose a tariff, for example of 25%, to all computers imported from Country y. The price of a computer from Country y will now cost the consumer in Country x \$500 instead of the original \$400. This will stimulate the consumers in Country x to buy computers domestically and thereby increasing their production. Nevertheless, tariffs may have unintended side-effects as it firstly will decrease the domestic competition, which could potentially decrease the productivity, and secondly could stimulate other countries to also impose a tariff which could eventually lead to a trade war. With respect to the Bitcoin, there are two main reasons why tariffs are not of great concern to Bitcoin users. The first one is that Bitcoin is more a currency instead of a good. Tariffs are solely implemented on goods or commodities and not on currencies. The second reason is that the Bitcoin is a decentralized currency, meaning that the currency is not owned or controlled by any government or other third party. Therefore, a country could implement restrictions on the use of Bitcoins but they cannot raise the price of a Bitcoin by means of a tariff.

2.4.3. No transportation costs charged when trading the goods

Using the previously mentioned example about buying a computer in Country x or y, we explain the effects of transportation costs on an efficient market. If no tariffs were to be implemented such that the price of computer in Country x remains \$450 and in Country y \$400, then consumers would want buy a computer from Country y again. However, when a computer is bought in Country y, it has to be sent to Country x in order for the consumer to be able to use it. The transportation of this computer is often charged with a so-called transportation fee. If the transportation fees exceed \$50, the total price of the computer will be over \$450 and the consumer in Country x would not be interested in buying the computer in Country y anymore, creating an inefficient market. For the Bitcoin, transportation costs are expressed in terms of transaction fees and are one of the most important factors for executing a profitable arbitrage strategy. The transaction fee of a Bitcoin has started at zero or close to zero but has increased significantly over the last couple of years. The increase of these fees has multiple reasons. New Bitcoins are produced by a process called mining. When Bitcoins are mined, so called miners use a software program to mathematically solve a problem and thereby producing a new block. As more Bitcoins get mined, the Bitcoin network increases the difficulty of the problems to be solved in order to receive a Bitcoin. This not only makes the mining process more time consuming but as the difficulty level increases also more electricity and process power is needed in order to mine a Bitcoin. In the early stages, Bitcoin could be mined using a regular processor in a computer and the transaction fee received by the miner was minimal and more seen as a 'donation' rather than a fee (Kaskaloglu, 2014). However, as the problems to be solved got increasingly difficult, the miners needed better equipment and more electricity which resulted in higher fees. Another reason why the Bitcoin transaction fees increased is

due to the fact that the reward a miner received from mining one block halves each four years. When the miners started, they received 50 Bitcoins for each block that they mined. However, since November 2012, this number halved to 25 Bitcoins. This makes the process of mining less profitable for the miners and thus they require higher transaction fees. The third and last reason is related to the speed of transactions. A miner which has high quality equipment will be able to find new blocks and thus create a Bitcoin at a faster rate than miners with equipment of lower quality. When a buyer wants to purchase a Bitcoin he or she places an order and waits for a miner to fill this order. Naturally, the miners will choose the orders with highest transaction fees since this will earn them the highest profit. For this reason, Bitcoin buyers who might be impatient for a miner to fill their order will place an order with a relatively high fee which will eventually raise the overall level of the transaction fees. Möser et al. (2015) examined the relation between the height of the transaction fee and the time of the transaction. Figure 5 shows their results.

Figure 5

Transaction Latency

		Quantiles of the latency distribution				
Fee	# Tx	10 %	25 %	50 % (median)	75 %	90 %
0	1503	180	444	1339	4270	13927
0.0005	5735	106	255	600	1244	2440
0.001	1905	90	212	520	1129	2135

Sample period: June 2012 to May 2013. See text for details.

Source: Möser, M., & Böhme, R. (2015, January). Trends, tips, tolls: A longitudinal study of Bitcoin transaction fees. In *International Conference on Financial Cryptography and Data Security* (pp. 19-33). Springer, Berlin, Heidelberg.

The table shows that half of the zero-fee transactions had to wait over twenty minutes for their order to be filled whereas paying a fee of 0.0005 Bitcoin reduced that time by half. And 10% of the zero-fee transactions had to wait for almost four hours to confirm. For the ones who paid 0.0005 Bitcoin, this only took 40 minutes (Möser, 2015).

2.5 The Bitcoin suitable for arbitrage?

Considering the Bitcoin, it does not tick the majority of the boxes in order to be an efficient market. This would suggest that the Bitcoin market is inefficient which would not be surprising since it is still a relatively new market. Even if the Bitcoin market were to be an efficient one, opportunities for arbitrage could still emerge. Efficient markets also experience arbitrage opportunities, yet these opportunities usually resolve itself so rapidly, often by automated trading software, that other traders such as

institutional and private traders have no possibility to take advantage of these arbitrage opportunities. This article aims to examine arbitrage which can not only be realized by online automated traders but also by other traders such as institutional- or even private traders. For this reason, it is beneficial for the Bitcoin market to be an inefficient market. This creates more time before the market corrects itself and thus more opportunities for profitable arbitrage remain, even for the non-automated traders. Two factors which have a considerable influence on the existence of arbitrage possibilities in the Bitcoin market are transaction costs and transaction time. The examination done by Möser et al (2015) shows that these two factors are linked to each other where paying a higher transaction fee leads to a shorter transaction time and vice versa. But if these transaction fees, and thus the transaction time, are not fixed, to what extent do these factors influence the arbitrage possibilities? And what value should be taken for these factors when examining arbitrage on the Bitcoin market?

As mentioned before, in the very beginning all transactions with Bitcoins had no transaction fees and thus Bitcoins were free to transfer. But as the difficulty of the mathematical problems to solve increased and the mining of Bitcoins got less rewarding, the transaction fee increased as well. So, as the demand for Bitcoin increases, the requirement for miners to solve the mathematical problems at an increasing speed increases as well, which automatically increases the transaction costs. This relationship is shown in figure 6. A clear observation which can be made from this figure is that, as soon as the interest in the Bitcoin rose and the Bitcoin entered a bull market in November, the transaction costs also increased exponentially. Starting with a value of approximately $5.00 at the beginning of November 2017, the average transaction costs reached a maximum value of $55.16 on the 22th of December 2017. This is an increase of more than a 1000% in less than two months. After the bull market, with the demand for Bitcoins decreasing again, the average transaction fee is now back to approximately $0.60.

Figure 6

Bitcoin Average Transaction Costs

Source: https://bitinfocharts.com/comparison/bitcoin-transactionfees.html#1y

Nicolas Houy (2014) studied the relationship between the Bitcoin transactions fees, the block size and the security of a decentralized market under different conditions. He concluded that any situation with a fixed fee is equivalent to a situation with a limited block size. And that either of these situations will lead to the condition where the security, and thus the long-term existence, of the Bitcoin cannot be guaranteed. In other words, these transactions fees will continue to exist and presumably increase in value as Bitcoins get more difficult to mine (Houy, 2014). Having a transaction fee which is submissive to the environment of the market and thus has an uncertain value, questions the validity of the examination if the current market value is taken. The value of these fees could change at a fast rate which will change the outcome of the entire examination. For this reason, this examination uses transaction action fees with a value of zero. It is realized that in the current environment this is assumption will most likely not be met. However, if a profitable arbitrage technique indeed is found, one could match this technique and deduct the transaction fee applicable at that time in order to get an accurate representation of the profits to be made. An example of such a calculation is given in the results section of this article to show how an arbitrage opportunity should be executed and what it's precise pay-outs would be if indeed performed. When performing a trade on an exchange, exchanges usually charge so called maker and taker costs as transaction fees[11]. Here, the maker fee is charged to someone who places an order for a price which is not already on the books. The taker fee is charged to someone who places an order which is already available and thus is immediately filled. In general, the maker pays a lower fee than the taker. This way the exchange tries to incentivise traders to place an order on the books which creates liquidity. This article does not use these fees in the profit calculations for the arbitrage techniques for multiple reasons. Firstly, these rates differ per exchange so these values could be taken from their site but the aim of the article is to give an idea of what arbitrage opportunities there are in general and not for one specific exchange. Secondly, these rates differ per size of transaction that is being performed. The size at which the arbitrageur performs is not known and thus also the value of the fees are unknown. Thirdly, another unknown factor is whether the trader is going to be a maker or taker when executing the arbitrage trade. For these reasons, the average transactions costs given by figure 6 are taken instead. This provides the reader with a good overall approximation of what the fees would be performing such a trade. But bear in mind that these fees could change depending on the different conditions the trade is performed at.

