CHARLES UNIVERSITY

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Institute of Economic Studies

Bachelor's Thesis

2021 **Vojtěch Suchánek**

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Arbitrage on the Cryptocurrency Markets: An Analysis of Potential Opportunities

Bachelor's Thesis

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Study programme: Economics and Finance

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Year of the defence: 2021

Declaration

1. I hereby declare that I have compiled this thesis using the listed literature and resources only.
2. I hereby declare that my thesis has not been used to gain any other academic title.
3. I fully agree to my work being used for study and scientific purposes.

In Prague on 19.7.2021 Vojtěch Suchánek

References

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Abstract

Cryptocurrency markets have currently a lot of attention both from the public and researchers. This thesis connects the well-documented field of arbitrage with the relatively new bitcoin phenomenon. Thanks to the efforts of cryptocurrencies for decentralization and non-regulation, they are an ideal asset for arbitrage trading. This study tries to answer whether price differences between cryptocurrency exchanges existed during the second and third quartal of 2021 and if it was possible to perform an arbitrage trading with positive profit. It analyzes several trading strategies and ways how to execute these trades. An important part of the study is the involvement of trading fees, which play a crucial role in total profitability but are often omitted in similar research. The findings confirm that price differences existed during the analyzed period, and their values allow for profitable arbitrage trading. The best performing strategy uses stable-coin USDT as a mean of transport money between exchanges, which lowers the time of one trade and allows multiple trades during one price difference spike. This strategy was able to gain 362.60% profit over the analyzed period. On the other hand, the distribution of trades over the analyzed period shows some irregularities, which might have a negative impact on the consistency of the profit.

Abstrakt

Trhy s kryptoměnami mají v současné době velkou pozornost jak veřejnosti, tak odborníků. Tato studie spojuje dobře zdokumentované pole arbitráže s relativně novým fenoménem bitcoinu. Díky decentralizaci kryptoměn a jejich snaze o minimální regulaci jsou ideálním aktivem pro obchodování arbitráže. Tato studie se snaží odpovědět, zda během druhého a třetího čtvrtletí roku 2021 existovaly cenové rozdíly mezi kryptoměnovými burzami a zda bylo možné provádět arbitráž se ziskem. Toho se snaží dosáhnout analýzou několika obchodních strategií a způsobů, jak tyto obchody provádět. Důležitou součástí studie je i započítání obchodních poplatků, které hrají zásadní roli v celkové ziskovosti, ale v obdobných výzkumech jsou často opomíjeny. Výsledky studie potvrzují, že během analyzovaného období existovaly cenové rozdíly napříč jednotlivými burzami a jejich velikost umožňuje provádění ziskové arbitráže. Strategie s nejvyšší ziskovostí využívá stable-coin USDT jako prostředek k převodu peněz mezi burzami, což snižuje čas jednoho obchodu a umožňuje více obchodů během jednoho delšího výkyvu v rozdílu cen. Zisk této strategie dosáhl za analyzované období 362,60 %. Časové rozložení obchodů za analyzované období je však výrazně nerovnoměrné, což by mohlo mít negativní dopad na dlouhodobou konzistenci ziskovosti.

Keywords

Cryptocurrencies, Bitcoin, Arbitrage, Trading, Arbitrage profitability, Cryptocurrency exchanges

Klíčová slova

Kryptoměny, Bitcoin, Arbitráž, Obchodování, Výnosnost arbitráže, Kryptoměnové burzy

Title

Arbitrage on the Cryptocurrency Markets: An Analysis of Potential Opportunities

Název práce

Arbitráže na trhu kryptoměn: analýza potenciálních příležitostí

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I am very grateful to my supervisor Mgr. Nicolas Fanta for his help and guidance throughout writing of this thesis. Also, I would like to thank my parents and girlfriend for the support during my studies.

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1. Introduction

Cryptocurrency markets have currently a lot of attention both from the public and researchers. Cryptocurrencies are interesting for their technical aspects, which are studied mainly by programmers, but also for their economic application, which takes the attention of economists. On the other hand, investors and the general public are also fascinated by their extreme volatility and potentially huge profits. This study connects the well-documented technique of arbitrage with the relatively new bitcoin phenomenon. Thanks to the efforts of cryptocurrency developers for decentralization and non-regulation, they are an ideal system for arbitrage trading. There are hundreds of exchanges, which are not directly connected to each other, which allows prices to differ on each exchange, especially during periods of fast price changes.

Existing research on cryptocurrency arbitrage usually covers a variably long period of one year with the last study in 2019 at the time of writing this study. The purpose of this work is to extend this research to 2020 and analyze it with a more practical approach. Another important feature is an analysis of possible profit including trading fees, which play a crucial role in the profitability of single trades, but they are often omitted in other studies. This work is intended for traders, who would like to start trading bitcoin arbitrage. It tries to prove whether opportunities to perform this type of trade exist and if it is profitable, rather than to find the best trading strategy. This study should work as a starting point for potential trades to build more sophisticated and optimized strategies on its findings.

This study consists of two main parts. The first part focuses on the analysis of price differences between selected exchanges. It studies their magnitudes, frequency, and distribution in time. Alongside this research, an analysis of price extreme values among analyzed exchanges was also performed. These results serve as supportive material for the second part, when the analyzed trading strategies were selected. The second part then examines the profitability of several trading strategies under different circumstances. These include different starting capitals, which are used to compare the effect of capital size on overall profitability, or implementation of stable-coin as a mean of transfer, which lowers trading time but increases total fee per transaction. At the end of the results section is a summary of total capital gain and an analysis of the distribution of trades during the analyzed period.

This study concludes that during the analyzed period, price differences occurred, and their mean value was 0.78%. This is in line with previous research, which also confirmed their existence. Regarding the profitability, several trading strategies proved to be profitable with the highest

profit of 362.60% over the analyzed period. On the other hand, some limitations exist, which might lower the total profit if these trades were actually performed, like a response of the market to these trades, especially with larger trading volumes. Also the distribution of trades over the analyzed period shows some irregularities, which might have negative impact on consistency of the profit.

2. Literature review

Arbitrage is a type of operation where the same asset is bought on one market for a lower price and sold on another market for a higher price. The spread between these two prices is a risk-free profit for the trader. These types of trade opportunities should not exist according to the law of one price, but empirical research shows that arbitrage opportunities arise in many fields. For further information see e.g. Gromb and Vayanos (2018).

Bitcoin is a digital currency based on blockchain introduced by a person or group of people using the alias Satoshi Nakamoto in 2008. It was meant to be a decentralized currency with substantial anonymity, but due to its high volatility and long waiting times to execute an operation, it failed in this role. Nowadays it is mostly used as an investment asset by traders who speculate on its future price movement.

Most of the research in this field is now focused on real applications of cryptocurrencies as a payment and transaction mechanism. For example, Bohme, et al. (2015) describe many properties of bitcoin, how it works, and how it can be used, or Ciaian, Rajcaniova, and Kancs (2016) who describe bitcoin price formation.

