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MASTER'S THESIS

ARBITRAGE IN CRYPTOCURRENCY MARKETS

Ljubljana, April 2024 TIMOTEJ GIACOMELLI

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EU – European Union
ECB – European Central Bank
DLT – Distributed Ledger Technology
ART – Asset-Referenced Tokens
EMT– Electronic Money Tokens
MiCA – Markets in Crypto-Assets

1 INTRODUCTION

When an individual enters into financial markets, one of the biggest problems they face is distributing their money among different assets. That is especially difficult since there are thousands of bonds, stocks, and other alternative assets from which the investor can choose (Francis & Dongcheol, 2013). Unfortunately, that is not an exception for individuals. With the additional complexity of having to specifically include the characteristics of their liabilities in the analysis, almost all financial institutions face the same issue. Although the structure of these issues differs a little, they are similar enough for us to group them under portfolio theory (Elton & Gruber, 1997). If we look at the market more thoroughly to see if there are arbitrage opportunities because of inefficiencies, it becomes evident that arbitrage opportunities arise in some instances. However, to take advantage of these inefficiencies, in some cases, we still have to hold a portfolio of assets between which the arbitrage occurs (Grone et al., 2021, p. 529).

The emergence of cryptocurrency trading has introduced new complexities and challenges to the positioning and optimization of portfolios. Cryptocurrency markets are highly volatile and characterized by frequent and substantial price fluctuations, making them unique in predicting future returns. It is crucial to find technical tools to deal with such underlying wild swings to trade these crypto-assets successfully as more investors and organizations, such as banks, hedge funds, and even governments, join the expanding cryptocurrency community (Clement & Mwambi, 2021). As a result of high price volatility, arbitrage opportunities arise on the market as a discrepancy between various cryptocurrencies when their exchange rates do not perfectly coincide. Arbitrage, in this context, is thus a risk-free exchange of different currencies and cryptocurrencies that ensures a sure profit (Grone et al., 2021). Suppose we decide we want to trade arbitrage on cryptocurrency markets. In that case, an important question arises: How do we take advantage of these market opportunities and optimize arbitrage trading to trade as efficiently as possible?

The purpose of this master thesis is to extensively examine cryptocurrency markets and the arbitrage opportunities that arise between one or more exchanges. To gain a competitive edge in real-life trading, it is essential to thoroughly understand the assets and their characteristics. Only with comprehensive knowledge of the assets can we dive deep into constructing a cryptocurrency portfolio designed explicitly for trading arbitrage opportunities across different cryptocurrency exchanges. Furthermore, the research will focus on optimizing trading by developing measures to assess the arbitrage algorithm's efficiency.

2 CRYPTOCURRENCY AS AN ASSET CLASS

The growing interest in cryptocurrencies as an alternative investment asset is undeniable, and their popularity continues to increase each year. Today, it is not uncommon for discussions related to money, investing, or trading to include mention of cryptocurrencies, and financial news outlets regularly report on price movements in cryptocurrency markets. This trend is exciting because the desire for cryptocurrencies is no longer limited to individual retail traders. Institutional investors and traders are also showing a keen interest in cryptocurrencies and are joining the hype around them (Hermans et al., 2022).

The hype surrounding cryptocurrencies is driven by several factors, including the increasing trust in the technology and idea behind cryptocurrency, as evidenced by the worldwide discussion among central banks regarding their own central bank digital currencies (from now on referred to as CBDC). Additionally, the recent public listing of companies such as Coinbase has helped to build trust and increase awareness of the potential benefits of investing in cryptocurrencies. Furthermore, the increasing acceptance of cryptocurrencies as a means of payment by merchants, such as Tesla's acceptance of Bitcoin and Dogecoin (Bitcoin was later removed as a means of payment), has further bolstered the legitimacy of cryptocurrencies as a viable investment asset. Naturally, many traders and investors are attracted by the potential for massive gains, the opportunities presented by the 24/7 trading environment, and the superior user experiences for retail traders offered by many new cryptocurrency brokers compared to traditional stockbrokers (Csiszar, 2022).