[11] https://www.kraken.com/help/fees

Chapter 3. Data

This article tests for three different arbitrage techniques. This means that three different analyses are conducted using three different data sets. Consequently, this section of the article will also be divided into three sub sections. This will provide a clear overview of what data is used for which technique and how this data is collected. However, there are some criteria which are applicable for all data sets and thus will be covered beforehand. For all datasets a frequency of hourly data is used. Daily data could be used as well but, like mentioned in the introduction section of this article, using hourly data decreases the chance of the market to correct itself which automatically increases the chances of finding a profitable arbitrage technique. Another criterion which holds for all three techniques, is that a time frame reaching from July 1st 2017 till July 1st 2018 is used. This is a period where the Bitcoin both experienced a bull market as well as a bear market. This provides the chance to not only examine the arbitrage opportunities in each market condition separately but also the transition period in between. All data concerning the crypto currencies from www.cryptodatadatadownload.com is retrieved in the following format:

Date	Symbol	Open	High	Low	Close	Vol. From	Vol. To
2017-07-01 11AM	BTCUSD	6252.45	6262.68	6249.28	6255.01	127.81	799595.58

- **Date:** the date and time at which those values were retrieved
- **Symbol:** the ticker given to the value, where the first variable has a value of one expressed in an number of units of the second variable
- **Open:** the value at which the previous hour was closed. In the example above, the open value of 11AM would equal the closing value of 10AM
- **High:** the highest value reached with the one-hour time frame
- **Low:** the lowest value reached within the one-hour time frame
- **Close:** the value at which the hour is closed, so in this example that would be the value of BTCUSD at 11.59AM
- **Volume From:** the value of BTCUSD transactions denominated in Bitcoins
- **Volume To:** the value of BTCUSD transactions denominated in US dollars

For all calculations performed in the analysis, the closing price for each crypto currency pair is taken. The close price is preferred rather than a high or a low in order to obtain a trend of which direction the prices are moving. If, for example, instead the high price was to be chosen, only a short period of the value of the Bitcoin in that hour is given. This could be as small as a matter of seconds, as long as that price is hit somewhere in the hour. This would not be representative for the value of the Bitcoin in that

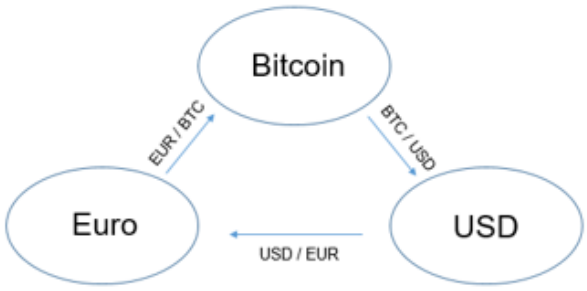
full hour. The aim of this article is to find arbitrage techniques which persist for a certain amount of time such that they can be executed by various types of investors. Taking a high price as a variable and using those only short-lived spikes to run the analysis will not result in a liable nor executable investment strategy.

3.1 Multiple Fiat Currency Triangular Arbitrage

For the first technique, a triangular arbitrage technique is used with one crypto currency, the Bitcoin, and two Fiat currencies, the US dollar and the Euro. Figure 7 presents how this arbitrage technique is executed. First, a Bitcoin is exchanged to US dollars, from this amount Euros will be bought after which these Euros will be exchanged back to Bitcoins. If the amount of Bitcoin after the transaction is larger than before, a profitable arbitrage technique is accomplished.

Figure 7

Multiple Fiat Currency Triangular Arbitrage



Three sets of data are required for the execution of this triangular arbitrage. First, the exchange rates of Bitcoins to US dollars. Second, the exchange rates of US dollars to Euros. Third, the rates of changing the Euros back to Bitcoins. With this technique we test for arbitrage possibilities using Fiat currencies on the same exchange. For this reason, it is essential to obtain the BTC/USD and BTC/EUR from one exchange. Cryptodatadownload.com provides data for both these exchange rates on numerous exchanges, in both daily and hourly frequencies. The exchange which is used for this analysis is GDAX. GDAX is currently ranked 6th in the top 100 exchanges ranked by trading volume[12]. Being ranked relatively high will provide the traders a high level of liquidity which is essential for performing a profitable arbitrage technique.

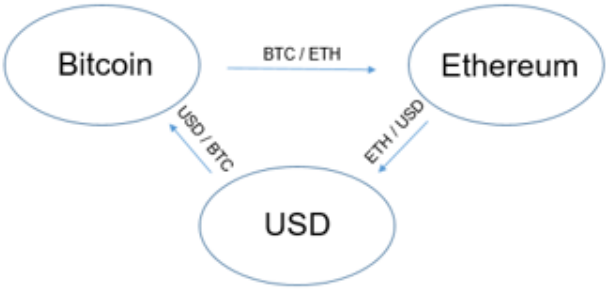
[12] https://coinmarketcap.com/rankings/exchanges/. GDAX is indicated as Coinbase Pro due to a rebranding. This ranking was obtained on August 20th 2018 but could change as a result of the volatile market and demands.

3.2 Multiple Crypto Currency Triangular Arbitrage

This technique is comparable with the first one, however here one Fiat currency is replaced by a crypto currency. The three variables for the multi crypto arbitrage are the Bitcoin, Ethereum and the US dollar. The manner at which the arbitrage is performed is almost identical to that of the first technique as shown in figure 8. A Bitcoin is exchanged for an X amount of Ethereum, this Ethereum is then sold for US dollars after which Bitcoins are bought back from those dollars. If the amount of Bitcoin after the trade is larger than before, a profitable arbitrage strategy is executed.

