**FACULTY
OF INFORMATION
TECHNOLOGY
CTU IN PRAGUE**

ASSIGNMENT OF MASTER'S THESIS

Title:	Cryptocurrencies exchange rates reporting tool
Student:	Bc. Adam Pečev
Supervisor:	doc. Ing. Štěpán Starosta, Ph.D.
Study Programme:	Informatics
Study Branch:	Web and Software Engineering
Department:	Department of Software Engineering
Validity:	Until the end of summer semester 2018/19

Instructions

1. Survey existing applications which collect data about cryptocurrencies and exchange rates between them. Focus on the following cryptocurrencies: Bitcoin, Monero, Ethereum.
2. Design and implement an application which collects data on exchange rates of selected cryptocurrencies on selected markets. The application will be able to find the best sequences of exchanges (using the collected data) which satisfies a criterion input by the user. The available criteria include positive profit on the found path and identical first and last currency. The application shall work with real-time data in real-time, allow working with historical data and analyse these results; it shall have a GUI and visualize the results (that is, the found path).
3. Test the application.

References

Will be provided by the supervisor.

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Prague February 16, 2018

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Master's thesis

Cryptocurrencies Exchange Rates Reporting Tool

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Department of Software Engineering
Supervisor: doc. Ing. Štěpán Starosta, Ph.D.

January 10, 2019

Acknowledgements

Declaration

I hereby declare that the presented thesis is my own work and that I have cited all sources of information in accordance with the Guideline for adhering to ethical principles when elaborating an academic final thesis.

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In Prague on January 10, 2019   . . . .

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Abstrakt

Tato práce popisuje současný trh s kryptoměnami. Následně definuje atributy kryptoměnových burz, které jsou relevantní pro provedení trojúhelníkové arbitráže. Na základě těchto atributů jsou analyzovány vybrané kryptoměnové burzy. Práce zároveň vymezuje klíčové požadavky důležité pro vytvoření aplikace, která stahuje data, zpracovává je a zobrazuje potenciální příležitosti vykonání trojúhelníkové arbitráže v reálném čase.

Klíčová slova   kryptoměna, směnný kurz, kryptoměnová burza, trojúhelníková arbitráž, Bitcoin, aplikace v reálném čase

Abstract

This work describes present cryptocurrency market. Then it defines attributes of cryptocurrency exchanges relevant to perform triangular arbitrage. On the basis of these attributes selected cryptocurrency exchanges are analysed. The work also specifies core requirements important to building an application downloading data, processing them and displaying potential triangular arbitrage execution opportunities in real-time.

Keywords   cryptocurrency, exchange rate, cryptocurrency exchange, triangular arbitrage, Bitcoin, real-time application

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Introduction

Since 2009, when Bitcoin as the first decentralized cryptocurrency and open-source software was released, a lot of various projects have been introduced. These projects involve new cryptocurrencies like Litecoin, Monero, Ethereum and hundreds of others, cryptocurrency exchanges, cryptocurrency markets, bots, whole new companies based on cryptocurrencies, etc. One of them – cryptocurrency exchanges – has attracted a lot of attention during last years. There are huge amounts of money on these exchanges [1], and this fact attracts people who want to somehow benefit from the market. On the one hand many frauds have happened [2, 3, 4] but, on the other hand, the whole cryptocurrency market expanded very much since then [5]. Even though the cryptocurrency exchanges operating Bitcoin and other cryptocurrencies are not so similar to the Foreign Exchange Market [6], there also do exist market inefficiencies [7, 8] from which one can benefit.

Apart from exploiting basic arbitrage opportunities[1], calendar effects[2] or present economic bubbles driven by diverse incentives, one can also look further. One of the other possibilities is to look into multiple exchange rates on given cryptocurrency exchanges. The topic of this thesis is to visualize how one can take advantage of these exchange rates by collecting data on cryptocurrency trading pairs. It will be observed how the price of these trading pairs changes and we will attempt to make use of it by using triangular arbitrage [9, 10, 11]. It will work with real-time data as well as with historical data. The visualization does not have to be used only for informational purposes but could be used for initiating a real trade as well.

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[1]https://files.stlouisfed.org/files/htdocs/publications/review/02/11/EmmonsSchmid.pdf
[2]http://aeconf.com/articles/may2005/aef060105.pdf

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Objectives

The main objective of this thesis is to explore a possibility of making a profit from gathering data of various exchange rates on the cryptocurrency exchange market. The gathered data will be then processed and visualized for a user. The whole process includes five main phases – survey, analysis, design, implementation and testing. I will mainly focus on fine survey, analysis and design which are supposed to be the building blocks of the basic visualization function. After it is possible to visualize the situation one will be able to build on top of it and make use of it – to trade the cryptocurrency if the profits are positive. On the other hand, if the profits are not positive then the thesis will show it is not worth using this technique on given cryptocurrency exchanges with given trading pairs.

1.1   Assignment Analysis

In this subchapter I will describe the assignment in more detail and I will focus on the best way how to accomplish that in its fullness. The next paragraph will add information about the Survey chapter. After that I will state every part of the thesis assignment description and then I will comment on it.

At the beginning of the Survey section I will write about cryptocurrencies as a phenomenon and quickly introduce the main and first cryptocurrency called Bitcoin. Then I will comment on cryptocurrency market as a whole – what types of the market are there and how large it is.

1. *Survey existing applications which collect data about cryptocurrencies and exchange rates between them. Focus on the following cryptocurrencies: Bitcoin, Monero, Ethereum.*

   I will survey some of the existing websites and software applications which collect data about cryptocurrencies as Bitcoin, Ethereum, Monero, etc. and the rates between them and alternative cryptocurrencies. That means mainly the cryptocurrency exchanges with the APIs they

provide. Then I will also survey programs which offer services like arbitrage trading or other techniques that involve exploiting various market inefficiencies. Price manipulation and trading with the aid of bots will be included.

2. *Design and implement an application which collects data on exchange rates of selected cryptocurrencies on selected markets. The application will be able to find the best sequences of exchanges (using the collected data) which satisfies a criterion input by the user. The available criteria include positive profit on the found path and identical first and last currency.*

   Apart from the design and the implementation I will also analyse which functional and non-functional requirements are appropriate for the application. After the formulation of these foundations and possible options the technologies will be determined as well as use cases and wireframes. Based on the given technologies a deployment model will be designed. The implementation will be described including challenges during the process and its possible obstacles.

3. *The application shall work with real-time data in real-time, allow working with historical data and analyse these results;*

   In order to ensure that the application could be used as a basis for possible extension in the future, the real-time aspect of the collected data is needed. The real-time data will be processed in real-time and transferred into useful information flow. To make sure the historical data are correct a reliable source will have to be chosen. One will be able to view the collected historical data in given context.

4. *it shall have a GUI and visualize the results (that is, the found path).*

   A Graphical User Interface will be integral to the whole application. As a matter of fact, it is a logical implication of the informational purpose of the thesis objective. The GUI will show relation between the trading pairs as well as the historical data.