Literature about cryptocurrency arbitrage is divided into two parts based on the type of arbitrage they examine. The first one explores so-called triangular arbitrage. This is a procedure where at least three currencies are involved and the trader performs a series of trades starting and ending with the same currency, but with more of it at the end. This could be done inside one exchange or among more exchanges. This type of arbitrage was studied with diverse results. Czapliński, Nazmutdinova (2019) claim that the possibility for triangular arbitrage using USD, EUR, and Bitcoin on the three biggest markets exist almost in every measured moment, but they did not account for transaction fees, which are a crucial factor in arbitrage. Pichl & Kaizoji (2017) tried to predict tomorrow's returns using advanced machine learning models and triangular arbitrage possibilities. They concluded that arbitrage possibilities exist, but neither

they did not account for fees. Han (2018) designed an intra-exchange cryptocurrency arbitrage bot, which he managed to be slightly profitable, but to gain more profit he suggests trading with higher amounts of capital.

The second type of arbitrage focuses on differences in the price of one asset, usually bitcoin, among more exchanges. Same "classical assets" like shares of one company are traded usually on a limited number of exchanges, which makes differences in price quite rare and short-lasting. On the other hand, as of writing this study, there are 303 exchanges listed on coinmarketcap.com, but this number is not finite since there is no official obligation to register an exchange and their number can fluctuate. Since these exchanges are not connected or regulated and there is a lot of them, their prices may differ and offer arbitrage opportunities. This confirms Kroeger and Sarkar (2017) who found that there was a statistically significant violation of one price theory during the period between 2012 and 2016. However, most of their result was based on BTC-e exchange which was shut down shortly after the publication of the study for participating in money laundering. Makarov and Schoar (2020) is another study confirming the existence of arbitrage opportunities. They found systematic price differences based on the locations of exchanges. Krückeberg and Scholz (2020) also confirmed the existence of arbitrage opportunities and location differences. Furthermore, they found increased price spreads after the introduction of big new exchange and after big fraud related to cryptocurrencies. Most interestingly they investigated increasing spreads over time, especially during the last two years of their research period – 2017 and 2018. In contradiction to these Crépelière and Zeisberger (2020) claim that during the period from October 2018 to June 2019 arbitrage is hardly possible after accounting for fees. This is even more surprising concerning the increasing tendency of spreads imposed by Krückeberg and Scholz (2020).

This study will try to continue in this path and investigate the second type of arbitrage during the year 2020 and its profitability. It will also map current fees among exchanges and examine the possibility to perform arbitrage using short sells, which was not done yet due to its relatively new broader implementation, starting around 2018.

3. Data

This study focuses on bitcoin, which has the highest market cap among all cryptocurrencies currently available.

This study examines bitcoin prices during the period from April 2020 to September 2020. The price of bitcoin increased from nearly 6.500 USD to over 10.500 USD throughout this period.

I have obtained data for seven cryptocurrency exchanges. These exchanges were selected based on the following conditions:

1. Exchanges had to allow trading cryptocurrencies with fiat money, in particular USD or EUR.
2. Exchanges had to allow trading from Europe and the USA.

The first condition ruled out exchanges allowing trading only between two cryptocurrencies, which is a widespread practice. In fact, the majority of exchanges listed on coinmarketcap.com allowed only this form of trading (coinmarketcap.com, 2021). This is connected with higher transaction fees since more transactions need to be performed and it also brings risk in form of long-term holding of cryptocurrencies while waiting for the arbitrage opportunity to occur. The second condition deals with exchanges that can be accessed only by citizens of one country. This is common for exchanges based in South Korea. The selection of exchanges was also largely limited by the availability of public historic data. Exchanges examined in this study are Binance, Kraken, Bitfinex, Bitflyer, Bitstamp, Coinsbit and Coinsbank. Data for Coinsbit are only for the period from the 6th of July to the end of the research period.

Most of the data were obtained from bitcoincharts.com using their API service, except for Binance and Bitfinex which we downloaded through their own API services. Obtained data are in a form of tick level data containing information about the time, volume, and price of each trade. Prices are against USD for almost all exchanges except for Binance whose prices are against EUR since it does not support BTC/USD trading. These prices were converted to USD using EUR/USD exchange rate obtained from histdata.com. Since forex exchanges do not operate during weekends, in contrast with cryptocurrency exchanges, the last known exchange rate was used for these missing periods.

I have divided price tick data into ten-second periods for each exchange. If more values were within one period, the first value was used. In case of missing values, I carried the last known value until the next non-empty value.

For the second part of my study, I collected relevant fee values for every selected exchange. These values were collected on the 24th of April 2021. Since exchanges update their fees based on current conditions of the cryptocurrency market like the price of cryptocurrencies, mining

costs, etc. these values might not be true for the examined period. But due to lack of data concerning historical fee structures, I must proceed with these values regardless of their potential inaccuracies.

4. Methodology

My analysis consists of two parts. Firstly, I explore whether bitcoin price differences between selected exchanges appeared during the examined period and their magnitudes. Based on these results I propose a trading strategy and evaluate its profitability.

For the first part, I examined data divided into ten-second intervals for all selected exchanges. For each interval, I obtained the lowest and highest price. Using the following formula, I computed the spread for each period:

$$Spread_t = \frac{max_t - min_t}{min_t}$$

where *min* and *max* are the lowest and highest prices obtained in the previous step.

There are several options for how to perform an arbitrage trade on bitcoin markets. The basic one is just to buy bitcoin on the exchange with a lower price, send it through a blockchain, and sell it on the exchange with a higher price. This option has very limited use since block-chain transaction lasts for several minutes, which might result in price correction and a loss. Another option might be to trade with options to fix the future price. This might be used for other assets, but since bitcoin options are a relatively new feature, there is low liquidity and limited strike prices, which make it impossible to use this for arbitrage trading. The method I use in this study involves fixing the price by short-selling the bitcoin on the sell-side exchange at the same moment as the buy of bitcoin is done on the buy-side exchange. This trade consists of several steps which are:

1. Buying bitcoin on a buy-side exchange.
2. Short selling bitcoin on the sell-side exchange.
3. Sending bitcoin through block-chain from buy-side exchange to sell-side exchange.
4. Closing short sell.
5. Selling bitcoin on the sell-side exchange.
6. Withdrawing buy-side exchange's initial capital plus half of the gain from the sell-side exchange.
7. Depositing withdrawn capital back to buy-side exchange.

Steps 1 and 2 should be done ideally at the same moment. The same applies to steps 4 and 5. The split of gain in step 6 should be split according to the leverage ratio used on sell-side exchange. This ratio will be described later in the text. There should be also noted that some exchanges charge fees for depositing, which will be applied at the beginning of trading when initial capital is distributed among selected exchanges. Other fees might be also applied at the end of trading when all funds are withdrawn.

In the last section of the study, I also analyzed another method that was similar to the previous one. The only difference was that steps 6 and 7 are performed throughout stable coin, which has a much faster transaction time allowing for several trades during a short period of price differences. On the other hand, this method is connected with additional fees, which might lower the total profit.