Figure 8

Multiple Crypto Currency Triangular Arbitrage



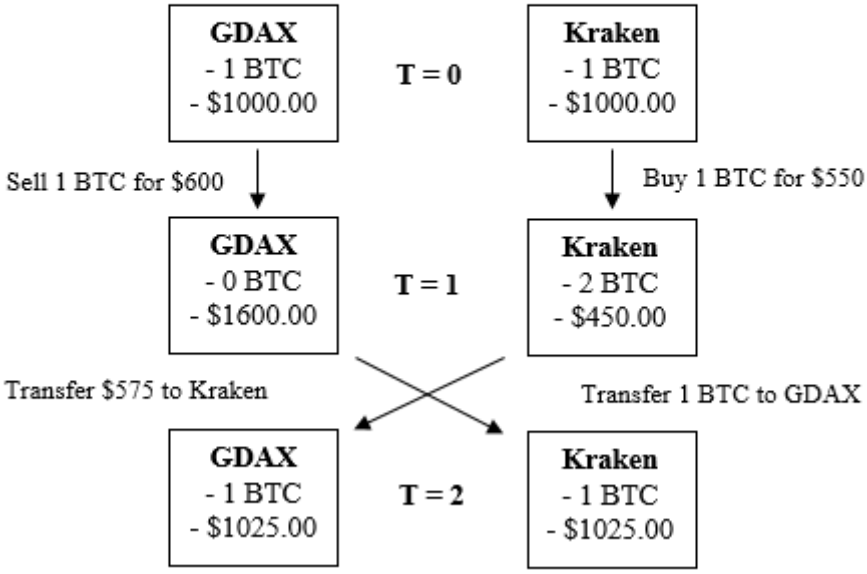
For this technique, all data is also obtained from cryptodatadownload.com and hourly frequency is used. For the time frame, a slightly different period is used. This is due to the fact that the data of the exchange rate between the Bitcoin and Ethereum earlier than October 26th 2017 is not available. Hence, for this analysis a time frame reaching from November 1st 2017 till July 1st 2018 will be used instead. This does reduce the original data set with an input of three months data, however with the remaining data set having a size of almost 6000 data lines this will not significantly affect the validity of the results of the examination. Furthermore, with the peak of the crypto bull market being December 2017 and the bear market following afterwards, both market conditions are also included in the alternative data set. All exchange rates related to Fiat currencies are obtained from www.dukascopy.com. This source provides a wide range of exchange rates and other trading related information, ranging from forex trading to general market information. Here, the EUR/USD exchange rate is obtained using an hourly frequency and the same period and method are used as for the crypto currencies data. One important element which has to be taken into consideration when using the Fiat currency pair is that these values are obtained in a different time zone than the values of the crypto currency pairs. The crypto currency pairs are obtained in Coordinated Universal Time (UTC) which is a time standard that equals Greenwich Mean Time (GMT). The Fiat currency pairs are obtained at GMT +02.00. This means that there is a two-hour difference between both data files and that simply matching all the hours and dates with each other will not be correct. This problem is solved by shifting all the values of the Fiat currencies to two hours later such that the values indeed reflect the same moment in time. So, for example, 2018.08.08 11AM in the Crypto data file will be matched with 2018.08.08 1PM in the Fiat currency file, and so on and so forth.

3.3 Inter-Exchange Arbitrage

For the third, and last technique multiple exchanges are used. For performing an arbitrage technique, liquid markets are crucial, especially with such a volatile market as the crypto market. If a Bitcoin is bought for a certain price but due to illiquidity the trader cannot buy back the Bitcoin on a different market, the chances are that the price of the Bitcoin changes in the meantime and thereby eliminating the profitable arbitrage opportunities. Hence, for inter-exchange arbitrage it is essential that those exchanges provide a certain level of liquidity. There are numerous sites which provide a top 10 ranking of exchanges by volume. Unfortunately, these sources usually have a varying order and mixture of exchanges which are present in their top 10. This stresses the fact that sites use different tools or programming language to obtain their information and thus the same site should be used to obtain as much data as possible. Nevertheless, although the sites do not provide the same ranking, some exchanges are included in almost all the rankings regardless of their position. Some of these are Bitfinex, Kraken, and GDAX. This indicates that on these exchanges sufficient trades are done in order to provide a liquid environment. To collect the data for inter-exchange arbitrage, the site www.cryptodatadownload.com is used. This site provides hourly data for all of the above-mentioned exchanges. However, due to an insufficient amount of data, Bitfinex cannot be used for the analysis. Consequently, Kraken and GDAX are used to test for inter-exchange arbitrage possibilities. For both exchanges, the BTC/USD exchange rate will be collected for the selected time frame of July 1st 2017 till July 1st 2018. A Bitcoin will be bought for a certain amount of US dollars on one exchange and simultaneously sold at the other exchange. If this Bitcoin can then be sold for more US dollars than the Bitcoin was originally bought for, a profitable arbitrage technique is performed. Note that, unlike Gandal and Halaburda (2014), when exercising this technique, the Bitcoins are not actually sent to the other exchange directly. Instead, both exchanges are provided with sufficient amount of funds in Bitcoins as well as a fiat currency, the US dollar in this case, such that a transaction can be performed on each exchange simultaneously without first having to send a Bitcoin from one exchange to the other. A hypothetical example of such a transaction would be where both GDAX and Kraken have 1 Bitcoin and $1000.00 on their balance. If the Bitcoin would cost $600.00 on GDAX and $550.00 on Kraken, a Bitcoin would be bought for $550.00 from the dollar funds on Kraken and simultaneously the Bitcoin on GDAX would be sold for $600.00 on GDAX. This will result in a balance of 0 Bitcoins and $1600 on GDAX and 2 Bitcoins and $450.00 on Kraken. After the transaction is successfully performed, $575.00 will be send from GDAX to Kraken and 1 Bitcoin will be send from Kraken to GDAX. This will create and ending balance of $1025.00 and 1 Bitcoin on both exchanges. The full transaction can be seen in figure 9. The total profit made by this transaction is $50.00 without being depended on the speed at which a Bitcoin is send from one exchange to the other. This process can sometimes take up to a couple hours which could possibly change the price of the Bitcoin in the meantime and eliminate any profitable arbitrage possibilities.

Figure 9

Inter-Exchange Arbitrage



3.4 Missing or wrong data

Unfortunately, during the process of cleaning the data, missing or wrong data was found in the sample used for the analysis. However, these gaps and errors were only minor in relation to the size of the sample. For all data obtained from www.cryptodatadownload.com, so this would refer to all data regarding the crypto currencies, data is missing from 11:00:00 till 15:00:00 on May 10th 2018. Presumably, this is caused by an error of the site during that time frame leading to a five-hour gap for all data. As for technique 1, the multi crypto triangular arbitrage, there was also data missing regarding the BTC/EUR exchange rate reaching from November 11th 23:00:00 till November 12th 08:00:00. And for technique three, the inter-exchange arbitrage, the data reaching from January 11th 2018 06:00:00 till January 13th 2018 13:00:00 appeared to be incorrectly obtained since the value of the BTC/USD exchange rate on Kraken showed a constant value for a number of consecutive hours, with a maximum of twenty-five hours. For this period the value of the BTC/USD is equalized with that of GDAX such that these values cannot affect the data nor the results of the analysis. Like said before, with a total sample size, for all three techniques combined, of approximately 35,000 data lines, these errors in the data are not of sufficient size in order to have any significant impact on the results this examination. Also, when performing a trade with any asset there is usually a difference between the price at which the assets are sold for and the price at which the assets are bought for, this is called the 'bid-ask spread'. When trading crypto currencies this spread also exists. It would be ideal to find the precise prices at which Bitcoins are bought and sold in order to be able to incorporate this spread in the profit calculations

of all arbitrage techniques. Unfortunately, such data is not available online but instead the prices are given in the format presented earlier in the article. Also, a bid-ask spread usually has such a small value that this will not significantly affect the profitable pay-outs for an arbitrage technique. For example, the average spread of Bitfinex and Kraken in US dollars for the last two years are $0.1562 and $0.5297, respectively[13]. Such values will not have a considerable impact on the profits if sizeable discrepancies are found with the closing prices in any of the three techniques.