5. *Test the application.*

   A part of the thesis will also consist of the tests of the application – risk-based testing applied with black-box testing.

1.2 Used Terms

Altcoin

A combination of two words – *alt* and *coin* – meaning alternative cryptocurrency. Generally, it is a cryptocurrency other than Bitcoin [12]. Often it is also used for other than the most popular cryptocurrencies in terms of market capitalization.

Cryptocurrency exchange

A trading exchange as an organized market where one can trade cryptocurrencies or other digital currencies or digital assets [13, p. 30][14].

Trading pairs

A pair which represents two different units of value – in this case two different cryptocurrencies or one cryptocurrency and one national currency. A typical example is BTC/USD.

Triangulation

A formation of a closed circle which represents a series of consecutive or even parallel buy orders. Used also for possibly profitable – in terms of triangular arbitrage – set of trading pairs.

Exchange market

A trading exchange as an organized market where one can trade national currencies or derivatives. It can be a cryptocurrency exchange, Foreign Exchange Market[3], etc.

Trading bot

A computer program which evaluates a situation on a cryptocurrency exchange and acts on behalf of a user – the owner. It analyses, offers various recommendations and even buys or sells a cryptocurrency.

Application

The software application, which is one of the objectives of this thesis, as a whole – both front-end and back-end.

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[3]https://www.forex.com/en-uk/education/education-themes/trading-concepts/what-is-forex/

1.3   Motivation

Cryptocurrency is a phenomenon which I have been interested in for years. The more I started to dive into this field the more I came across various cryptocurrency exchanges. After that at some point I started trading and started thinking about different market inefficiencies and how to exploit them. Since my major is Software Engineering one of the exploitations that came to my mind was an arbitrage made automatically by a bot. That led me to the triangular arbitrage. Since the success of the triangular arbitrage depends also on a response speed of a trader, a software solution might be the right way how to deal with this practice. Another part of my motivation came from the fact that I always wanted to connect my interest in cryptocurrencies with my university studies.

Survey

In this section context to the whole diploma thesis is given. There is a brief introduction of Bitcoin and other cryptocurrencies. Then I survey current major cryptocurrency markets and cryptocurrency exchanges. In addition, I describe how the price of cryptocurrencies there is created and how they provide information about trading through their API. I also present some of the existing software applications and websites which collect data about the cryptocurrencies as Bitcoin, Ethereum, Monero and the rates among them.

2.1 Cryptocurrencies

This subchapter describes Bitcoin, the technology and principles behind it and Bitcoin difficulties in brief. Next to Bitcoin, it also describes alternatives to Bitcoin and difficulties of such alternatives. This subchapter is not indispensable for understanding of the realization of the work's objective. Yet, it provides information which ensures a comprehensive view and big picture – how the cryptocurrency works behind the buy and sell orders on a cryptocurrency exchange.

2.1.1 Bitcoin

Bitcoin is the world's first invented decentralized cryptocurrency [15]. It is a peer-to-peer, open-source worldwide payment system with current market capitalization of around $76 billions [16]. It was invented by an unknown person or a group called Satoshi Nakamoto in 2008 and the open-source code was released in 2009 [17, 18]. Since then, many other cryptocurrencies have been created and launched. One of the Satoshi Nakamoto's incentives to create Bitcoin were an independence of centralized authority and a privacy protection [19]:

"The traditional banking model achieves a level of privacy by limiting ac-

cess to information to the parties involved and the trusted third party. The necessity to announce all transactions publicly precludes this method, but privacy can still be maintained by breaking the flow of information in another place: by keeping public keys anonymous. The public can see that someone is sending an amount to someone else, but without information linking the transaction to anyone. This is similar to the level of information released by stock exchanges, where the time and size of individual trades, the 'tape', is made public, but without telling who the parties were."

Blockchain

The main technology behind Bitcoin is blockchain. One can imagine the blockchain as a public ledger [20, 21, 22]. It records all the Bitcoin transactions which have happened within the payment network. The blockchain consists of blocks which are connected in a way that one block contains a hash of the previous block header, the previous block contains a hash of the block header before the previous block and so on. One can imagine this scheme as a linear connected sequence of blocks.

Block and Transactions

The first block (also called the genesis block [23]) was created in 2009 [24]. The blocks are files which store transaction data. The block data can be divided into the following parts [25]:

- Magic number – value always 0xD9B4BEF9 (4 bytes)[4]

- Blocksize – number of bytes following up to end of block (4 bytes)

- Blockheader – consists of other 6 items (80 bytes)

- Transaction counter – positive integer (1–9 bytes)

- Transactions – the non-empty list of transactions

The transactions are units as well. They are comprised of several items, such as: how much money is sent, from which address the money is sent, to which address the money is sent, etc., including witnesses [26]. The witnesses are data which are connected to signatures needed in order to verify the transactions [27]. These signature-related data were segregated from the block in 2017 because of the problems in the Bitcoin network as it is mentioned below in the Difficulties of Bitcoin.

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[4]https://github.com/bitcoin/bitcoin/blob/master/src/chainparams.cpp

Wallet

One of the important aspects of bitcoin ownership is that an owner does not have the cryptocurrency (e.g. 10 bitcoins) on himself or herself. The owner possesses private keys which are required in order to be able to manipulate cryptocurrency on specific addresses.

When a user wants to send certain number of bitcoins the simplest way is to download a software wallet. According to [28], the main purpose of the software wallets is to create public keys and store the corresponding private keys which represent an ownership of a cryptocurrency. There are two main software wallet types:

1. desktop wallet – e.g. Bitcoin Core[5], Electrum[6], Exodus[7]

2. mobile wallet – e.g. Mycelium[8], Coinomi[9], Copay[10]

Some software solutions – wallets – can handle more cryptocurrencies than just one (e.g. Coinomi). They ensure sending transactions and recording new received transactions of the cryptocurrency. One can usually also see the transaction history and set transaction fees. When a new sending of a cryptocurrency is initiated the wallet creates a new transaction. This transaction is broadcast by the wallet to the broadcast network over TCP [29]. There are some disadvantages of the software solutions, e.g. the software is installed on an operating system on a computer which may be often connected to the internet. The computer can be infected with a malware and this malware can exploit this situation which could result in private keys theft [30, 31, 32]:

- It could take screenshots of the computer screen including the exposed private keys.

- If the software wallet is not encrypted the potential malware could send a command to the software in order to send the cryptocurrency to a specific address as soon as the software is launched.

- If the private keys are not encrypted (or incorrectly encrypted) a malware could steal them.