Using results from the analysis of price difference I selected exchanges which most frequently had either the lowest or highest prices. In combination with their fee structures as another criterium, I distributed a fictive capital of 10,000 USD and 100,000 USD between them and performed back-testing of several trading strategies to analyze potential profit. The process of selecting exchanges and distributing capital will be described in more detail in the next section with concrete results as supportive arguments.

5. Results

5.1. Price differences

In this section, I will describe results from the analysis of price deviations between selected exchanges. In Figure 1 are displayed magnitudes of price deviations for two scenarios, with all exchanges and without Coinsbank. While analyzing data containing all exchanges, I recognized that data for Coinsbank are often responsible for big spikes in price deviations. After a detailed review of these spikes, it seems like they are caused by random trades, occasionally even several hundreds of USD above rates of other exchanges followed by a return to the previous level. These spikes occur quite frequently so they might not be just outliers, but some systematic data error. Since these spikes may largely affect the potential profitability of arbitrage trading strategies and their authenticity is uncertain, I decided to exclude Coinsbank from further analysis. Because these data might potentially be still valid, I wanted to mention this exchange here as a possibility that cryptocurrency arbitrage might be much more profitable if these data were correct. But even if this is the case, trading via less liquid exchanges like Coinsbank might

bear substantially higher risk connected with their liquidity, security, and credibility. Even though, some market making strategies exist which place orders above or bellow the current price and wait for these spikes to occur, and then perform the arbitrage.

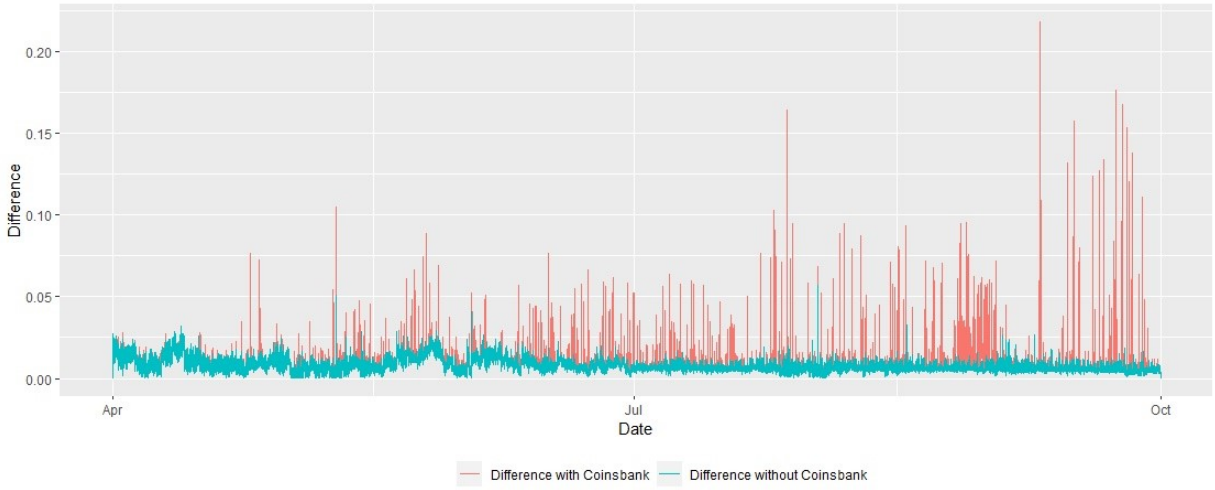

Figure 1 – Comparison of price variances between exchanges including and excluding Coinsbank

To take a closer look at differences after excluding Coinsbank, Figure 2 A) was included. It shows the same values as in Figure 1, but only those without Coinsbank, and zooming in to allow a more detailed view on the shape of differences. It seems like differences oscillate around some trends in the first half of the graph, which represents the period from April to June. Compared to the second period from July to September, where differences also oscillated, but around constant value about 0,6%. This might mean, that during the first period some exchanges had persistently different exchange rates compared to others. Another explanation might involve an increased amount of large rapid market changes during the first period compared to the second. This would mean that exchanges did not change their prices at the same speed and thus increased price differences appeared. If we look at Figure 2 B), this scenario is not the case. The first third and the last third of the examined period, which both had different oscillation behavior, have relatively similar price changes. Furthermore, the second third of examined period for the price is quite stable, but both types of oscillation types are observed during it. Another possible reason could be that the Coinsbit data start at the beginning of July. Since this adds one more exchange to the dataset, it should not reduce the volatility of price differences, but rather does not affect it or increase it. If the price of Coinsbit was inside the minimum and maximum values for the given ten-second interval, it would not affect the difference. If it were one of the extreme values, it would increase the difference. But since the beginning of these data in the figure differences became more stable, this should not be the

reason. Just to make sure that this is true, I add Figure 2 C) which omits Coinsbit data from the analysis. It does not show any change of the shape of differences, so it confirms that the implementation of Coinsbit data is not the reason for these two periods to differ.

Figure 2 – A) Comparison of price variances between exchanges after excluding Coinsbank. B) Development of bitcoin price during the examined period. Kraken data were used for this graph. C) Comparison of price variances between exchanges after excluding Coinsbit.

In Figure 2 A) are also visible difference spikes like those in Figure 1 when Coinsbank was included, and which lead to her exclusion. In opposite to them, spikes in Figure 2 A) are much lower. After closer examination, I also found that they occurred during periods of rapid price changes, and they are caused by an inability of exchanges to adjust their prices at the same speed. It might be partially visible in comparison to Figure 2 A) and Figure 2 B).

Let us look at the magnitude of price differences. Based on the calculus, where minimal and maximal prices are found for each interval and then subtracted minimum from maximum, the values cannot be negative. As shown in Figure 3 A), most of the differences are less than 1%. Specifically in 78,24% of analyzed periods was the difference between prices lower than 1%. On the other hand, just 1,19% of all differences were higher than 2%. The mean value for these differences is 0,78%, while the median value is 0,66%. Figure 3 B) shows a histogram for the period from April to June, which is the first period with more volatile differences based on the division from Figure 2 A). Figure 3 C) shows a histogram for the period from July to September, which had differences oscillating around stable value around 0,006. The mean value for the first period is 0,95% and the median value is 0,90%. For the second period, the mean value is 0,61% and the median value is 0,59%. We can expect that more trading opportunities occurred during the first period.