While cryptocurrencies may seem a well-known asset class to the general public due to Bitcoin's widespread media coverage and popularity, the reality is more complex. For those unfamiliar with Bitcoin, it is the first and most popular cryptocurrency, with the highest market capitalization since the birth of cryptocurrencies. Though many people may have a general understanding of the price movements of Bitcoin, understanding cryptocurrencies as an investment class is not typical. The cryptocurrency market is widespread with scams and fraudulent activities, making it difficult for investors to separate reliable sources of information from unreliable ones. Furthermore, while cryptocurrencies may appear to be a simple and accessible investment option, the reality is that investing in cryptocurrencies requires a deep understanding of the assets and the complex market dynamics that can impact price movements.

This chapter will provide a comprehensive overview of cryptocurrency as an asset class. We will begin by defining cryptocurrency and examining the role of cryptocurrency in the broader context of crypto-assets. Then, we will examine how crypto-assets meet the functions of money and explore the benefits and drawbacks of investing in crypto-assets. Ultimately, we will discuss how to classify different crypto-assets under a new regulation from the European Union, Markets in Crypto-Assets Regulation (MiCA), which was approved in April 2023.

2.1 What is Cryptocurrency?

The world of cryptocurrencies is a relatively new frontier for financial markets, leading to many misconceptions and a lack of universal agreement on their definition. Despite this, the average person can gain a general understanding of cryptocurrencies by exploring the highest-ranked search engine results on Google or any other search engine, which can help to construct a framework of concepts. However, many of these definitions are flawed and require a more accurate explanation. Nevertheless, for an easier understanding of the topic, let us look at what cryptocurrency is in a very simplified version.

Cryptocurrency, crypto-currency, or crypto is a term commonly used to refer to a type of digital currency that is decentralized and operates on a digital network. It exists only on this network and has no physical form like cash. This decentralized nature means no single entity has complete control over the asset. Unlike fiat currencies such as the US dollar or Euro, transactions can be carried out without intermediaries such as banks or financial institutions. Instead, transactions are processed and validated through a decentralized system of computers. This decentralized nature is one of the main defining characteristics of cryptocurrencies (Frankenfield, 2023a).

Although cryptocurrencies were initially introduced as a form of currency, a closer inspection reveals critical limitations in classifying them as a form of money (which will be elaborated on later). For this reason, authoritative entities such as the European Central Bank (ECB) and the Internal Revenue Service (IRS) classify "cryptocurrencies" as a specific type of asset instead and try to avoid the use of the word "currency." Given the variation in naming and definitions among these and other entities and our location in the European Union (EU), this research will follow the ECB's classification and definitions, which refer to **cryptocurrencies** as **crypto-assets**. We will also consider other sources when the ECB's coverage is insufficient or additional information is necessary.

2.2 What are Crypto-Assets?

Based on the ECB vocabulary, we are talking about crypto-assets when referring to cryptocurrencies. Even though we will follow ECB classifications, there are some discrepancies between older and newer sources of ECB and other European Union institutions when defining crypto-assets. However, to ensure the consistency of its analysis over time and across technologies, the ECB has chosen to define crypto-assets as follows.

> **Definition**: Crypto-assets are a new type of asset recorded in digital form and enabled by the use of cryptography that is not and does not represent a financial claim on, or a liability of, any identifiable entity (Chimienti et al., 2019).

The emphasis lies on the regulatory, economic, and business aspects of crypto-assets as a novel type of asset rather than on the technologies required for their existence, which are not unique to them. One of the notable features of crypto-assets is that they do not represent a claim on any discernible entity, resulting in their value being solely supported by the anticipation that other users will be willing to pay for them in the future instead of being based on an anticipated cash flow that users can utilize to establish their expectations. Users attribute value to them based on two beliefs:

1. The asset supply will remain limited, and
2. the market will recognize who has the right to sell each unit.

The scarcity of a crypto-asset and the ability to demonstrate ownership of each unit make a crypto-asset market possible. In this market, supply-side users can offer their units for sale, and demand-side users are willing to bid on them.