In addition, there are also hardware (offline) wallets, e.g., Trezor[11] or Ledger[12]. They are supposed to be safer than the software wallets. The reason is that

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[5]https://bitcoin.org/en/bitcoin-core/
[6]https://electrum.org/#home
[7]https://www.exodus.io/
[8]https://wallet.mycelium.com/
[9]https://www.coinomi.com/en/
[10]https://copay.io/
[11]https://trezor.io/
[12]https://www.ledger.com/

they are securely programmed stand-alone pieces of hardware which require a specific procedure in order to send cryptocurrency. They isolate the private keys of the cryptocurrency addresses on a secure chip when the device is connected (usually using USB) to the computer with internet connection [33]. When one wants to send cryptocurrency, a transaction is created in the affiliated application and subsequently sent to the device (hardware wallet) where it needs to be signed. The signature is done only when the user confirms the transaction on the device.

The last type of a wallet is a normal piece of paper (or an object like Cryptosteel[13]). It can carry the private keys or a Backup Seed Phrase which is usually a list of words sufficient enough to recover a wallet [34]. This type of a wallet is not secure on its own. There is some other supplementary item which provides safety of this type of wallet needed. For example a safe box where one can deposit the paper or the Cryptosteel-like item so nobody else can read it.

Network and Nodes

The broadcast network is comprised of peers (nodes). In reality a node is usually a server or a storage device which has the Bitcoin client software installed. The node stores the entire blockchain as well [35, 36]. It also must be connected to the internet. The nodes communicate with each other and if they receive a message and evaluate it as a valid transaction, they broadcast it as well so the transaction is received by all the nodes. However, if this particular transaction has already been broadcast, they never broadcast it again. The nodes act also as checkers of incoming transactions – they check that the transactions comply with the Bitcoin protocol. Otherwise they reject them.

Miners, Nonce, Target and Proof of Work

Another important component of the Bitcoin system are the miners. According to [37], they have two main purposes:

1. The primary purpose of miners is to record history of transactions in a way that is computationally and financially impractical to modify by anyone. That ensures security and confidence in the system. They basically hold the post of a distributed arbiter.

2. Secondary purpose is an issuance of new bitcoins.

Every miner needs to be connected to the network through one or more nodes and pick up the new transactions in the network. In addition, he or she needs

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[13]https://cryptosteel.com/

information about the last created block in the blockchain. Thus, some nodes are administered by the miners themselves, so they have immediate access to the broadcast network. When they are connected, they take the new transactions in the network (unconfirmed transactions or unordered transactions) and put them together along with other items such as Coinbase (Generation) transaction. Then they build a block header from these items [37]. One of the items in the block header is called Nonce. The miners hash this header and after hashing it they check if the hash is lower than the Target. The Target is a 256-bit number [38, 39, 40]. If it is lower than the Target, they just found (mined/generated) next block and broadcast this information to the network in the same way as the transactions are broadcast. This successful result is called Proof of Work [19, 41]. If the hash is not lower than the Target they change (usually just increase) the Nonce and hash the header again until they (or someone else) find the next block. The hashing algorithm that is used is SHA256 two times in a row – SHA256(SHA256(block header)). The lower the Target is the smaller chance to mine a block. For the reasons of low latency in transactions and transaction confirmation time predictability, the broadcast network strives for mining 1 block every 10 minutes [42, 43]. Since the attributes like the number of active miners and overall hashing power are changing over time there also is a need to change the difficulty of finding the next block. In other words, the Target needs to be changed over time in order to comply with the 10-minute creation time. It is adjusted every 2016 mined blocks [44], i.e. approximately every 14 days. A successful miner gets two bonuses as a reward [19]:

1. The first one is the transaction fees included in the mined block.

2. The second one is a bounty of 12.5 BTC at the moment. This bounty is agreed upon by everyone in the network and it must comply with the Controlled Bitcoin Supply [45, 16, 46] – i.e. 50% reduction every 210,000 mined blocks.

This results in two important facts – the supply limit in total is 20,999,999.9769 bitcoins [47, 48] and 2140 is the year when the last bitcoins should be mined [49, p. 2].

Difficulties of Bitcoin

Even Bitcoin has its drawbacks. Some of them appeared after a few years of existence and running. The adoption by the general public and so an increase of transactions per hour brought the scalability problem of Bitcoin [50, 51] to the surface. The core of the problem lays in two parameters:

- Average block creation time – Every 10 minutes on average is a block mined (created/found) and since the confirmed transactions are depen-

dent on the block mining there is only a limited number of transactions which can be confirmed in 10 minutes.

- Block size limit – Until 2017 was the system set as follows: 1 block can handle only 1 MB of data and consists of both data related to signatures (witness-related data) and the transactions. Since 2017 the Segregated Witness (SegWit) solution [27] by the inventor Pieter Wuille has been in practice. It segregates data related to signatures from the transactions data. It also cancels the block size concept and constructs a block weight concept which results in 4 MB as a maximum size of a block. All in all, the SegWit solution increases throughput of the Bitcoin network.

Another problem is the worldwide energy consumption of Bitcoin mining. For instance, according to [52], this consumption is comparable to the electricity consumption of whole Ireland.

2.1.2 Other Cryptocurrencies

There are hundreds of other cryptocurrencies apart from Bitcoin [53] – so-called Altcoins – e.g. Ethereum, Monero, Litecoin. They were launched usually after the Bitcoin's success and they are presented as:

1. better alternatives to Bitcoin

2. whole new cryptocurrencies based on different principles

A good representative of the first option, i.e., better alternatives to Bitcoin, is Litecoin[14] [54, 55]:

- It shows around 4x faster transaction processing.

- Its mining algorithm – Scrypt – is more suitable for basic user's CPUs compared to Bitcoin's SHA-256 which can be quickly calculated with the ASIC miners which complicates the network decentralization.

- Transaction fees are cheaper.

One of the representatives of the second option, i.e., new cryptocurrencies based on different principles, is Ethereum[15] [56]:

- Programmed to provide Smart Contracts – allowing to perform irreversible and traceable credible transactions without third parties involved. They are usually used to facilitate a transaction within the blockchain. That means it works much more as a platform than just a currency.

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[14]https://litecoin.org/
[15]https://www.ethereum.org/

- Strives for changing into proof-of-stake system – that will change the rewarding system on the blockchain. It will also be more energy efficient and will be more about bandwidth capacity rather than hash rate. Lastly it should be also less competitive on the validator (former miner).

- The transaction confirmation lasts just seconds.

Difficulties of Other Cryptocurrencies

Altcoins is a term which includes a wide range of different cryptocurrencies. On the one hand these can be interesting innovative projects with an active expanding community, but on the other hand they can also be pure scams. One of the main quality indicators is the white paper which is presented alongside the coin, a transparent active developer community and a competitive advantage. Next to the formal characteristics of the altcoin, in the beginning there is also a risk of Pump and Dump frauds [57, 58, 59]. The vulnerability occurs when low price and low market capitalization are present at the altcoin. A typical procedure is as follows:

- A closed group of people sets a time when everyone of them starts buying a predefined altcoin and spreading the news about the price movement (which is the "pump" part).

- That temporarily increases demand for the coin and also the price itself increases.