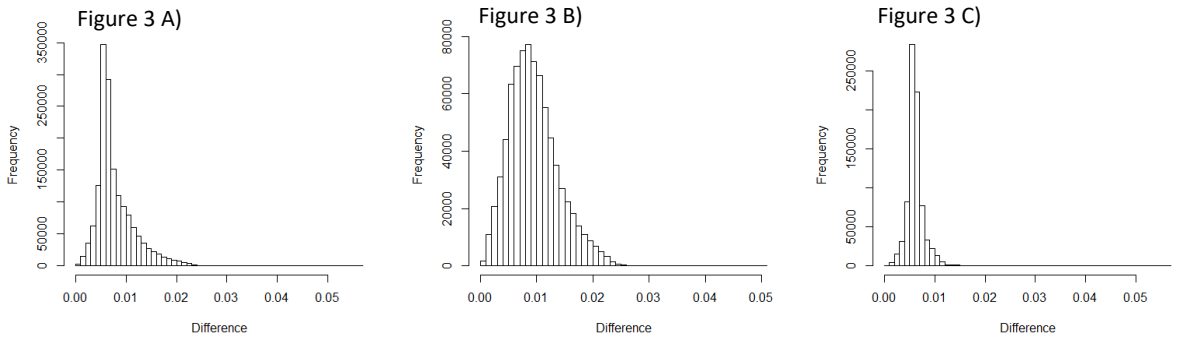

Figure 3 – A) Distribution of price differences between analyzed exchanges for the full examined period. B) Distribution of price differences between analyzed exchanges for the period from April to June. C) Distribution of price differences between analyzed exchanges for the period from July to September.

The next thing I analyzed from these data is the distribution of minimal and maximal prices among analyzed exchanges. This distribution is very useful for deciding the best capital distribution for arbitrage trading strategy, which I will use in the second part of my study. The distribution of minimal and maximal prices among exchanges is shown in Figures 4 A) and B). Every time a price of the exchange is used as a minimum, this fact is recorded. In the end, the total amount of occurrences for every exchange is divided by the total amount of periods. This gives a percentage distribution of minimum price among exchanges. This same process is repeated for maximum prices. Figure 4 A), which represents minimal prices, shows that mostly represented exchange in this category is Bitflyer with over 41%, followed by Coinsbit with 21%, Bitstamp with 15%, Bitfinex with 11%, Kraken with 10%, and Binance with only 2%. It should be also mentioned that Coinsbit is in the second place even with data available only for

the second half of examined period. As shown in Figure 4 B), the situation is very different with maximum values. Most of the time Binance has the highest price among all exchanges. It has 95,1% followed by Bitflyer with 1,8%, Bitfinex with 1,7%, Bitstamp with 0,6%, Kraken also with 0,6% and Coinsbit with 0,2%. This might imply that Binance has systematically higher bitcoin prices compared to other exchanges. Another explanation for this result might be, that Binance is the only exchange that does not support trading with USD. Prices used were for BTC/EUR pair and they were converted into BTC/USD using forex USD/EUR exchange rate. This might imply some systematic overpricing for BTC/EUR exchange rate.

Figure 4 A)

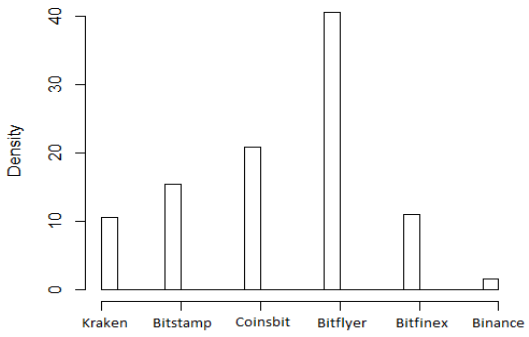

Figure 4 B)

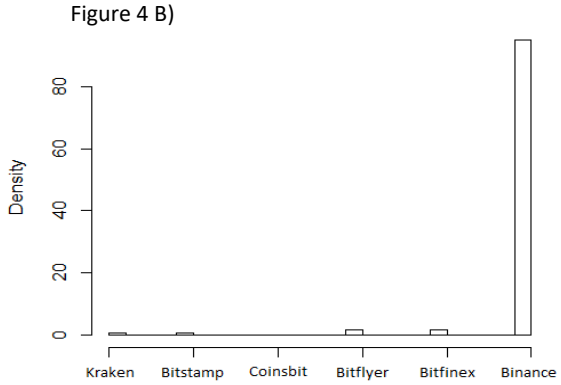

Figure 4 – A) Histogram representing the distribution of minimal prices among exchanges. B) Histogram representing the distribution of maximal prices among exchanges.

Based on these results I decided to investigate arbitrage bitcoin trading strategy for exchanges Kraken, Bitstamp, Coinsbit, Bitflyer, and Bitfinex on the buy-side and Binance on the sell-side.

In this section, I described the results of the analysis of differences in prices of bitcoin on several selected exchanges. Results show that differences exist, and their magnitudes vary across the examined period.

5.2. Arbitrage profitability

5.2.1. Trade structure and fees

In this section, I will formulate an arbitrage trading strategy based on findings at the end of the previous section. I will also take into account the fee structures of selected exchanges. Then I will test two basic strategies and their profitability. Concerning these results, I will tune their

parameters to yield the highest profit. I will try to formulate these trading strategies in a theoretical way with round thresholds to avoid overfitting the data.

Table 1 shows fee structures for five exchanges that were selected as buy-side exchanges based on the results from the previous section. These fees were collected on the 24th of April 2021 when the price of bitcoin was about 50.000 USD. Since all exchanges claim that they adapt their fees according to the current market situation these fees might not be valid for the examined period and the following profit might not be accurate. These inaccuracies are mostly related to Blockchain transaction fees since they are denominated in bitcoin. All examined exchanges lower their fees based on the volume of trades during the past 30 days. In this study, I will use the starting level fees, which are the highest.

Exchange	Trading – taker side	Deposit	Block-chain transaction
Kraken	0.26%	0	0.00015 BTC
Bitstamp	0.50%	0	0.0005 BTC
Coinsbit	0.20%	0.80%	0.00001 BTC
Bitflyer	0.10%	0	0.0004 BTC
Bitfinex	0.20%	0.1% / 60 USD	0.0004 BTC

Table 1 – Buy-side exchange fee structures.

As shown in Table 1 there is a deposit fee on Bitfinex which is either 60 USD or 0.1% of deposited capital, whichever is greater. These fees are equal when depositing 60,000 USD, which makes it almost untradable for fictive capital of 10,000 USD. The only other exchange charging deposit fee is Coinsbit with 0.8%, which is quite high compared to trading fees. On the other hand, it has the lowest Blockchain transaction fee. Table 2 shows the fee structure for the single sell-side exchange which is Binance.

Exchange	Trading – taker side	Deposit	Shorting
Binance	0.1%	0	0.03%

Table 2 - Sell-side exchange fee structure.

The total transaction fee for Binance is 0.33% of traded capital. This consists of a 0.03% shorting fee and three times 0.1% trading fee, during short sell, closing the short sell, and selling transferred bitcoin. The shorting fee is charged on a daily basis. The duration of shorting is expected within one hour based on the length of a blockchain transaction, which is described in more detail further. The only case when the fee would be counted twice would be if the trade happened over midnight. Since this is not frequent and doubling this fee should not have a big impact compared to magnitudes of other fees, I will calculate with 0,03 % for all trades.