Typically, a central record of the number of issued asset units and their ownership is maintained by a trusted bookkeeper to support such beliefs of market participants. When assets are in digital form, counterfeiting can be as easy as copying and pasting, unlike physical goods, which require specific skills and resources to be counterfeit and can be vetted by experts. Consequently, a trusted central party is usually responsible for controlling the number of units and maintaining ownership records in the case of assets in digital form. However, in the case of crypto-assets, cryptographic techniques are used to replace the trusted bookkeeper in the recording process. Keeping records with these techniques eliminates the need for a central party to control any unauthorized increase in crypto-assets issued (on a distributed ledger) and to get the network of users to reach a consensus on the ownership of the assets (Chimienti et al., 2019).

Nevertheless, even though the emphasis of the crypto-asset definition is not on the technologies required for their existence, it plays an essential role in understanding their characteristics. Exploring the technology behind crypto-assets, specifically Distributed Ledger Technology (DLT) and Blockchain, is crucial since it underpins the existence and functionality of these digital assets. By understanding the role of DLT in enabling crypto-assets, we can grasp this emerging asset class's potential benefits and limitations.

2.2.1 Distributed Ledger Technology (DLT)

A distributed ledger is the technology that makes it possible for a record of information to be shared across a network of users and allows for the validation of new assets and transfers without the need for a trusted bookkeeper. Distributed ledger technology (DLT) refers to a set of protocols and infrastructure that simultaneously enables validation, access, and record updating in a networked database. When we say validation, we mean the processes and protocols used to verify the authenticity, integrity, and accuracy of data or transactions in a distributed ledger (Frankenfield, 2023b). The main innovation that DLT introduces is the ability to distribute the validation of the recording of new assets and their subsequent transfer among a set of users. They are responsible for ensuring that only legitimate transactions are added to the distributed ledger and that all network participants agree on the ledger's state. This technology enables users to participate in the validation process, no matter their probable conflicting motives. As is generally the case with crypto-assets, the network of users may not be restricted, which allows taking part in the validation of any user without requiring proof of identity. To validate transactions on a DLT network, a voting process is utilized among network users, where the user's voting power is determined by the specific protocol being used. Utilizing a protocol voting process should prevent the formation of coalitions that could potentially take control of the network (Chimienti et al., 2019).

However, Unrestricted DLT networks, commonly used for recording crypto-assets, lack clear governance. Consequently, the only available tool for governing the ownership of these assets is typically distributed validation. That poses a challenge to crypto-asset usability, as coordinating any changes becomes difficult due to the validation mechanism's aim of preventing a single user or a small coalition of users from modifying the content and operation of the distributed ledger. Even if a sufficient number of users agree to update the protocol, other users can decide whether to accept the new rules or stick with the old ones. If this occurs, a "fork" may emerge, resulting in two sets of users who rely on distinct information on individual holdings, which may never be reconciled (Chimienti et al., 2019).

On this point, it is imperative to highlight that any assets in digital form can be recorded on a distributed ledger without altering their economic and legal characteristics. Therefore, the same regulations could apply to both their DLT and non-DLT counterparts. Regulatory scrutiny is warranted for assets, regardless of whether they are recorded on a distributed ledger or not, as their economic characteristics and associated risks remain the same. Assets representing a claim on a specific entity do not fall under the definition and analysis of crypto-assets, no matter the technology they use for bookkeeping. That excludes electronic money, financial instruments, funds, central bank money in the form of cash or reserves, and the theoretical concept of a central bank digital currency (Chimienti et al., 2019).

As a reader, one may question why we are discussing distributed ledgers instead of blockchain, which is commonly associated with crypto-assets (cryptocurrencies). That is because not all crypto-assets utilize blockchain as their underlying technology. Blockchain is only a specific type of distributed ledger; some crypto-assets use a different type as their technology. For instance, IOTA is a crypto-asset that uses a directed acyclic graph (DAG) instead of a traditional blockchain. However, due to the limited number of crypto-assets using a different type of distributed ledger, we will focus on blockchain to understand how transactions are generally processed in practice (Bitstamp, 2022).