[13] https://data.bitcoinity.org/markets/spread/2y/USD?c=e&f=m10&sd=10&st=log&t=l

Chapter 4. Methodology and Results

4.1 Multiple Fiat Currency Triangular Arbitrage

If no arbitrage possibilities would exist, the prices of the Bitcoin in Euro and in USD would move parallel to each other with a constant difference of the exchange rate EUR/USD. Because then, at any given moment, selling a Bitcoin for Euros should earn you the same amount as when a Bitcoin is sold for USD and then exchanged to Euros. This leads to the following formula:

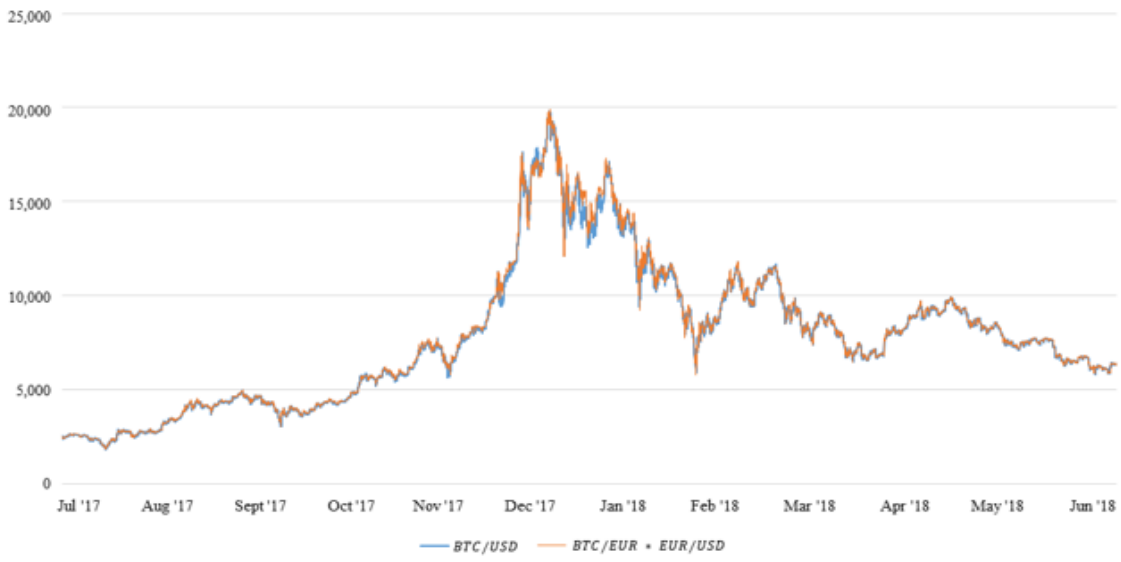
$$\frac{BTC}{USD} = \frac{BTC}{EUR} * \frac{EUR}{USD} \qquad (4.1)$$

Two functions that move parallel with each other should naturally also be perfectly correlated with each other, since a price drop in variable x would also result in the same price drop in variable y. They follow the same movements and therefore move parallel with each other.

When examining the correlation between the variable $\frac{BTC}{USD}$ and $\frac{BTC}{EUR} * \frac{EUR}{USD}$, we find a correlation coefficient of 0.999219. This means that both variables are highly correlated with each other and thus also follow the same price movements. In general, this would suggest that few or little arbitrage possibilities would emerge using this arbitrage technique. However, since the dataset is of substantial size, having some outliers in the data would not significantly affect the results for the correlation coefficient but will create arbitrage possibilities. By graphing both prices next to each other, it becomes visible whether there are any discrepancies between them in our sample. Figure 10 shows the price movements of both variables.

Figure 10

Bitcoin Price Trends in Dollar's and Euro's



Throughout the period the prices follow roughly the same trend line. However, in the middle of the sample some discrepancies can be seen between both prices. Figures 11 displays a closer look at the period where the largest discrepancies can be found between both prices. This period is from November 2017 till January 2018. What can be observed is that especially in the end of the months November and December the prices tend to vary from each other. These price differences suggest that there are some possibilities for arbitrage using this technique.

Figure 11

Possible Arbitrage Opportunities Technique 1

These possibilities, however, should be examined in order to get a precise answer to whether there are indeed significant price differences, when and by how much these prices differ from each other. Testing for these possibilities is done by comparing the values of both variables for each data line in the entire data set. If they indeed differ, discrepancies should be found. These discrepancies are found by subtracting the $\frac{BTC}{EUR} * \frac{EUR}{USD}$ from the $\frac{BTC}{USD}$. This difference is then divided by the Bitcoin Dollar price in order to get a percentage difference between both prices. Like said before, if both prices indeed move in line with each other, no significant discrepancies should be found. Figure 12 shows the results of this examination. What we observe is that, similar to what figure 10 depicts, on average the prices do move parallel with each other but some significant price differences do emerge. The average difference between both prices for the entire dataset is -0.68%. This means that in general the price of the Bitcoin denoted in Euros is slightly higher than that of the Bitcoin price in USD, corrected for the exchange rate. Nonetheless, with a dataset of almost 9,000 lines this is only a minor difference. When looking at the outliers, we observe that the 5.00% line is crossed multiple times, especially in the negative half of the graph.

Figure 12

Price Discrepancies Sample Technique 1

Note. These discrepancies are found by subtracting the $\frac{BTC}{EUR} * \frac{EUR}{USD}$ from the $\frac{BTC}{USD}$. This difference is then divided by the Bitcoin Dollar price in order to get a percentage difference between both prices

A couple spikes that stand out when analysing the figure, these points refer to the following dates with their corresponding values:

- 30 November 2017 8 PM - 9.06 %
- 07 December 2017 10 AM - 10.56 %
- 22 December 2017 6 AM 13.34 %

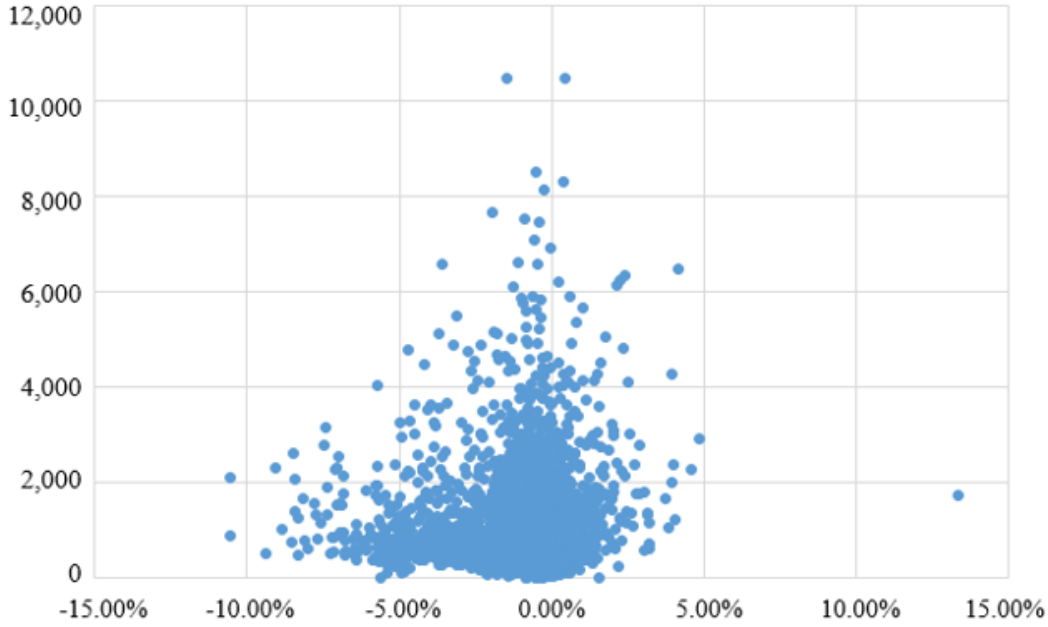
Notice that most of the spikes happen in the middle of the dataset, between November 2017 and January 2018. Considering this period, we notice that a number of consequential events took place. The price of the Bitcoin reached its all-time high and some online exchanges such as Nicehash were hacked[14]. These events create an instable market where investors could sell their Bitcoins in order to protect their funds. The Euro market could respond more heavily to these events relative to the US market, or vice versa, creating a price discrepancy between the two. If a price discrepancy occurs, one would also expect that the volume of traders will go up at that certain moment in time since arbitrageurs will try to take advantage of these opportunities and thereby correcting the market. Figure 13 shows the correlation between the price difference as explained above and the volume of trades from GDAX. Here, the horizontal axis shows the percentage price difference between the Bitcoin price in Euro and Bitcoin

[14] https://www.reuters.com/article/us-cyber-nicehash/hackers-steal-64-million-from-cryptocurrency-firm-nicehash-idUSKBN1E10AQ

price in USD divided by the exchange rate. The vertical axis shows the volume of trades from GDAX which were executed at that specific time. This volume is denominated in Bitcoin units.