Since Trading fees and Deposit fees are denominated in percentages and Blockchain transaction fees are denominated in bitcoins, it is difficult to determine total transaction costs for each buy-side exchange. To be able to do this, I added Table 3. It shows total transaction costs for each exchange on different price levels of bitcoin for a transaction with 2,000 USD. Table 4 shows the same, but for transactions with 20,000 USD. Bitcoin levels are selected base on the price range during the examined period.

Exchange	6500 USD	7500 USD	8500 USD	9500 USD	10500 USD
Kraken	0.6388%	0.6463%	0.6538%	0.6613%	0.6688%
Bitstamp	0.9925%	1.0175%	1.0425%	1.0675%	1.0925%
Coinsbit	1.3333%	1.3338%	1.3343%	1.3348%	1.3353%
Bitflyer	0.5600%	0.5800%	0.6000%	0.6200%	0.6400%
Bitfinex	3.6600%	3.6800%	3.7000%	3.7200%	3.7400%

Table 3 – Total transaction fees for each exchange for 2,000 USD transaction.

Exchange	6500 USD	7500 USD	8500 USD	9500 USD	10500 USD
Kraken	0.5949%	0.5956%	0.5964%	0.5971%	0.5979%
Bitstamp	0.8463%	0.8488%	0.8513%	0.8538%	0.8563%
Coinsbit	1.3303%	1.3304%	1.3304%	1.3305%	1.3305%
Bitflyer	0.4430%	0.4450%	0.4470%	0.4490%	0.4510%
Bitfinex	0.8430%	0.8450%	0.8470%	0.8490%	0.8510%

Table 4 – Total transaction fees for each exchange for 20,000 USD transaction.

These fees are computed as follow:

$$Total\ fee\ =\ 0.33\ \%\ + Trading\ fee + \ Deposit\ fee + \frac{Price\ level * \ Blockchain\ transaction\ fee}{Transaction\ amount}$$

As it can be seen in the equation, these fees already contain Binance 0.33% fee. The last element in the equation transforms the blockchain transaction fee expressed as a fraction of a bitcoin to a percentage of the trade. Every fee is smaller in Table 4 compared to the according fee in Table 3. This is caused by the fixed Blockchain transaction fee. There is also visible how trading with higher volumes lowers the transaction costs and thus increasing the profit. But trading with higher volumes might also be limited by lower volumes avaible at the best price, which might lead to executing parts of trades with worse price and thus a decrease in profit. To analyze possible trading volumes and the optimal capital, order-book data would be needed.

5.2.2. Trading strategy with lower capital and its result

Based on these fees, I decided to test trading 10,000 USD on Kraken, Bitstamp, Coinsbit, and Bitflyer as buy-side exchanges and Binance as sell-side exchange. I will split the capital equally between these exchanges at the beginning, having 2,000 USD on each. I will also short sell with a 100% leverage ratio. This means, that for trade with 2,000 USD on the sell-side exchange,

only 1,000 USD will be used on Binance. This is connected with higher risk because if the price of bitcoin increases by more than 50% during the process of a trade, the capital on Binance invested in it would be lost. As mentioned in the previous section, high price differences seem to occur during dramatic price changes, which makes this a valid consideration. On the other hand, this extreme case might happen only if the price would increase by 50% within a relatively short period of time, which is quite rare even on a daily basis. Furthermore, two simultaneous trades would be needed for this to happen, because if only one trade was in process, the remaining capital on Binance would cover the leverage. A potential investor might increase or decrease this ratio based on his risk management and desired capital leverage. The profit split in step 6 should then be adjusted according to this change as mentioned before. I consider 100% leverage for this type of transaction relevant for the purpose of this study.

After setting this basic trading strategy, I decided to test for potential trades. I computed possible gain for each buy-side exchange for each ten-second period including fees. The gain is computed as the price difference between buy-side and sell-side exchanges having according fees deducted. I used a scenario with 2,000 USD on each exchange. Results were divided into five groups and are presented in Table 5. The table shows in how many intervals the gain was within the given range. There was a total of 1,581,121 intervals for every exchange.

Exchange	0% - 0.5%	0.5% - 1%	1% - 1.5%	1.5% - 2%	> 2%
Kraken	357,820	107,494	34,916	3,754	30
Bitstamp	141,266	44,785	8,876	118	1
Coinsbit	0	0	0	0	0
Bitflyer	67,055	12,125	386	0	0

Table 5 – Number of intervals with gain within corresponding range.

As it can be seen from the table, Kraken has the most profitable periods in every category, followed by Bitstamp and Bitflyer. Surprisingly, there was no profitable period for Coinsbit. Based on these results, I decided to proceed with three scenarios:

A) Trading only on Kraken, having 6,666 USD on Kraken and 3,334 USD on Binance.
B) Trading on Kraken and Bitstamp, having 3,333 USD on every exchange including Binance.
C) Trading on Kraken, Bitstamp, and Bitflyer having 2,222 USD on every buy-side exchange and 3,334 on Binance.

Scenario c) was added after observing the performance of the first two.

Before simulating the trading, I needed to set the time of each transaction. This depends mostly on the time needed to send bitcoin from buy-side exchange to sell-side exchange and on time needed to send USD back to buy-side exchange. As of writing this study, the median confirmation time for one block in the block-chain for the last 12 months is 12.6 minutes. This was obtained from blockchain.com (2021). The withdrawal time for Binance, as shown on their web, should be around 30 minutes. The deposit time on Kraken, as presented on their web, is 0 – 5 business days. On internet forums, some people asked about the precise deposit time, and it seems that for bank account located in Europe, the deposit time is within one business day. Based on this information, I decided to set the time of one transaction to 24 hours for this study.

Results of these trading simulations are shown in Table 6. They are computed by dividing the total profit by initial capital. The total profit is a sum of gains of every transaction, where a transaction is performed when the price difference hits the corresponding border.

	0.5%	1%	1.5%	2%
A)	37.23%	28.12%	15.90%	4.19%
B)	35.19%	25.07%	14.21%	2.89%
C)	31.61%	18.19%	8.63%	1.91%

Table 6 – Profit of three scenarios with different trading borders.

Table 6 shows, that scenario A) with a trading border of 0.5% has the highest profit of 37.23%. It is followed by scenario B) with 0.5% border, scenario C) with 0.5% border and scenario A) with 1% border. If analyzed by scenarios, all scenarios have the highest profit with 0.5% border followed by 1% border, 1.5% border, and 2% border. This means that during the analyzed period, a higher frequency of trades with a lower gain was more profitable than waiting for higher gains which occurred less frequently.

Table 7 shows how many trades were performed for each scenario and the corresponding border.

	0.5%	1%	1.5%	2%
A)	72	34	14	3
B)	115	54	23	4
C)	135	56	21	4

Table 7 – Number of trades performed for each scenario and border during the examined period.