2.2.2 Blockchain

There are many definitions of blockchain, depending on which perspective we look at it. However, we are going to define it as follows.

Definition: Blockchain, at its core, is a peer-to-peer distributed ledger that is cryptographically secure, append-only, immutable (extremely hard to change), and updateable only via consensus or agreement among peers (Bashir, 2017, p. 16).

In a simplified explanation, blockchain is essentially a type of database or record of information shared among a network of users (Chimienti et al., 2019). Unlike a traditional database, a blockchain consists of blocks designed to store sets of information, with each block having a specific storage capacity. One of the primary distinctions between a traditional database and a blockchain is the data structure utilized. While databases arrange their data in tables, blockchains arrange it in blocks. Blocks are comprised of a collection of transactions that are grouped logically, and the size of a block can vary depending on the blockchain's type and design. Generally, a block contains a reference to the preceding block in the chain, except for the first block, known as the *genesis block*, which is hardcoded when the blockchain is created. The precise structure of a block may vary. However, certain elements are fundamental to its operation, including a block header, pointers to the previous block, a timestamp, a nonce, a transaction counter, and the transactions themselves (Bashir, 2017, pp. 16-24). When a block is filled, it is closed and linked to the previous block in the chain, creating a chain of data. Each block in the chain is given a specific timestamp when added to the chain, and once filled, it becomes an immutable component of the timeline. Immutability is a defining characteristic of decentralized blockchains, which ensures that any data entered into the blockchain cannot be altered (Hayes, 2022). To better understand the general structure of a blockchain, a reader can refer to the following illustration.

Figure 1: Blockchain Structure

Source: Adapted from Bashir (2017)

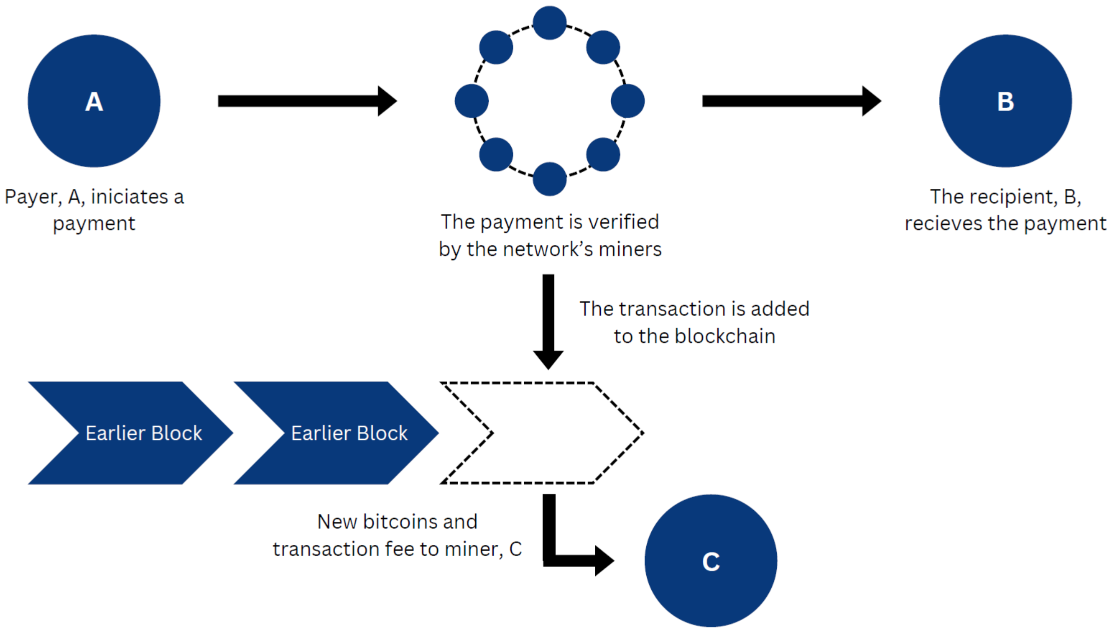
However, how does a new block get accumulated on the blockchain? The process of accumulating blocks in a blockchain can be broken down into several steps.