- After that the people in the closed group start selling the altcoin (which is the "dump" part) and the price decreases.

It is hard to stop this kind of activity because it is not illegal among the cryptocurrencies due to non-existent regulation. Despite the fact that it is difficult to see through this problem there are initiatives which try to show at least a suspicious behaviour of an altcoin as CoinCheckup[16].

In order to give a big picture of the relationship between Bitcoin and the Altcoins – Monero, Ethereum and other cryptocurrencies – I attach a table 21 from CoinMarketCap website [60]. The table shows the top cryptocurrencies sorted by the market capitalization – it is comprised of a position, name, market capitalization[17], price, volume[18] in the last 24 hours, circulating supply and a price graph. At first sight there is a similarity among various cryptocurrencies – Bitcoin, XRP, Ethereum, Stellar, Litecoin and Cardano – regarding the 7-day price graphs. I will discuss this similarity later in the thesis in the chapter about the trading bots.

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[16]https://pumpdump.coincheckup.com/
[17]https://www.investopedia.com/terms/m/marketcapitalization.asp
[18]https://www.investopedia.com/terms/v/volumeoftrade.asp

Name	Market Cap	Price	Volume (24h)	Circulating Supply	Price Graph (7d)
Bitcoin	$69,932,663,624	$4,018.93	$6,005,274,973	17,400,800 BTC	
XRP	$14,652,245,641	$0.363333	$523,970,380	40,327,341,704 XRP	
Ethereum	$11,784,334,602	$113.83	$2,072,289,926	103,522,619 ETH	
Stellar	$3,059,239,734	$0.159714	$96,417,066	19,154,499,889 XLM	
Bitcoin Cash	$3,057,453,495	$174.85	$98,026,943	17,485,863 BCH	
EOS	$2,607,337,029	$2.88	$849,686,463	906,245,118 EOS	
Litecoin	$1,912,765,765	$32.22	$423,149,043	59,372,874 LTC	
Tether	$1,841,411,846	$0.991915	$4,035,702,897	1,856,421,736 USDT	
Bitcoin SV	$1,698,998,485	$97.21	$179,908,888	17,477,861 BSV	
Cardano	$1,008,635,193	$0.038903	$30,192,241	25,927,070,538 ADA	
Monero	$950,614,447	$57.26	$14,181,945	16,602,171 XMR	

Table 21: Top cryptocurrencies sorted by the market capitalization, from CoinMarketCap [60]

2.2   Cryptocurrency Market

As well as there are various physical and non-physical markets like farmers'
market, e-commerce or Foreign exchange market (Forex), there is also a market
with cryptocurrencies. This market has existed since the time people wanted
to trade cryptocurrencies with each other. One can sell or buy (exchange) a
cryptocurrency on a cryptocurrency market. It also works as a place where
the prices of given cryptocurrencies are established.

The cryptocurrency market comprises many different types. The main one
is definitely cryptocurrency exchange market. The total market capitalization
according to CoinMarketCap [5] is over \$136 billion which is similar to some
of the world's biggest companies like IBM [61]. There are some other smaller
cryptocurrency markets as markets on the Darknet[19] [62] where cryptocurren-
cies can also be used as an anonymizing element of trading goods (including
illegal ones). Other small cryptocurrency markets are the local ones. In the
Czech Republic it could be places like Paralelní Polis[20] and events created by
these local places and organizers. On these events people can learn about var-
ious cryptocurrencies and buy or sell them between each other without using
any intermediaries like a cryptocurrency exchange as well. From the market
capitalization and triangular arbitrage points of view, the most interesting are
the cryptocurrency exchanges, and that is also the reason why I will mainly
focus on them from now on.

According to [63, p. 30] and [64, p. 2–3], one of the precursors of the
triangular arbitrage opportunities are liquidity[21] and spread[22] on a market.
The higher the liquidity on the market (with selected trading pairs), the bet-
ter opportunity windows of triangular arbitrage may appear. The same but
reversed applies to the spread as well – the lower the spread on the market
(with selected trading pairs), the better the opportunity windows of triangular
arbitrage may appear. These two concepts along with volume are connected
with each other and affect each other [65]. In addition to liquidity and spread,
there are other aspects which matter in order to execute a successful triangular
arbitrage on a cryptocurrency exchange:

1. Trading pairs – There must be an opportunity to execute triangular
   arbitrage. The more trading pairs are available on a cryptocurrency
   exchange, the higher the possibility there will be an opportunity to create
   a triangle of cryptocurrencies. This attribute is more easily achieved on
   the cryptocurrency exchanges operating with various altcoins.

2. Trading fees – Trading fees have an influence on a success rate of trian-
   gular arbitrage opportunity. They differ across all the cryptocurrency

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[19]https://en.wikipedia.org/wiki/Darknet_market
[20]https://www.paralelnipolis.cz/
[21]https://www.investopedia.com/terms/l/liquidity.asp
[22]https://www.investopedia.com/terms/s/spread.asp

exchanges. Some of them operate Maker-Taker model [66] (e.g. Kraken). It says that Takers are those who place an order which is immediately matched by an existing order. The Makers are the other ones – those who place an order which does not get filled immediately and is placed on the order book. Later it is matched by an order of another customer. The Taker fees are ordinarily higher than the Maker fees.

3. API capabilities – Since the cryptocurrency prices are changing every second or even faster the communication between an API and a user is important. There can be various APIs provided and different protocols and architectures used by a cryptocurrency exchange in order to communicate with a user. The most common ones are these two:

   - REST – an architectural style based on HTTP protocol [67]
   - WebSocket – a communication protocol dependent on TCP [68]

   REST API calls are usually limited on the number of requests that can be executed. WebSocket APIs work on a notification basis (or Push technology[23]) by definition. That means that a user is notified by the server when there is an update of data which the user subscribes to. Both approaches may be suitable – the bottom line is which cryptocurrency exchange is used and which functionality a user needs.

On the grounds of all the above-mentioned factors, several cryptocurrency exchanges and their attributes will be discussed below. The attributes will be the following:

- basic information about a cryptocurrency exchange

- volume ranking which indicates liquidity and spread [65] on a cryptocurrency exchange

- trading pairs listed on a cryptocurrency exchange

- trading fees charged on a cryptocurrency exchange

- APIs supported by a cryptocurrency exchange

Coinbase Pro

Coinbase Pro[24] formerly GDAX is a San Francisco based cryptocurrency exchange launched in 2012. It is a product of Coinbase and is meant to be a cryptocurrency exchange for advanced traders. It has more than 20 million users. According to CoinMarketCap, it is the 19th among the cryptocurrency

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[23]https://www.techopedia.com/definition/5732/push-technology
[24]https://pro.coinbase.com/

exchanges considering the volume of the last 30 days [1]. According to the Blockchain Transparency Institute it is the 5th in a similar ranking considering 24-hour volume [69].