Interestingly, scenario C) with a 0.5% border has the most trades even though it has the lower profit among scenarios on 0.5% border. It shows that having the capital split among more exchanges might provide more trading opportunities, but not having the capital on the best-performing exchanges might hurt the total profit instead. Obviously, lower barriers have higher trade numbers because if the price difference hits the higher border, it had to hit the lower border as well. Also, the number of trades increases as the number of buy-side exchanges increases. This makes sense since when one exchange hits the border when it is the only buy-side exchange, it would usually hit the border even when the capital is split among other exchanges as well. The only scenario when this does not hold is when trading with lower volume makes the fixed Blockchain transaction fee lower the profit enough, so it does not hit the border.

5.2.3. Higher capital strategy and comparison

For the second strategy with 100,000 USD, I decided to use a similar approach as in the first one, but to change Coinsbit for Bitfinex, since with larger capital, fees on Bitfinex are similar to other exchanges and Coinsbit fees are almost the same thus being the highest among analyzed exchanges. This means that I will trade on Kraken, Bitstamp, Bitflyer, and Bitfinex as buy-side exchanges and Binance as sell-side exchange. I will split the capital equally between these exchanges at the beginning, having 20,000 USD on each and I will also use a 100% leverage ratio for short selling.

I started by computing possible gain for each buy-side exchange for each ten-second period including fees. Results were divided into five groups and are presented in Table 8. The table shows in how many intervals the gain was within the given range. There was a total of 1,581,121 intervals for every exchange.

Exchange	0% - 0.5%	0.5% - 1%	1% - 1.5%	1.5% - 2%	> 2%
Kraken	446,698	125,330	39,722	5,456	42
Bitstamp	232,753	67,236	19,645	614	4
Bitfinex	22	1	1	0	0
Bitflyer	93,910	23,341	1,065	3	0

Table 8 – Number of intervals with gain within corresponding range.

Like in Table 5, Kraken has the most profitable periods in every category, followed by Bitstamp and Bitflyer. Bitfinex has very few periods with a positive gain. If compared with Table 5, every category for exchanges Kraken, Bitstamp, and Bitflyer, which are represented in both tables, is

substantially higher in Table 8. For example, Kraken has 617,248 periods with positive gain in Table 8, compared to 504,014 in Table 5. This represents a 22.47% increase. Based on these results, I expect the profit for this strategy to be higher than the previous one. I will use similar scenarios as in the previous strategy:

A) Trading only on Kraken, having 66,666 USD on Kraken and 33,334 USD on Binance.
B) Trading on Kraken and Bitstamp, having 33,333 USD on every exchange including Binance.
C) Trading on Kraken, Bitstamp, and Bitflyer having 22,222 USD on every buy-side exchange and 33,333 USD on Binance.

I will use the same assumptions about the length of one trade as in the previous strategy.

Results of trading simulations are shown in Table 9. They are computed the same way as for the first strategy.

	0.5%	1%	1.5%	2%
A)	37.66%	30.54%	15.91%	4.22%
B)	38.38%	28.39%	15.47%	4,49%
C)	35.90%	22.96%	10.82%	2.47%

Table 9 – Profit of three scenarios with different trading borders for 100,000 USD strategy.

Table 9 shows, that scenario B) with trading border 1% has the highest profit of 38.38%. It is followed by scenario A) with 0.5% border, scenario C) with 0.5% border and scenario A) with 1% border. If analyzed by scenarios, all three scenarios have the highest profit with 0.5% border followed by 1% border, 1.5% border, and 2% border. These are similar results as in the first strategy. All of the results from Table 9 are higher than in Table 6. Scenario and the border with the highest profit switched to scenario B) from scenario A) both for 0.5%. In Table 9 the highest profit rose by 1.15%.

Table 10 shows how many trades were performed for each scenario and the corresponding border.

	0.5%	1%	1.5%	2%
A)	73	37	14	3
B)	129	61	25	6
C)	159	70	26	5

Table 10 – Number of trades performed for each scenario and border during the examined period.

By comparing Table 10 with Table 7 it could be seen that in Table 10 all numbers eighter increased or stayed the same. The highest increase in the number of trades is in scenario C) with a 0.5% border, which rose by 24 trades.

Based on the results in this section, trading with higher capital is more profitable, which was expected. This is probably caused by the flat blockchain fee. Although the increase in the highest profit was not crucial, the most profitable scenario changed. On the other hand, it should be mentioned that trading with higher capital could lead to lower profitability on each trade since the availability of bitcoin for the best price, both on the buy-side and sell-side exchange might be limited and thus the trade must be performed with a worse price. To analyze the total impact of this limitation, the order book data should be analyzed.

5.2.4. Different lengths of trades

As Makarov and Schoar (2020) suggest, the price differences, and thus also arbitrage opportunities, usually exist for several hours or even days. Even in my results, some trades occurred within a couple of days after the trade before. This might imply that, if the time between trades could be lowered, one price difference could be traded more than once, and thus the total profitability might increase. To decrease this time, the other ways to transfer the money from sell-side exchange back to buy-side exchange must be used. One possibility is to use another cryptocurrency with a lower transaction time than bitcoin and a more stable price. The ideal solution is to use a stable coin such as Tether (USDT). This coin aims to be equal to 1 USD. Trading fees are the same as for bitcoin, but the blockchain fee on Binance, which is the only sell-side exchange, differs based on the used network. It is mostly within the 0.8 to 1 USDT range, with only one exception, which is a trade via the ERC20 network, which costs 10 USDT. The length of a transaction using USDT is approximately 2 minutes if the TRC20 is used (Kraken, 2021). This method has a 1 USDT transaction fee on Binance. Combining this with trading times mentioned previously in the text, the possible time to perform this trade is under an hour. There might be cases when the blockchain transaction might take longer, especially with bitcoin. To cover this, I will analyze two scenarios, for trades with the length of 1 hour and trades with the length of 2 hours.

Performing more trades in one price difference spike might significantly improve profitability. Another factor, which even more improves the performance, is that repeating the trade after a

relatively short time period might lead to even more profitable trade. This possibility is supported by the existence of trades with higher borders, at least for the three lowest borders used in this study. To give an example, lest assume usage of a trading strategy with border on 0.5% and the price difference uniform increase from 0% to 1.5% over 1.5 hours followed by a rapid decrease back to 0%. If the original trade length of 24 hours was used, there would be just one trade when the price difference hits 0.5%. If the length of trade was 1 hour, there would also trade when the price difference hits 0.5%, but also second trade one hour after the first one with 1.5% profit. The profit increased from 0.5% to 2% because of the second described effect. On the other hand, the profit decreases by additional costs of another blockchain transaction. In this case, the total transaction fee consists of a sell-side taker fee when USD is exchanged into USDT, then 1 USDT for a block-chain transaction to buy-side exchange, and buy-side exchange taker fee when converting USDT back to USD. The total fees for each buy-side exchange for this transaction are shown in Table 11.

	Kraken	Bitstamp	Coinsbit	Bitflyer	Bitfinex
Fee	0.36%	0.6%	0.3%	0.2%	0.3%

Table 11 – Fees for sending money back from sell-side exchange to buy-side exchange using USDT.