1. First, a node (network stakeholder) initiates a transaction by signing it with its private key.
2. The transaction is then spread to peers using the protocol, which validates the transaction based on predetermined criteria. Validation typically requires multiple nodes.

3. Once validated, the transaction is included in a block, which is then transmitted throughout the network. At this stage, the transaction is confirmed.
4. The newly produced block is added to the blockchain, and the next block is cryptographically linked to it using a hash pointer. At this point, the block receives its first confirmation, and the transaction gets a second confirmation.
5. As new blocks are created, transactions are continually reconfirmed every time. In the case of the Bitcoin network, six confirmations are typically required for a transaction to be considered final.

Although steps 4 and 5 are not mandatory for confirmation of the transaction, they are used for further transaction reconfirmations and block confirmation (Bashir, 2017, p. 24).

Figure 2: Overview of the Blockchain Process



Source: Adapted from Gerba & Rubio (2019).

2.2.3 Cryptography

Cryptography, a core element of crypto-assets, comes into play in accumulating new blocks into the blockchain. It is a crucial aspect of blockchain technology, providing the security and immutability that sets it apart from traditional databases. A digital signature is a cryptographic mathematical algorithm that verifies the authenticity of a message, ensuring that it has not been changed during transmission. The transactions on a blockchain are secured using digital signatures, making it possible to associate a message with an entity from which it originates. For generating a digital signature, private and public keys are needed.

A *private key* is a unique, randomly generated number kept private by the owner. If another entity acquires the private key, the public key cryptography is made vulnerable, as this key is used to decrypt messages. On the other hand, the *public key* is the counterpart of the private key and is shared publicly by the private key owner. If someone then wishes to send the publisher of the public key an encrypted message, they can do so by encrypting the message using the published public key and sending it to the owner of the private key. The owner of the private key can then decrypt the message using the private key they securely hold. At the same time, nobody else can decrypt the message because they cannot access the private key.

Every user (node) on the network has a public and private key. The private key is used to sign transactions, while the public key is used to verify the signature. When a node initiates a transaction, it signs it with its private key and broadcasts it to the network. The other nodes on the network can then verify the transaction using the sender's public key. As the signatory keeps the private key secure, the authenticity of the signed data signature is ensured. The digital signature ensures the transaction is authentic, and the cryptography makes it impossible for anyone else to alter the transaction without the private key. That is because the signature is unique to the transaction and cannot be generated using any other private key. If someone tries to tamper with the transaction, the signature will no longer match the original, and the network will reject the altered transaction.

Another critical aspect of blockchain technology cryptography is the use of *hash functions*. A hash function takes a data input and produces a fixed-size output (hash). The output is unique to the input, and even a tiny change in the input data will produce a completely different hash. In a blockchain, every block contains a hash pointer to the previous block in the chain, ensuring the chain's integrity. When a new block is added to the chain, its hash pointer includes the hash of the previous block in the chain. If someone tries to alter a previous block, the hash pointer in the subsequent blocks will no longer match, and the network will reject the altered block. That makes it extremely difficult to change any data on the blockchain since it requires changing all the subsequent blocks in the chain.

In examining blockchain technology, we have come to understand the pivotal role cryptography plays. It provides the necessary security and immutability for maintaining a trustless, decentralized network. The features of digital signatures and hash functions are instrumental in guaranteeing the authenticity and integrity of transactions and blocks within the chain. Having unpacked blockchain technology to this extent, we now possess a foundational understanding of its workings, mainly how it facilitates transactions for crypto-assets. However, It is worth emphasizing that exploring blockchain technology is far from exhaustive. The discussion in this chapter represents merely a scratch on the surface of this complex, highly sophisticated technology.

The primary focus of this research is not to navigate the depths of blockchain technology’s technical intricacies. Instead, we aim to comprehend its underlying mechanisms clearly enough to explore crypto-assets as a distinctive asset class and understand their theoretical operation. With this understanding in place, we can now transition the discussion towards examining how crypto-assets fulfill the fundamental role of money.