1. Trading pairs: It operates more than 30 trading pairs which include BTC, LTC, ETH, ETC, BCH, ZRX and others [70].

2. Trading fees: The fees depend on a 30-day trading volume. I will take the lowest – worst – one ($0m–10m) into consideration. That is 0.3% Taker fee and 0% Maker fee for all the trading pairs [71].

3. API capabilities: There are public and private endpoints. The private ones are intended for order and account management. The public ones are intended for public market data. The latter is the one which would be used. There are three possible APIs provided [72].

   - REST (with HTTP used) – The limit is 3 requests/sec. which is 180 requests/min per IP considering the public endpoints. Or there is up to 6 requests/sec. which is 360 requests/min. per IP in bursts. The typical options as Product Order Book or Product Ticker are available.

   - WebSocket – It is publicly available but there is maximum connections limit set as 1 connection per 4 sec. per IP. One needs to read the message stream and use only the messages relevant to him.

   - FIX (Financial Information eXchange) – This API is used to enter orders, receive fills and submit cancel requests so there is no applicability of that for the purpose of this thesis.

Coinmate

Coinmate[25] is a London based cryptocurrency exchange with a technology background created by a Czech company – Profinit[26] and launched in 2014. It is one of the smaller (below the first 100) cryptocurrency exchanges worldwide according to CoinMarketCap [1]. According to the Blockchain Transparency Institute it is the 27th in a similar ranking considering 24-hour volume [69].

1. Trading pairs: There are 11 trading pairs containing BTC, LTC, ETH, BCH cryptocurrencies. Every one of them is in a trading pair with EUR, CZK and BTC (naturally except BTC/BTC) [73].

2. Trading fees: Only the basic fees (30-day trading volume is less than 10,000 EUR) are taken into consideration. There are two groups of trading pairs in the sense of the fees [74].

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[25]https://coinmate.io/home
[26]https://profinit.eu/klienti/

- The first one contains trading pairs which include LTC and, moreover, BTC/EUR, BTC/CZK. The Taker fee is 0.25% and the Maker fee is 0.12%.

- The second one contains trading pairs which include ETH and BCH. The Taker fee is 0.15% and the Maker fee is 0.05%.

3. API capabilities: There are three suggested approaches how to communicate with Coinmate [75].

- REST (with HTTP used) – There is a limit of 100 requests/min. or the IP address is banned otherwise. One can easily get the Order Book, Ticker, etc.

- WebSocket – Coinmate uses Pusher[27] which is a hosted mainly WebSocket API [76].

- XChange Java library[28] – It is a Java library that streamlines API of more than 50 cryptocurrency exchanges and creates a consistent interface.

Bittrex

Bittrex[29] is a Seattle based cryptocurrency exchange launched in 2014. According to CoinMarketCap, it is the 40th among the cryptocurrency exchanges considering the volume of the last 30 days [1]. According to the Blockchain Transparency Institute it is the 9th in a similar ranking considering 24-hour volume [69].

1. Trading pairs: It operates more than 100 trading pairs which includes the major (in terms of market capitalization) cryptocurrencies as BTC, LTC, XMR, ETH, BCH, XLM, etc. as well as the minor ones as XZC (Zcoin) or EXP (Expanse). It is divided into four groups of markets – USD market, Bitcoin market, Ethereum market and USDT market [77].

2. Trading fees: There is one global fee applied in all the trades – 0.25% [78].

3. API capabilities: There are three distinct groups of APIs – Public, Market, Account. The only one needed for the purposes of this thesis is the Public group which does not require any API key [79, 80].

- REST (with HTTP used) – There is a limit of 1 request/sec. because of Bittrex itself. It updates the data at regular intervals of 1 sec. The REST API provides common functionality such as Order Book, Ticker, Market Summary, etc.

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[27]https://pusher.com/
[28]https://github.com/knowm/XChange
[29]https://international.bittrex.com/

- WebSocket – The Websockets API is also possible to use. One needs a SignalR[30] client. SignalR is a library mainly for ASP.NET developers.

Bitstamp

Bitstamp[31] is a Luxembourg based cryptocurrency exchange launched in 2011. It started as an alternative to the then dominant Mt. Gox[32] – by contrast primarily focusing on the European market [81]. According to CoinMarketCap, it is the 28th among the cryptocurrency exchanges considering the volume of the last 30 days [1]. According to the Blockchain Transparency Institute it is the 6th in a similar ranking considering 24-hour volume [69].

1. Trading pairs: It operates exactly 15 trading pairs. There are XRP, LTC, ETH, BCH where each of them is in a trading pair with USD, EUR and BTC. Then there are three more trading pairs – BTC/USD, BTC/EUR and even EUR/USD [82].

2. Trading fees: There are various options according to 30-day USD volume. I will take into consideration only the one which is less than 20,000 USD. That means it is the worst one and is 0.25% for all 15 trading pairs. There is also a minimum order size 5 EUR, 5 USD and 0.001 BTC for Euro, USD and Bitcoin denominated trading pairs respectively [83].

3. API capabilities: There are three accessible APIs – REST, Websocket, FIX [84].

   - REST – There is a limit of 600 requests/10 min. which is 1 request/min. on average. It provides common functionality such as Ticker and Order Book as well as Hourly Ticker, Trading Pairs Info, etc.
   - WebSocket – Bitstamp uses Pusher for the WebSocket streaming. It handles Live Orders, Live Ticker, etc.
   - FIX – It is based on FIX 4.4 standard and it works as a gateway. It performs routing and translation of FIX messages from clients to appropriate calls to REST or WebSocket APIs and vice versa. It enables to get data of Live Ticker, Order Book, etc.

Bitfinex

Bitfinex[33] has its headquarters in Hong Kong and was founded in 2012. Although it has experienced an extensive security breach [85], according to Coin-

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[30]https://www.asp.net/signalr
[31]https://www.bitstamp.net/
[32]https://www.mtgox.com/
[33]https://www.bitfinex.com/

MarketCap it is the 6th among the cryptocurrency exchanges considering the volume of the last 30 days [1]. According to the Blockchain Transparency Institute it is the 2nd in a similar ranking considering 24-hour volume [69].

1. Trading pairs: There are more than 300 trading pairs operating. Almost every cryptocurrency is in a trading pair with BTC, ETH and USD. In addition, one can also trade JPY (Japanese Yen), however, only with eight cryptocurrencies altogether [86].

2. Trading fees: The fees depend on a USD equivalent of the order execution during the last 30 days. I will take into consideration only the one which is less than 500,000 USD. Bitfinex also divides the fees into two types depending on a trade type – Taker fee and Maker fee. The first one is 0.2% and the latter is 0.1%. One can also place a hidden order always with the Taker fee. If (another) limit order matches this hidden order then the trader pays the Maker fee [87].