Figure 13

Correlation Price Discrepancies and Volume Transactions From GDAX



What can be observed is that the highest trade volumes are centred around the 0.00% price difference and that the trade volumes around the outliers are lacking. This means that the majority of the trades are performed when there is no significant difference between the prices of the two variables. This is contradicting to what would be expected if arbitrageurs indeed took advantage of these price differences. There are two situations which could explain these results. The first one is a situation in which the arbitrageurs do take advantage of these possibilities by trading on them but that the proportion of arbitrageurs trading at that specific moment compared to the regular traders that trade every day is relatively so small that the volume of these arbitrageurs does not spike. A second situation is one at which arbitrageurs simply do not discover these opportunities and therefore also do not trade on them. This would mean that indeed arbitrage possibilities emerge and are left open for private traders to take advantage off. Another noticeable feature of figure 13 is that the correlation is leaning slightly to the left side of the graph. It can be clearly observed that numerous trades are performed around the -5.00% value but at the 5.00% value the trades are lacking. This means that when the value of the Bitcoin denominated in Euros, corrected for the exchange rate, is higher than that of the Bitcoin denominated in US dollars, investors do seem to notice these discrepancies or at least increase their trading whereas vice versa not so much. Either way, the results show that, in general, the prices of the Bitcoin in Euros and Dollars follow a parallel path where occasionally price discrepancies appear, possibly triggered by certain events in the crypto market. This leads to the acceptance of the hypothesis formulated in the first section of this

article where, if done correctly, exercising a triangular arbitrage using the Bitcoin, the US dollar and the Euro profitable arbitrage opportunities will be established.

4.2 Multiple Crypto Currency Triangular Arbitrage

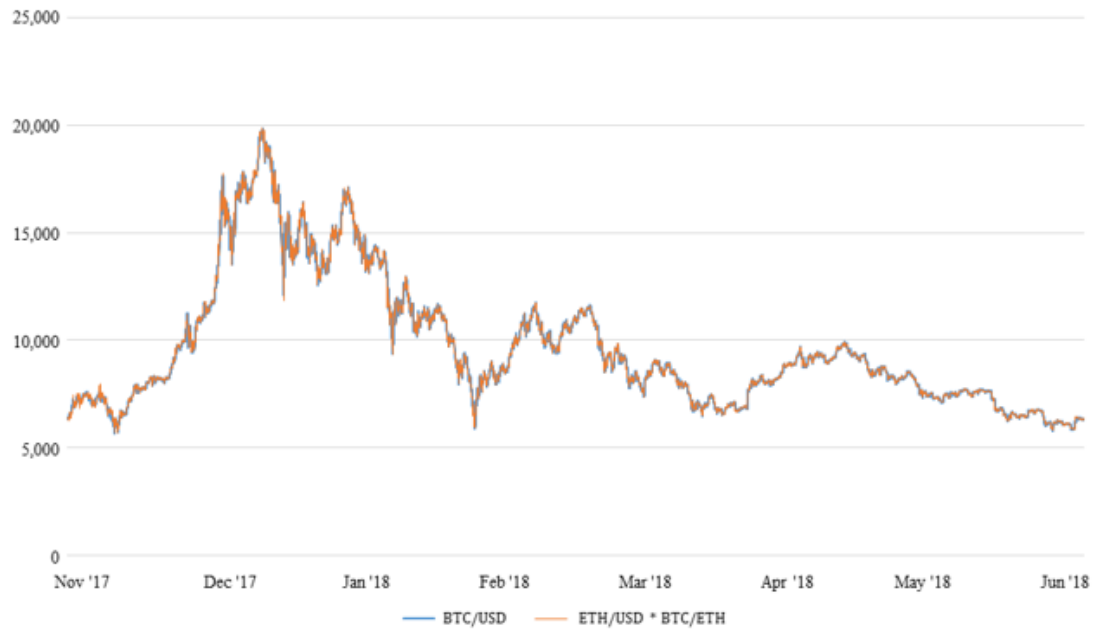
For the second technique, we compare the prices of two cryptocurrencies on the same exchange. In theory, when there are no price discrepancies to be found, the price of the Bitcoin should equal to the price of an Ethereum times the amount of Ethereums that can be bought with one Bitcoin. This results in the following equation:

$$\frac{BTC}{USD} = \frac{ETH}{USD} * \frac{BTC}{ETH} \qquad (4.2)$$

One would expect that being on the same exchange, the prices will not differ significantly from each other, being corrected with for the BTC/ETH exchange rate. If the online exchange where they are provided, in this case GDAX, has a sophisticated tracking system they would have a calculator build in their software which continuously compares the relative prices with their exchange rate and give a signal once they diverge. This would then be automatically corrected for and no considerable price discrepancies should be found. Again, a first check is done by plotting both variables in a graph to see whether the prices indeed move in line as expected, figure 14 shows the results.

Figure 14

Price Trends Bitcoin and Ethereum

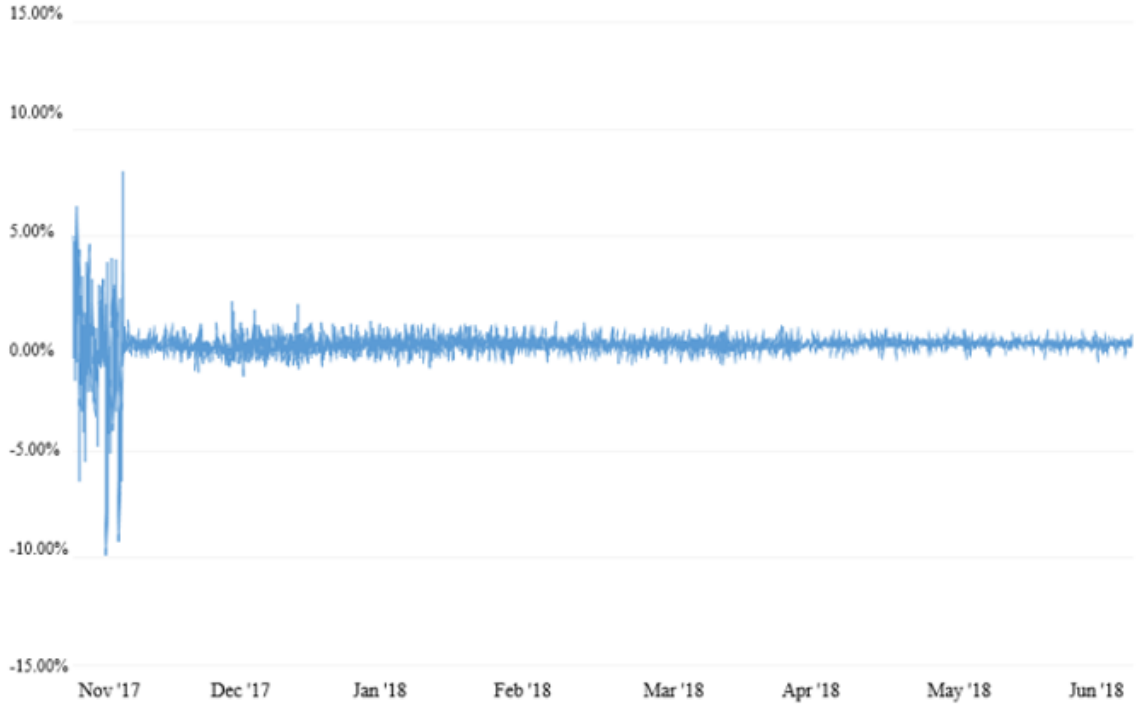


What can be seen is that indeed the prices of both variables move almost perfectly in line with each other. This would suggest that, as expected, the online exchanges check for price discrepancies between their provided assets and thus no profitable arbitrage techniques are to be found using this technique.