2.3 Crypto-Assets and the Fundamental Role of Money

At the beginning of this chapter, we mentioned that crypto-assets have limitations when classifying them as currency (a form of money), which is why entities such as the ECB avoid using the word "cryptocurrency." Now let us examine why this is a case for crypto-assets, and their name can be misleading. To fully understand money and the role of digital currencies like crypto-assets in this aspect, it is essential to define the functions of money in an economy. While there is no unified definition of money due to various debates among economic schools, functions of money are (mostly) agreed upon. These functions can be divided into three layers: primary, secondary, and tertiary (Gerba & Rubio, 2019).

2.3.1 Functions of Money

The primary functions of money include its use as *a medium of exchange* and a *measure of economic value* (unit of account). The secondary functions relate to its role as a *store of value* and a standard for payments. The tertiary layer reflects its contingent functions, such as its use as a basis for credit or a source of liquidity for wealth (Gerba & Rubio, 2019).

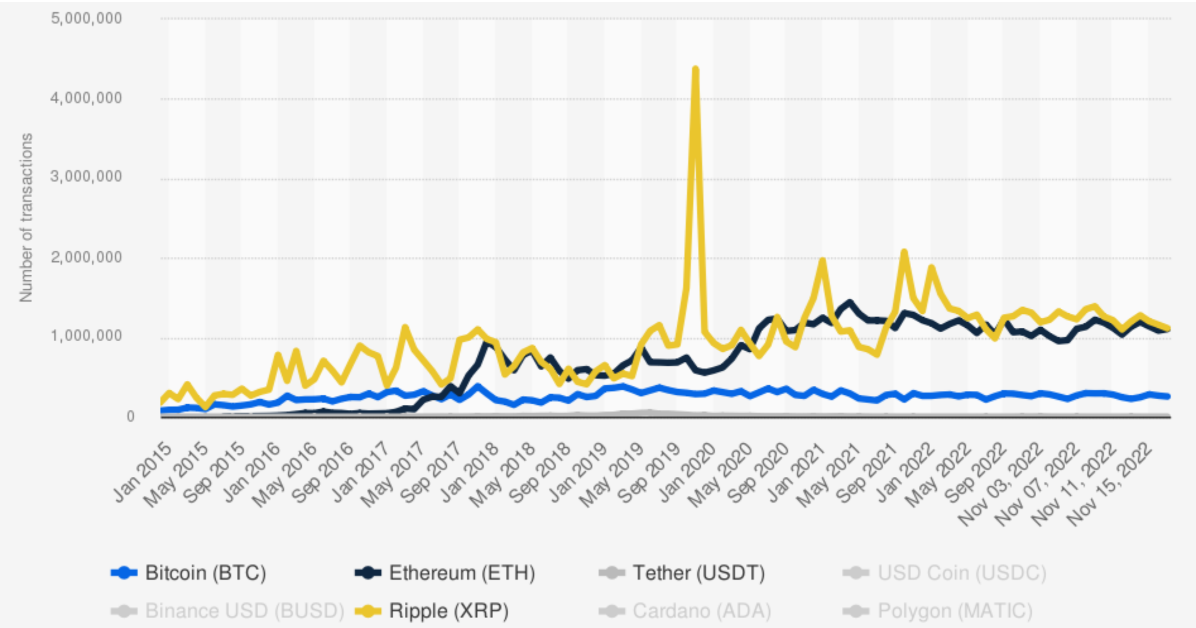
We will examine how crypto-assets meet the functions of money on primary and secondary levels, which are the most essential. Whether crypto-assets can be classified as money depends on their ability to perform the functions that traditional money is capable of. Additionally, if crypto-assets are considered money, assessing the extent to which they are utilized and how they may affect the economy is crucial. Whether they can be regarded as money has not been studied extensively, with conclusions suggesting that, theoretically, crypto-assets can serve as money for anyone with internet access. However, in practice, this function is limited to a small number of people and is used alongside traditional currencies. Based on the limited evidence available, crypto-assets are primarily seen as a store of value rather than a medium of exchange. There is also little indication that crypto-assets are being used as a unit of account (Gerba & Rubio, 2019).