3. API capabilities: There are two accessible APIs – REST and Websocket [88].

   - REST – There is a limit between 10 and 90 requests/min. which is between 1 request/6 sec. and 3 requests/2 sec. on average. Each endpoint has its own limit. For example, limit of the Ticker is 20 requests/min. If a user exceeds the limit his or her IP address is blocked for 10 to 60 seconds. There are two types of endpoints again – Public and Authenticated. Only the first type would be used. It provides common functionality such as Ticker and Order Book as well as Trades and Stats.

   - WebSocket – Bitfinex also supports WebSocket protocol where all the sent and received messages via the WebSocket channel are encoded in JSON format. It divides into Public channels and Authenticated channels. Public channels provide Order Books, Raw Order Books, Trades and Ticker.

Binance

Binance[34] is a Malta based [89, 90] cryptocurrency exchange founded in 2017. It is capable of sustaining 1,400,000 orders/sec. [91]. According to CoinMarketCap, it is the 1st among the cryptocurrency exchanges considering the volume of the last 30 days [1]. According to the Blockchain Transparency Institute it is also the 1st in a similar ranking considering 24-hour volume [69].

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[34]https://www.binance.com/en

1. Trading pairs: It is possible to trade more than 100 cryptocurrencies through more than 300 trading pairs [92]. Even though it does not support any fiat currency [93], it intends to support it in the future [94].

2. Trading fees: Binance runs Maker-Taker model as well. There are multiple levels of fees depending on 30-day BTC volume and BNB (Binance coin) balance. One can use BNB for transaction fees and in that case he or she has a discount of various percentage rates depending on time. I will take into consideration the General level which is set as less than 100 BTC or greater than or equal to 0 BNB. Then the fees equal 0.1% both for Maker and Taker fees [95].

3. API capabilities: There are two accessible APIs – REST and WebSocket [96].

   • REST – The limits are weighted in favour of a specific request type. Maximum of the request weight is 1200/min. In addition, there is a maximum limit of raw requests which is 5000/5 min. If a user exceeds the limits his or her IP address is blocked for 2 minutes up to 3 days. The desirable endpoint would be Symbol order book ticker which has a weight of 2 in order to get all trading pairs on the cryptocurrency exchange.

   • WebSocket – Binance offers Trade Streams and Ticker Streams. The latter is pushed every second to a client. All the stream connections are valid for 24 hours maximum. On top of that, the connection must be maintained by ping pong messages (heartbeat) every 10 minutes.

Kraken

Kraken[35] is a cryptocurrency exchange founded in 2011 and based in San Francisco. It is the largest Bitcoin exchange in view of euro volume and liquidity [97, 98]. According to CoinMarketCap, it is the 18th among the cryptocurrency exchanges considering the volume of the last 30 days [1]. According to the Blockchain Transparency Institute it is the 4th in a similar ranking considering 24-hour volume [69].

1. Trading pairs: Kraken operates 20 cryptocurrencies and 5 fiat currencies [99]. In total there are 73 trading pairs [100]. Regarding fiat currencies, one can trade Canadian dollars, US dollars, British pounds, Euros and Japanese yen.

2. Trading fees: The fees comply with Maker-Taker model. There is no common trading fee for all the trading pairs. Each trading pair has its

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[35]https://www.kraken.com/

own trading fees. I will take into consideration only the first tier of each trading pair. The tiers are determined according to the last 30-day "Fee Volume Currency" volume. All the realized trades are always converted to the equivalent value of this Fee Volume Currency. Fee Volume Currency is USD for all the trading pairs right now. In the first tier there is 0.16% Maker fee and 0.26% Taker fee for each cryptocurrency except two cases – dark pools[36] and USDT/USD trading pair. Dark pools do not follow Maker-Taker model and has 0.36% trading fees. USDT/USD trading pair has both 0.2% Maker and Taker fee [101].

3. API capabilities: There is only one option available – REST API [102]. WebSocket API or any other similar API is not provided [103].

   - REST – The limit for Public calls is 1 request/sec. One does not need an API key in case of using the Public calls. API key is needed only for Private calls where there is a call counter. Call counter may exceed a maximum (which varies depending on user's verification level) and then the user's API access is suspended for 15 minutes. Endpoint calls increase the call counter by zero, one or two depending on the endpoint type. The call counter is also decreased by one automatically every 1 or 2 or 3 seconds again depending on user's verification level [104].

Huobi

Huobi[37] is a cryptocurrency exchange founded in 2013. It is based in Singapore and founded in China. In 2018, Huobi had to create the Communist Party committee. This was the first case when a Chinese blockchain company had to do this [105]. According to the Blockchain Transparency Institute, the real 24-hour trading volume of BTC/USDT trading pair is around 26% of the reported one [106]. One of the reasons might be wash trading[38] as stated by BTI. According to CoinMarketCap, it is the 3rd among the cryptocurrency exchanges considering the volume of the last 30 days [1].

1. Trading pairs: Huobi operates more than 400 trading pairs. There are five quote cryptocurrencies[39] – USDT, HUSD (Huobi Stable Coin), BTC, ETH and HT (Huobi Token). It does not support fiat currencies [107].

2. Trading fees: Huobi comply with Maker-Taker model. Each currency has its own Maker fee and Taker fee. Nevertheless, all the trading fees – both Maker and Taker – are equal to 0.2% [108].

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[36]https://www.investopedia.com/terms/d/dark-pool.asp
[37]https://www.hbg.com/en-us/
[38]https://www.investopedia.com/terms/w/washtrading.asp
[39]https://www.investopedia.com/terms/q/quotecurrency.asp

3. API capabilities: Huobi's API supports all the trading pairs. There are two typical APIs provided – REST API and WebSocket API [109].

   - REST – There are two types of requests. Those which need a signature and those who do not. Market Data and Symbols&Currency data requests do not need a signature and are public. The request limits are specified as 100 requests/10 sec. which is 10 requests/sec. for each API key on average. Since there is no need to provide an API key for the public requests and there are no other request limits provided, the public request limits are unknown. In this case I would follow the already mentioned provided limits.

   - WebSocket – There are two types of WebSocket data. Market Data and Accounts and Orders. The first one would be used and there is no authentication (API key) required for it. One can subscribe to Market Data or request it at once.

OKEx

OKEx[40] is a Belize based cryptocurrency exchange founded in 2014 with offices in Hong Kong and Malta [110, 111]. According to the Blockchain Transparency Institute, its official volume is not true and its top trading pairs are engaging in wash trading [106]. The BTI claims that the real volume of BTC/USDT trading pair is around 11% of the reported one. According to CoinMarketCap, it is the 2nd among the cryptocurrency exchanges considering the volume of the last 30 days [1].

1. Trading pairs: OKEx operates more than 300 trading pairs. There are four quote cryptocurrencies – BTC, USDT, ETH, OKB (OKEx Utility Token) [112]. It does not support fiat currencies except the OTC Trading [113].

2. Trading fees: OKEx runs 30-day trading volume-based Maker-Taker model. The volume is counted in BTC. I would take Tier level 1 into consideration. That means the cumulated volume is less than 100 BTC, Maker fee is 0.1% and Taker fee is 0.15% [114].