Nevertheless, these assumptions have to be verified by analysing the price discrepancies per each data line separately. Here, the discrepancies are calculated in the same manner as done in the first arbitrage technique. By subtracting the value of $\frac{ETH}{USD} * \frac{BTC}{ETH}$ from the $\frac{BTC}{USD}$, and dividing this value by the Bitcoin Dollar price. This way, the entire data set can be analysed to see if any price discrepancies, and thus arbitrage possibilities, can be found which were not captured by figure 14. This analysis shows some very interesting results as can be seen in figure 15. In the beginning of the sample period there are some price discrepancies to be found, ranging from +8.00% to about -9.50%. However, after a spike of 8.00%, which corresponds with 12 November 2017 06:00:00, the prices of both variables seem to converge. After this date, the price discrepancies do not reach any value higher than 2.00%.

Figure 15

Price Discrepancies Sample Technique 2



Note. the discrepancies are calculated by subtracting the value of $\frac{ETH}{USD} * \frac{BTC}{ETH}$ from the $\frac{BTC}{USD}$, and dividing this value by the Bitcoin Dollar price in order to get a percentage difference.

There are two possible explanations which could justify these results. The first is an error in the data, this means that from half November onwards the prices of the Bitcoin and Ethereum given by GDAX do not correctly reflect the real prices of these cryptocurrencies but instead somehow incorrect prices are provided. However, when checking the data, both prices seem to follow normal trends and do not include any errors or even cells which have a constant value for multiple hours or days. In order to verify whether this data indeed reflects the correct values, the prices of Bitcoin given on GDAX are compared to the prices given on Kraken. This test is performed in the next section of this article. The second explanation could be that, like stated above, after half November an internal system is implemented by

GDAX which tracks the discrepancies between the currencies provided by them. If these prices differ significantly from their exchange rate, a correction will be made. Regardless of whether this explanation indeed is the correct one or these results can be explained by another rationale, a correlation coefficient of 0.99988 shows that this technique is unlikely to present any arbitrage opportunities in the near future. This means we have to accept the previously formulated hypothesis stating that no 'risk-free' profit can be obtained when exercising a triangular arbitrage using the Bitcoin, Ethereum and the US dollar.

4.3 Inter-Exchange Arbitrage

For the third and final arbitrage technique the Bitcoin prices of GDAX and Kraken are compared to each other to check for any discrepancies which could result in profitable arbitrage. In the previous section, with the second arbitrage technique, the inter-exchange arbitrage possibilities were already briefly covered by analysing the price differences of Ethereum between GDAX and Kraken. With the exception of some spikes, the prices of the two exchanges were generally similar. In this section, the same analysis will be performed into greater depth regarding the Bitcoin prices. Figure 16 shows that, like Ethereum, the Bitcoin prices between the two exchanges do not appear to have any sizeable discrepancies.

Figure 16

Bitcoin Price Trends GDAX and Kraken

These results are supported when looking at the correlation coefficient between the two exchanges. With a coefficient of 0.99959 the prices between both exchanges prove to be highly correlated which would suggest that not many arbitrage possibilities will be present. Nevertheless, when focusing at the middle of the graph, there are some differences to be found. This is primarily in the period ranging from November 2017 till January 2018. If we zoom in at that period we notice indeed that the prices do not always follow the same path. This can be seen in figure 17. Especially in November and December numerous differences can be found between the prices of both exchanges.

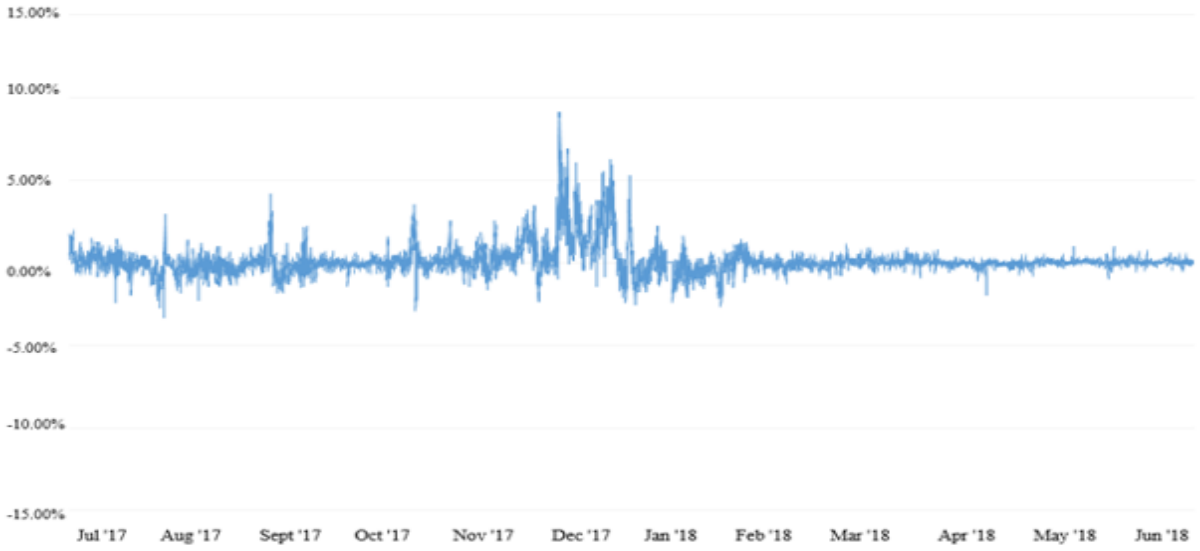
Figure 17

Possible Arbitrage Opportunities Technique 3

Such price differences indicate that there could be arbitrage opportunities when performing inter-exchange arbitrage technique. Nevertheless, similar to the other techniques, these assumptions have to be verified by analysing all the data lines separately. This analysis is done by deducting the price of a Bitcoin on Kraken from the price of a Bitcoin on GDAX. Both these prices are denoted in USD. This value is then divided by the price of a Bitcoin on GDAX to obtain the percentage difference in relation to the price on GDAX. This is done for the entire sample in order to get a clear overview of the price discrepancies between the two exchanges. The results of this analysis are shown in figure 18. If we take a look at these results we notice one relatively large spike and a couple smaller ones.

Figure 18

Price Discrepancies Sample Technique 3



Note. This figure is obtained by deducting the price of a Bitcoin on Kraken from the price of a Bitcoin on GDAX. Both these prices are denoted in USD. This value is then divided by the price of a Bitcoin on GDAX to obtain the percentage difference in relation to the price on GDAX.