These fees are quite significant and may even lower the total profit of the strategy. If the price difference spike has magnitude just to hit the border and these fees are in use, the trade would not be performed. Further in this section, I will analyze whether using this approach has a positive or negative effect on the total profit. The optimal solution to this problem is to combine both approaches. Firstly, the profit without the USDT strategy fees should be computed and the trade should be potentially performed. When the transaction is closed and money should be sent from sell-side exchange to buy-side exchange, the potential profit for USDT transaction and repeating the arbitrage with current prices should be computed and the way of transferring money back should be chosen based on this result. Eventually, if the potential profit is in a given small range under the profit border for USDT transactions, there might be set some waiting time to see whether the price difference rises enough to make the USDT transaction profitable. Another optimization might be to hold USDT instead of USD on buy-side exchanges, which might eliminate fees connected with exchanging these currencies. On the other hand, this is connected with the risk of a devaluation of the stable coin. But these are just suggestions for improvement for a potential trader and I will proceed with an analysis of only the USDT transaction strategy.

Because of the high Bitstamp fee for this type of trade and comparability with previous trading scenarios, I will use scenario A) with only Kraken as buy-side exchange and Binance as sell-side exchange. I will analyze it for both initial capitals, 10,000 USD and 100,000 USD, and both new trade time horizons, one and two hours for a trade. I will use the same calculation as in previous strategies. The results are shown in Table 12.

2 hours	0.5%	1%	1.5%	2%
10,000 USD	152.34%	63.33%	10.73%	1.47%
100,000 USD	155.16%	64.41%	10.80%	1.48%

Table 12 A) – Profit for 2-hours trades.

1 hour	0.5%	1%	1.5%	2%
10,000 USD	347.40%	111.33%	13.00%	1.47%
100,000 USD	362.60%	116.38%	13.08%	1.48%

Table 12 B) – Profit for 1-hour trades.

As Table 12 shows, this change has different effects on each border. The difference in profit between 10.000 USD and 100.000 USD starting capital is larger compared to 24-hours trades for almost every border. The only border, which decreased this difference is 2% border for both trading times. The highest difference between these two starting capitals is the 0.5% border with 1-hour trades. This difference is 18.2%. For the 2 % border, the total profit decreased approximately by 2.8% in both trade lengths and initial capitals. It is probably caused by the increase in fees and decrease in the number of trades. The profit is even lower than the border for one trade. This is because the border is set to be a price difference between two exchanges, which is equal to profit on the buy-side capital, not the total capital. Surprisingly, the profit of 1.5% border also decreased by approximately 2.7% for 2-hours trades and by 5.1% for 1-hour trades. On the other hand, the profit of the 1% border more than doubled for 2-hours trades for both starting capitals and reached over 63% and 64%. For the 1-hour trades, the profit almost quadrupled and reached 111.33% for 10,000 USD starting capital and 116.38% for 100,000 USD starting capital. But the most extreme increase experienced 0.5% border, whose profit increased more than 4 times for 2-hours trades reaching 152.34% for 10,000 USD starting capital and 155.16% for 100,000 USD starting capital. For 1-hour trades the profit increased more than 9 times reaching 347.40% for 10,000 USD starting capital and 362.60% for 100,000 USD starting capital. This makes it by far the most profitable strategy in this study.

Table 13 shows number of trades for each border and starting capital.

2 hours	0.5%	1%	1.5%	2%
10,000 USD	231	71	10	1
100,000 USD	234	72	10	1

Table 13 A) – Number of trades for 2-hours trades

Table 13 B) - Number of trades for 1-hour trades

2% and 1.5% borders have the same number of trades for both starting capitals and corresponding trade lengths. The other two borders have more trades for 100,000 USD starting capital. Both 2% and 1.5% border have a lower number of trades compared to 24-hours trades. The number of trades for 2% border decreased from 4 to 1 for both trade lengths and the number of trades for 1.5% border decreased from 14 to 10 for 2-hours trades and to 12 for 1-hour trades.

1 hour	0.5%	1%	1.5%	2%
10,000 USD	381	111	12	1
100,000 USD	392	114	12	1

On the other hand, the number of trades for 1% border increased from 34 to 71 for 2-hours trades and to 111 for 1-hour trades for 10,000 USD starting capital and from 37 to 72 for 2-hours trades and to 114 for 1-hour trades for 100,000 USD starting capital. Similarly, the number of trades for 0.5% border increased from 72 to 231 for 2-hours trades and to 381 for 1-hour trades for 10,000 USD starting capital and from 73 to 234 for 2-hours trades and to 392 for 1-hour trades for 100,000 USD starting capital. Based on these results, the shortening of the trade length, as described previously in this section, leads to significant improvement in total profit for lower borders, but to decrease in total profit for higher borders.

5.2.5. Performance

In this part, I will summarize and visualize the total performance of analyzed trading strategies. In previous sections, I analyzed several trading strategies that varied by the number of exchanges, initial capital, and length of one trade. The most profitable analyzed strategy is trading 100,000 USD on Kraken as buy-side exchange and Binance as sell-side exchange combined with sending money back from Binance to Kraken via USDT, which shortened the duration time to 1 hour. This strategy achieved 362.60% profit. Figure 5 shows the distribution of trades during the analyzed period for this strategy.

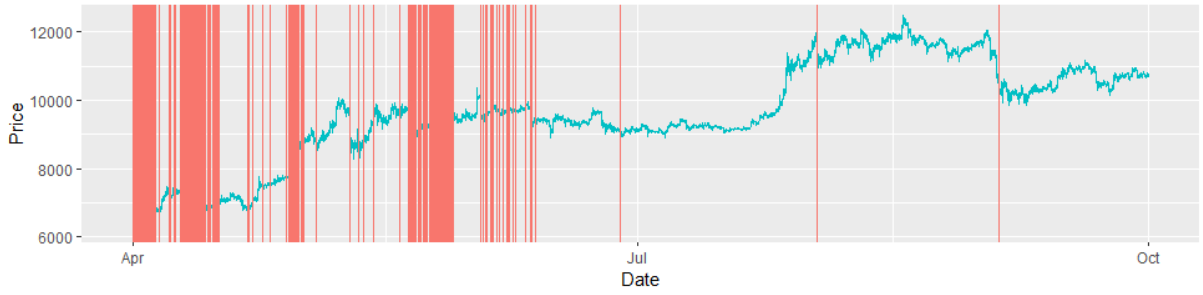

Figure 5 – Distribution of trades during analyzed period with bitcoin price

As it can be seen in Figure 5, most of the trades happened during the first half of the examined period. Furthermore, many times a series of trades occurred within several following days with multiple trades during one day. For example the first day of the study there were 24 trades, which is the maximum possible trades during one day with 1-hour trades. On the other hand, if this strategy was really performed, it could possibly shift the prices closer and in the end, some of these trades might not be performed. To have a better understanding of how much would this arbitrage strategy influence the market, the order book data should be analyzed. Even though, this could provide just approximate idea about it, since it would allow to analyze just the total available resources and compare it to this trading strategy volumes, but not the market response to these potential trades. This is a common issue for many back-testing practices.