3. API capabilities: There are two types of endpoints – Public and Private. Since the Public one is available for acquiring information and market data it is sufficient. There is no authentication needed. OKEx supports both REST API and WebSocket API [115, 116].

   - REST – The current version of the API is v3. The limit for the REST API requests varies depending on a specific endpoint. If there is no specific endpoint limitation the general REST API limit

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[40]https://www.okex.com/

is applied. That is 6 requests/sec. One of the prospective endpoints which could be used is Get All Token Pairs Information which is limited to 20 requests/2 sec. which is 10 requests/sec. on average.

- WebSocket – This API is recommended for accessing market related information and trading depth. All the incoming messages – from the client point of view – has to be decompressed. There is a connection limit of 1 connection/min. and subscription limit of 240 subscriptions/hour. In addition, there is a limit of 50 outgoing message commands/sec. One needs to maintain a connection by ping pong messages (heartbeat) every 30 seconds.

DigiFinex

DigiFinex[41] is a cryptocurrency exchange founded in 2017 in Seychelles with offices in Singapore and China [117]. According to the Blockchain Transparency Institute, DigiFinex most likely participates in wash trading. E.g. the BTC/USDT trading pair evinces 99% of the 24-hour traded volume is not real [106]. According to CoinMarketCap, it is the 5th among the cryptocurrency exchanges considering the volume of the last 30 days [1].

1. Trading pairs: DigiFinex operates more than 100 trading pairs. There are five quote cryptocurrencies – USDT, BTC, ETH, DFT, TUSD. It supports only stablecoins[42] instead of fiat currencies.

2. Trading fees: In November 2018 DigiFinex introduced Maker-Taker model. Next to this model they also implemented level-based fees. There are 7 levels – from General through VIP1 to VIP6. The levels depend on 30-day trading volume and DFT (DigiFinex Token) holdings. General level would be taken into consideration which means less than 100,000 USDT and less than 100 DFT. Then the Maker fee is 0% regardless of DFT condition, Taker fee is 0.2% and Taker fee in compliance with DFT condition is 0.15% [118].

3. API capabilities: There is only REST API available [119].

- REST – In order to execute any request API key must be provided. It means there is no public endpoint so one needs to register even for Market Information such as Ticker or Market Depth. The limits are 60 POST requests/min. which is 1 request/sec. on average and 180 GET requests/min. which is 3 requests/sec. on average. If any limit is exceeded the 5 min. ban will be applied.

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[41]https://www.digifinex.com/en-ww/
[42]https://www.investopedia.com/terms/s/stablecoin.asp

Analysis

In this chapter the problem definition is formulated from a mathematical point of view. Then the functional and non-functional requirements are determined. They establish the core properties and characteristics of the work. They also set the limits of this work and describe it in more detail. There are tables in both subchapters dealing with requirements in order to outline each requirement briefly. After that the requirements are described more thoroughly one by one.

3.1   Problem Definition

3.2   Functional Requirements

All the functional requirements were defined based on the thesis assignment and the already explored functionality of the existing data collecting applications. First, I provide a table 31 of the functional requirements together at one place and then I describe them in full detail one by one.

#	Name of the functional requirement
1	Collect data from selected cryptocurrency exchanges
2	Process collected data in order to display potential profit
3	Store the processed data in a database
4	Display the processed data using GUI
5	Display collected historical data
6	Sort the processed data
7	Highlight the profitable paths
8	Filter data sources

Table 31: Functional requirements

F1 – Collect data from selected cryptocurrency exchanges

The application will collect (download) selected cryptocurrency data – cryptocurrency pairs – from the selected cryptocurrency exchanges. This action will be performed on a regular basis. If some of the selected cryptocurrency exchanges do not respond it will collect data from the other ones.

F2 – Process collected data in order to display potential profit

The collected data will be processed in a way within the meaning of the Triangular arbitrage [9, 10, 11]. That means a situation where there is a succession of three or more new buy orders on different cryptocurrency pairs across one or more cryptocurrency exchanges – e.g. a successive buy of ADA for BTC, ETH for ADA and BTC for ETH (i.e. BTC → ADA → ETH → BTC). Both at the beginning and at the end there is the same cryptocurrency (e.g. BTC). There are three different possible outcomes. Either the final amount (balance) can be higher (positive) or lower (negative) or the same as the initial one. In other words, there is some percentage of earnings. The application will not buy or sell any of the cryptocurrencies. It will display potential percentage of earnings of such an operation instead. In addition, it will store the data in a database. Hence, the collected data will be processed in order to satisfy two separate requirements. Firstly, in a way which is suitable for displaying the required data. Secondly, in a way which is suitable for storing the data.

F3 – Store the processed data in a database

The application will store selected data in a database in order to display them for the purpose of potential comparison or for an analysis of cryptocurrency exchange inefficiencies development with time. The data will be stored in a format which is suitable for the subsequent displaying. Owing to correctness of the historical data the already gathered data will be used.

F4 – Display the processed data using GUI

The processed data (from F2) will be displayed using Graphical User Interface. The application will display various paths (sequences of cryptocurrencies) and potential instant profit/loss from the corresponding transaction orders including mentioning the cryptocurrency exchange fees. One can get remotely to the processed data, thus to the GUI over the internet accessing a web page. That is convenient for any user who wants to examine the data without installing any additional software (except the web browser). It also improves readability and intelligibility of the processed data.

F5 − Display collected historical data

Not only real-time data will be displayed. Along with them will also be possible to search for and display historical data. A user will be able to choose a point in time and thereafter the corresponding data will be displayed. The historical data will be presented in the context of percentage of earnings at that point in time.

F6 − Sort the processed data

The collected and processed data will be sorted primarily in descending order in terms of the potential percentage of earnings. The reason is that the profit is the core of the problem I address. So the first thing one would like to know is if the triangular arbitrage is profitable at the selected point in time. Ascending order will also be possible to use because of knowing the worst sequences of cryptocurrencies on the list might be valuable to a user as well. Other types of sorting will be supportive.

F7 − Highlight the profitable paths

The most interesting part of the exploration is whether there will be profitable paths on the selected cryptocurrency exchanges with the selected trading pairs. That is the reason why the highlighting of the profitable paths is interesting and important for a user. Hence, the application will highlight these paths.

F8 − Filter data sources

The application will allow a user to choose which particular cryptocurrency exchanges will be included in the data processing. The reason is a user might trade just on a subset of the suggested cryptocurrency exchanges so he or she might be interested only in this particular subset of the exchanges. There could be a better path after including the other cryptocurrency exchanges, but it would be useless to the user. In addition, the cryptocurrency market has been changing since it came into existence. As a result of it, various cryptocurrency exchanges have changed in the volume of trade or they even discontinued [2] by the proprietors. Under these circumstances it is possible that the suggested cryptocurrency exchanges could act similarly in the future and so it is reasonable to let the user choose.