Comparable to the other two techniques, the largest deviations indeed happen in the middle of the figures which corresponds to the months November, December and January. Some dates in particular are:

- 07 December 2017 5 AM 9.13 %
- 24 December 2017 12 PM 6.29 %
- 30 December 2017 1 PM 5.32 %

Especially when considering the prices between two different exchanges, events such as hacks, as mentioned with the first technique in this section, can have a significant impact on the price discrepancies. If one exchange experiences any difficulties such as frozen accounts, delays in transaction or even a hack, one can imagine that this will have a consequential impact on the price of the Bitcoin on that particular exchange. The other exchange, which has not experienced the same issues, will have a less volatile Bitcoin price and thus discrepancies between the two exchanges emerge. The dates which show the largest discrepancies do not seem to be caused by any major events on either one of both exchanges. December 7th 2017 is the date at which the Bitcoin, with a gain of $2500.00 in one day, experienced the largest single day gain in history at that date[15]. Such a historical event could possibly have had an impact on the interest off traders in the Bitcoin. With Kraken being a European exchange and GDAX an American exchange, the two markets could respond differently to such news creating a discrepancy in the prices. This is tested by plotting the trading volumes of both exchanges. If arbitrageurs indeed take advantage of the mispricing one would expect that the volume would increase around the dates of the largest discrepancies. Figure 19 and 20 give the trading volumes of both GDAX and Kraken in the month December respectively.

[15] https://cointelegraph.com/news/bitcoin-goes-parabolic-blows-past-14000-to-post-2500-single-day-gain

Figure 19

Bitcoin Transaction Volume Kraken December 2017

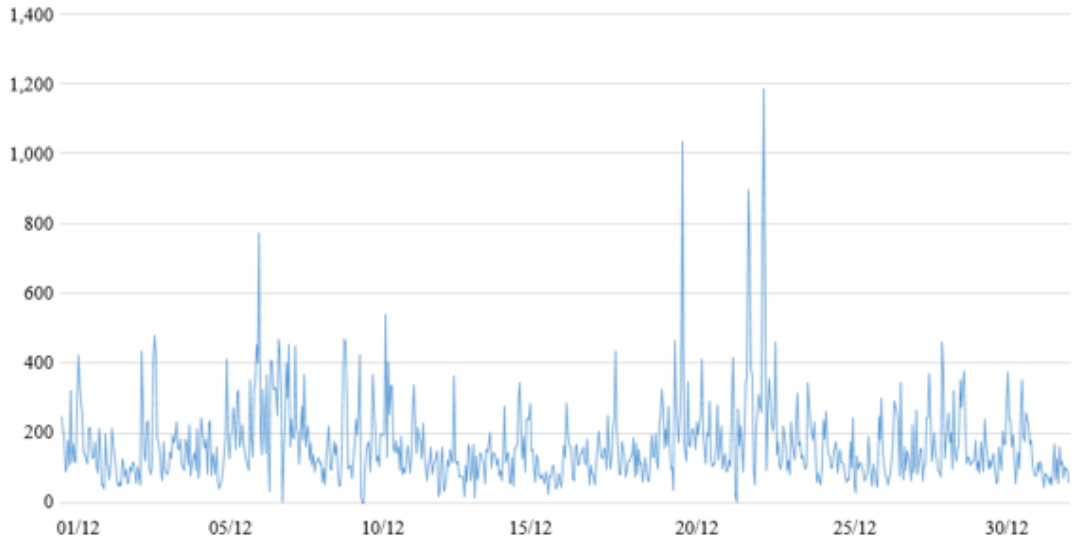
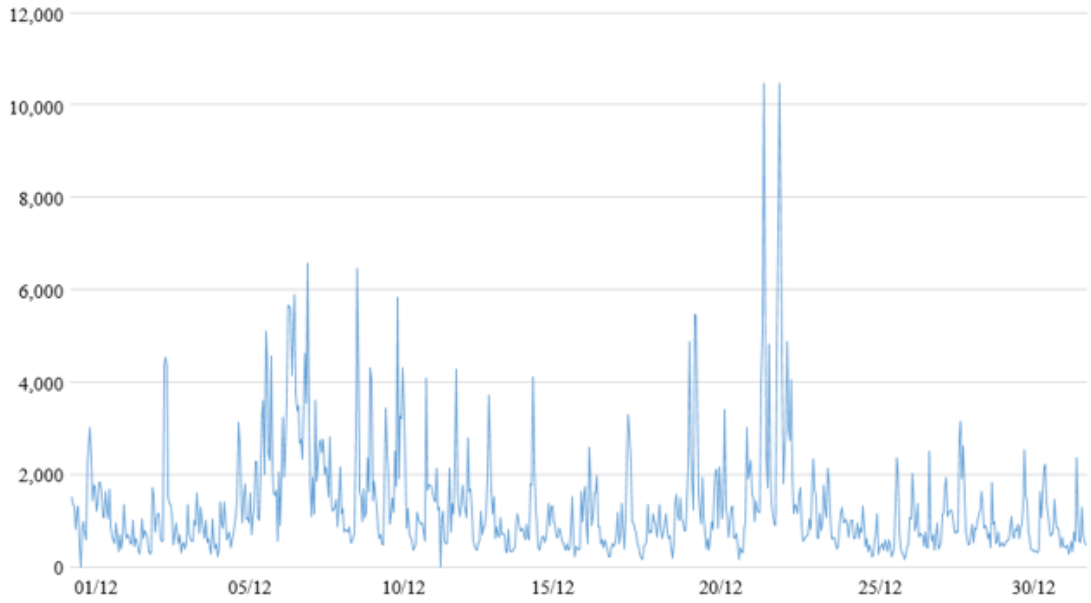


Figure 20

Bitcoin Transaction Volume GDAX December 2017



The figures show some interesting results. Both exchanges have roughly two periods where the trading volume is significantly higher, one around the 5th of December and one around the 20th of December. Especially on Kraken one spike at the beginning of the month is observed. This spike corresponds with 2 AM on the 7th of December, a date which also showed the largest discrepancy of the entire sample. This suggests that for some reason a significant share of traders sold their Bitcoin on Kraken at that specific moment in time which caused the Bitcoin price to drop on Kraken relative to that on GDAX creating a discrepancy between the two exchanges. Another date which should be highlighted is the 22nd

of December, a date which shows exceptional spikes on both exchanges and also a date which created the largest discrepancy in the first technique examined by this article. Again, for this date it is examined whether any specific events happened which could have caused these outcomes. This indeed turns out to be the case since on the 22nd of December the Bitcoin experienced one of its largest drops in the price in a single day with a fall of about 45% from its maximum of $20,000[16]. These results show that when such a moving event as the drop in the price on the 22nd of December happens, this can have considerable influences on the Bitcoin prices on different exchanges. Such events seem to create discrepancies between the exchanges and therefore arbitrageurs should be alert for such opportunities when similar events occur. Conclusively, we cannot ignore the fact that also for the third technique multiple arbitrage opportunities have emerged in the sample period. Therefore, it should be concluded that deviations from the LOP and PPP exist and thus the hypothesis formulated in the introduction section of this article stating that exercising a multi-exchange arbitrage technique using the Bitcoin will result in a 'risk-free' profit has to be accepted.