Figure 6 depicts the development of total capital over the examined period. It shows all studied strategies with both starting capitals and shows only 0.5% and 1% borders, which were the most profitable.

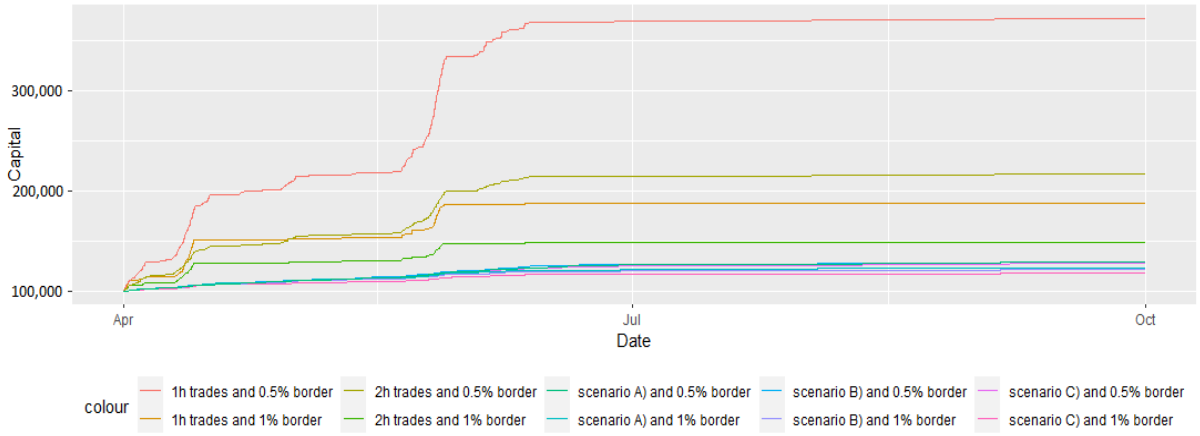

Figure 6 A) – Capital development for 100,000 USD starting capital.

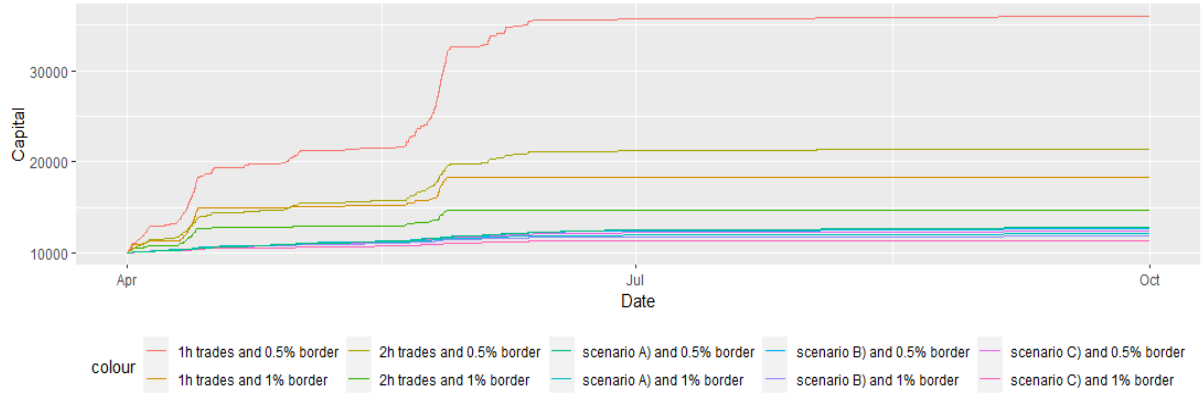

Figure 6 B) – Capital development for 10,000 USD starting capital.

Periods with high growth in total capital are the same as the period with the high frequency of trades in Figure 5, which is the expected outcome. The most interesting finding from these two figures is that most of the profit was realized during approximately the first two months of the examined period. This brings questions about what caused this disproportion and whether arbitrage trading using these strategies is profitable in the present. To answer these questions, a larger time period should be analyzed. Possible explanations might be that either the first period or the second period is an exception, and the other is a normal state. Or maybe there are some parts of a year during which the profitability is high which repeats every year. Another explanation might involve that some global change happened during June, which caused the difference in prices between exchanges to decrease, or maybe somebody started to trade these opportunities on even lower borders and with such volume, that the difference does not reach these values anymore.

6. Conclusion

The main purpose of this study was to analyze whether the findings in previous literature about price differences among cryptocurrency exchanges were true also in 2020 and also if these differences might be profitably traded under trading fees. In the first part of my study, I confirmed that price differences occurred during the examined period. Their magnitudes were mostly under 1%, but they occasionally even exceeded 2%. I also found that Binance might overprice the bitcoin since it has the vast majority of time periods with the highest bitcoin price. Another finding was that during the first third of the analyzed period, the price differences were more volatile and had higher volume. This was also observed during the trading part of the study when most of the trades happened during this period.

In the second part, I analyzed fee structures of examined exchanges and in combination with results from the first part, I propose three trading strategies and then analyzed their profitability. They all ended up being profitable. Since some fees had a fixed value, I also tested for two starting capitals, 10,000 USD and 100,000 USD, to see how trading with larger capital influences the total profit. As expected, the larger starting capital was more profitable for all scenarios even though the differences were not significant. There should also be noted that in real trading this might not be true, since when trading with larger capital, not all the capital might get the best price, which lowers the overall profit. To observe the total impact of this limitation, order book data should be analyzed. The best performing strategy in this part would yield 38.38% over the analyzed half a year.

In the last part, I analyzed a modified strategy that uses stable-coin to transfer money back from sell-side exchange to buy-side exchange, which takes less time allowing for multiple trades during one longer arbitrage opportunity, although it is also connected with additional fees. This approach turned out to be the best performing strategy with total profit reaching up to 362.60%, but there are some limitations to this result. The most important is that the used method does not cover the potential impact of its own trades on the market, which might prohibit some trades by converting the prices closer and thus lower the difference. This is especially true for larger trading capitals. Another limitation is that most trades were performed during one-third of the examined period and might not be possible again, which highly disturbs its consistency.

My work contributes to the existing literature by extending the examined period for arbitrage trading on bitcoin. The main contribution is in the examination of profitability with fees. Most of the literature research just whether price differences exist and if it analyzes the profitability,

fees, which play a crucial role, are often omitted. Finding in this work might be useful for potential investors who seek whether this type of arbitrage is profitable. For them, this study might be a starting point from which they start to build their own trading strategies. The purpose of this study is not to find the best trading strategy, but to analyze whether this strategy might be profitable. There are many ways to improve and optimize my strategies.

Potential further research in this area might focus on extending the examined period of price differences and profit in arbitrage trading. The important question which arises from my study is whether the period of intensive trades repeats and what causes it.

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