3.3   Non-Functional Requirements

All the non-functional requirements delimit major capabilities of the program from a distance. They set criteria that can be used to evaluate various operations of the system. In addition, they are chosen in a way which minimizes contradiction among each and every one of them in spite of the fact that non-functional requirements often go against each other. They are also defined based on the thesis assignment and the already explored functionality of the existing data collecting applications. They generalize and support the functional requirements. First, I provide a table 32 of the non-functional requirements together at one place and then I describe them in full detail one by one.

#	Name of the non-functional requirement
1	Real-time communication
2	Modifiability of the sources
3	Fault-tolerant system
4	Data reliability
5	Open-source code
6	Platform independence
7	Source code readability
8	Usability
9	Extensibility
10	Testability
11	Accessibility

Table 32: Non-functional requirements

N1 – Real-time communication

In an application like this the response time is an important element in order to fulfil one of the core requirements. One of the key attributes of cryptocurrency trading is the speed – how fast one can buy or sell assets. In the spirit of this attribute it is important to keep up with the traders and provide real-time information about potential profit of the triangular arbitrage. Real-time does not mean a precise period of time. The time period is relative to a specific cryptocurrency exchange – e.g. how often individual exchanges refresh or provide the trade-related data.

N2 – Modifiability of the sources

This non-functional requirement is moderately connected with the eighth functional requirement (F8). A cryptocurrency exchanges change often in time in

terms of the traded volume or they even close and stop working due to various reasons. Considering these potential issues, the modifiability of the sources is desired. An administrator of the application will be able to easily change (add, delete or adjust) the sources of data – i.e. cryptocurrency exchanges and their APIs – used for collecting and subsequently processing the finally displayed data.

N3 – Fault-tolerant system

The application will show signs of a fault-tolerant system in terms of a potential number of data sources. Firstly, the functionality will enable using multiple sources of data – i.e. cryptocurrency exchanges and their APIs – which will prevent the application from collapsing due to a reason there is only one source which stops with data provisioning. Secondly, when one of the viable sources stops providing data then the application will not stop working and will continue with the rest of the viable sources.

N4 – Data reliability

The application will comply with the data reliability owing to the fact that I will gather the data on my own. No intermediaries will be used. The reason is that there have been issues of reliability of the cryptocurrency exchange intermediaries like CoinMarketCap in the past [120, 121, 122]. One of the appropriate methods to overcome the problem is to choose credible cryptocurrency exchanges and connect to them directly or using a library. This shifts the potential reliability problem to the particular sources (cryptocurrency exchanges).

N5 – Open-source code

Whole application will be managed as an open-source project which has several advantages. Some of them are:

- Transparency – everyone who wants to use the software can read the source code and assure himself of not-malicious intentions of the project. In addition, progress of the project will be trackable (e.g. via timestamps) and everyone will be able to see it.

- Increase in use and collaboration – since the project will be open-source it will be easy to share and so more persons will be able to learn about it or to join it.

- Reliability – software will have greater potential to be reliable because more people who are interested will be able to contribute easily and test the application in the future.

- Independence – even if I stop developing the software it will continue to exist and will be developed by its users.

N6 – Platform independence

The program will work as a web application which means one will be able to run it on a web browser. The platform independence will be ensured by the web browser which can be installed on all the major popular operating systems (Windows, OS X/macOS, other Unix-based systems). The advantage of using the web browser is not only the platform independence but also the accessibility which is described in eleventh non-functional requirement (N11) below.

N7 – Source code readability

The code of the application will be easy to follow and will support the best practices of the code readability (e.g. commenting on complicated parts, meaningful variable naming, skilful use of programming language facilities, short functions which meet the Separation of Concerns principle[43]

N8 – Usability

User testing which will be held at the end of the application creation process will ensure the usability of the application. Several human testers will verify that the application is easy to understand and one can move with ease within it. They will provide me with feedback on what is not fully clear.

N9 – Extensibility

It will be easy to add or modify a subset of already included sources – cryptocurrency exchanges – in the application. This requirement is particularly important in case of a cryptocurrency exchange's API maintenance or change. In addition, it is also important to fulfil this requirement in case there is a new promising cryptocurrency exchange coming into existence. As a matter of course, the code will take a future growth into consideration.

N10 – Testability

In view of the fact that the application will follow the Separation of Concerns principle along with the open-source paradigm and the source code readability it will be easier to test it both as a whole and as separate parts. The testing will include but will not be limited to user testing as I have already mentioned in N8.

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[43]https://books.google.cz/books?id=pFHYk0KWAEgC, p. 85

N11 − Accessibility

The application functionality will be accessible (in terms of how to get to the application's outputs) over the internet and WWW[44]. That enables working with the data and the whole application from any place connected to the internet and so increases its accessibility.

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[44]https://www.w3.org/TR/webarch/

Design

4.1 Selected Technologies

4.2 Use Cases and Scenarios

4.3 Deployment Model

4.4 Wireframes

Implementation

Testing

Conclusion

We described the fundamental principles of Bitcoin and other selected cryptocurrencies which are helpful to understand the big picture of the thesis. What they are, how they work and what difficulties they face. After that we surveyed the cryptocurrency market and determined the largest part of it – cryptocurrency exchanges. There were attributes of cryptocurrency exchanges selected based on significance to triangular arbitrage successful execution. We then surveyed several high-profile cryptocurrency exchanges according to the selected attributes. Afterwards, the work's core requirements were analysed and defined.

In the future, we will create design for the implementation including wireframes and deployment model. On top of the design we implement an application which displays triangular arbitrage opportunities on selected cryptocurrency exchanges and perform testing.

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Acronyms

ADA Cardano

API Application programming interface

ASIC Application-specific integrated circuit

BCH Bitcoin Cash

BNB Binance Coin

BSV Bitcoin SV

BTC Bitcoin

CPU Central processing unit

CZK Czech koruna

DFT DigiFinex Token

EOS EOS (cryptocurrency)

ETC Ethereum Classic

ETH Ethereum

EUR Euro

EXP Expanse

FIX Financial Information eXchange

GDAX Global Digital Asset Exchange

GUI Graphical user interface

HT Huobi Token

HTTP Hypertext Transfer Protocol

HUSD Huobi Stable Coin

IP Internet Protocol

JPY Japanese yen

JSON JavaScript Object Notation

LTC Litecoin

MB Megabyte

OKB OKEx Utility Token

OS Operating system

OTC Over-the-counter

REST Representational state transfer

SHA Secure Hashing Algorithm

SV Satoshi Vision

TCP Transmission Control Protocol

TUSD TrueUSD

URL Uniform Resource Locator

USB Universal Serial Bus

USD United States dollar

USDT Tether

WWW World Wide Web

XLM Stellar

XMR Monero

XRP Ripple

XZC Zcoin

ZRX 0x (protocol)

User's Manual

Contents of enclosed CD