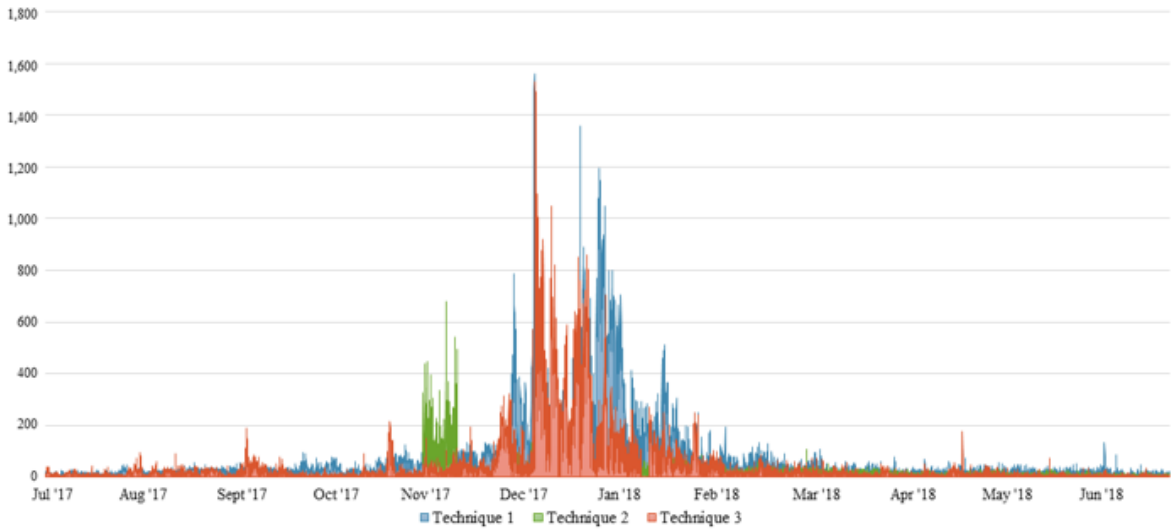
4.4 Comparing the three techniques

When comparing the results of all three techniques based on the analyses shown above, we observe similarities as well as differences. All three techniques seem to have the most opportunities in the period ranging from November 2017 until January 2018. This is a period in which the Bitcoin experienced a bull market and where thus a lot of movement but also volatility occurred. These active and volatile periods show to create arbitrage possibilities for all three techniques. Nevertheless, these opportunities seem to disappear in an early stage of the sample period for the second technique. By the end of November, the prices of the two variables abruptly converge and no significant discrepancies are to be found after this change. Like said before, this could be due to an adjustment in the software made by GDAX with regards to price discrepancies of assets provided on their exchange. Contrarily, technique one and three show similar results. They both follow the same pattern and show the largest discrepancies around December 2017. Still, even here differences are present. For technique three, the discrepancies do not reach any higher than 9.13%, whereas for technique one the 10% level is crossed multiple times. These results are confirmed when calculating the average deviation of the sample for technique three. With a value of 0.09%, compared to the -0.68% of technique one, combined with the absence of large discrepancies the results suggest that although both techniques show opportunities for arbitrage, technique one has a larger probability to find arbitrage opportunities with larger profits. In this last section we provide a comparison between the techniques based on the absolute values in US dollars of the price differences they all experienced. This provides a better insight in what the exact price differences were, which technique experienced the largest differences and with what frequency. Figure 18 shows the results of this comparison.

[16] https://www.businessinsider.nl/bitcoin-price-drops-plunges-friday-december-22-2017-12/?international=true&r=UK

Figure 21

Absolute Price Discrepancies for Each Technique in US Dollars



This figure is a good representation of early formulated conclusions regarding the three techniques. Here, it is clear to see that technique one and three indeed follow roughly the same pattern and the second technique is only profitable in the month November. An interesting aspect to highlight is that with both technique one and three a discrepancy between prices of almost $1600 is reached. A trade performed with at the maximum discrepancy using the first arbitrage technique will give the following pay-outs:

Example: Multiple Fiat Currency Triangular Arbitrage

$$Pt = Dmax - T\left(\frac{btc}{usd}\right) - T\left(\frac{usd}{eur}\right) - T\left(\frac{eur}{btc}\right)$$

$$Pt = \$1562.32 - \$14.87 - \$117 - \$14.87$$

$$Pt = \$1415.58$$

- Pt = profits made at time t
- $Dmax$ = the maximum discrepancy in the sample
- $T(\frac{btc}{usd})$ = the average transaction costs given by figure 6 on December 7th 2017
- $T(\frac{usd}{eur})$ = transaction costs given by dukascopy.com[17]
- $T(\frac{eur}{btc}) = T(\frac{btc}{usd})$

This particular trade would lead to a profit of $1415.58. However, one should be reminded that this is the maximum discrepancy found for not only the first technique but for the entire sample. Such an opportunity is very rare to find and even more difficult to actually perform a trade on it before the market

[17] https://www.dukascopy.com/swiss/english/about/fee-schedule/?c1#tradingCommissions. Value of Bitcoin on December 7th 10 AM used which was $15600 with a 0.75% fee according to dukascopy.

corrects itself. Discrepancies of a couple hundred dollars are more common to find in the sample and more likely to be executed successfully. When comparing the average absolute deviation from the LOP for all the three techniques we get the following results. Technique one has an average deviation of $64.73, technique two of $22.49 and technique three of $43.59. These values are significantly lower than the one given by the example above. Nevertheless, throughout the sample profitable opportunities are found and this confirms that the main research question formulated in the introduction section of this paper has to be accepted and thus profitable arbitrage techniques, net of transaction costs and currency fees, can be executed in the Bitcoin market by means of violations of the Law of One Price.

Chapter 5. Conclusion and Future Research

The goal of this article is to provide new insights in the arbitrage opportunities of the Bitcoin market. This is done by providing an answer to the following question: 'Can profitable arbitrage techniques, net of transaction costs and currency fees, be executed in the Bitcoin market by means of violations of the Law of One Price?' In order to be able to provide a profound answer to this question, three different arbitrage techniques are examined. These techniques are ordered by the following structure: Multiple Fiat Currency Triangular Arbitrage, Multiple Crypto Currency Triangular Arbitrage and Inter-Exchange Arbitrage. A more precise description of how the techniques are executed can be found in chapter four of this article. All three techniques show opportunities for profitable arbitrage in the sample period ranging from July 1st 2017 until July 1st 2018. For all data used for this examination closing prices are taken with an hourly frequency. I find that the largest opportunities present themselves in the period ranging from November 2017 till January 2018, a period in which the Bitcoin experiences a bull market and high levels of volatility. Nevertheless, these opportunities seem to disappear for the second technique after November 2017, whereas technique one and three provide opportunities also after this month. The abrupt disappearance of opportunities for the second technique could be caused by an amendment in the software used by GDAX. Technique one and three follow the same pattern and both show significant deviations from their LOP. Nevertheless, the first technique, which corresponds with Multiple Fiat Currency Triangular Arbitrage, shows the largest swings and overall a more significant discrepancy. Altogether a conclusion can be drawn that various arbitrage opportunities are present in the Bitcoin market but that these opportunities most likely emerge when the Bitcoin experiences a bull market paired with high levels of volatility. In such a situation, arbitrage technique one, where a triangular arbitrage is performed using the Bitcoin, USD and EUR, shows the highest probability of performing a profitable arbitrage trade. Nonetheless, the reader should realise that the Bitcoin market is still a very young, immature market with a highly volatile nature. Prices are known to fluctuate very drastically on a daily basis. Therefore, this article does not aim to provide any investment advice with regards to the future but merely an analysis of events in the past. Caution should be exercised when investing in the Bitcoin and it is not advised to use any sorts of debt investments with this currency. For future research it would be interesting to also include the Japanese Yen as a currency since this is one of the largest currency pairs with the Bitcoin. The JPY is not included in this article since few to none exchanges provide the option to exchange Bitcoins to JPY as well as USD, as explained in the introduction section of this paper. No one knows what the future holds for the Bitcoin but to my opinion it is only a matter of time until governments find the right regulation and tools to start using crypto currencies on a day-to-day basis. The technology behind the Bitcoin, the block chain, opens up a lot of new doors to all kinds of industries and businesses and is very exciting to be present and maybe even participant off all these new developments.

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