Medium of Exchange

This function of money facilitates the buying and selling of goods and services, eliminating the need for a double coincidence of wants, a problem that can occur in bartering. For example, a person who wants to sell a goat in exchange for potatoes can sell it for money (currency) and then use it to purchase potatoes.

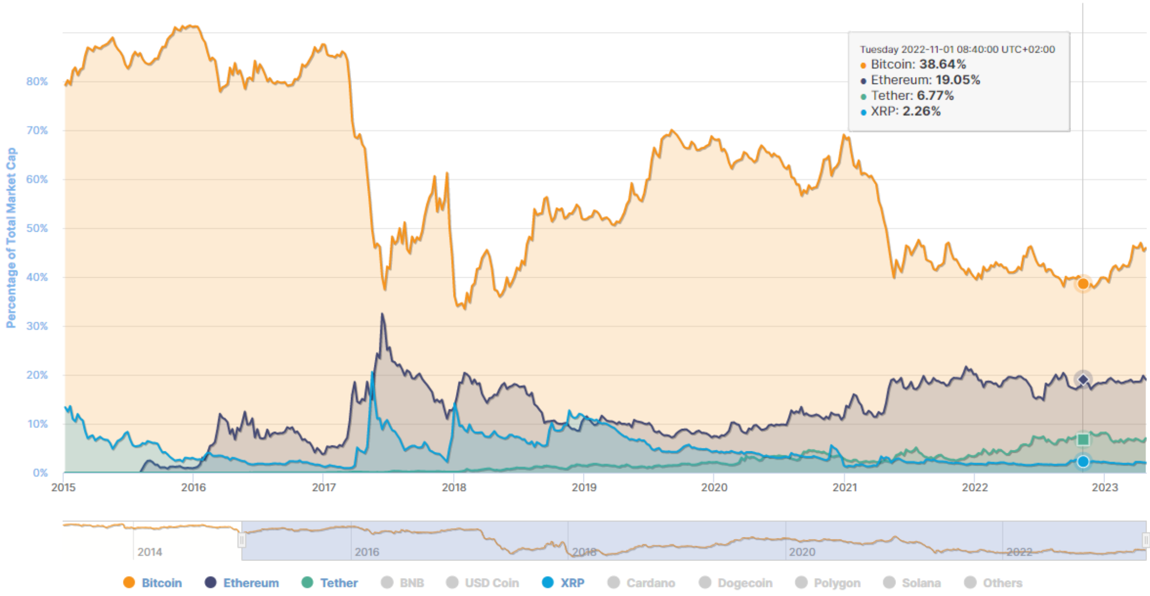
As long as retailers are willing to accept a currency as payment, it can be used as a medium of exchange. Although the number of retailers accepting crypto-assets worldwide is growing, this does not necessarily mean the currency will be widely used. To determine if a crypto-asset is indeed a medium of exchange, it is vital to monitor the number of transactions conducted in that currency over time (Gerba & Rubio, 2019). The following two figures show the daily transactions from 2015 to 2022 for all the most recognized crypto-assets and their market share on the crypto-asset market, respectively. The number of transactions is slowly increasing, but it is far from significant acceptance. For comparison, the total number of non-cash payments in the euro area in 2021 was 114 billion. That makes it, on average, 312 million daily non-cash transactions (European Central Bank, 2022).

Figure 3: Number of daily transactions on the blockchain in Bitcoin, Ethereum, Ripple, and Tether



Source: Statista (2023a).

Figure 4: Market share of Bitcoin, Ethereum, Tether, and Ripple



Source: CoinMarketCap (n.d.a).

Measure of Value (unit of account)

Money expresses the value of various commodities, and this measure is universally accepted and standardized. Transactions become simple and quick, with money serving as a unit of account (which means it can be used to value goods and services, record debts, and make calculations).

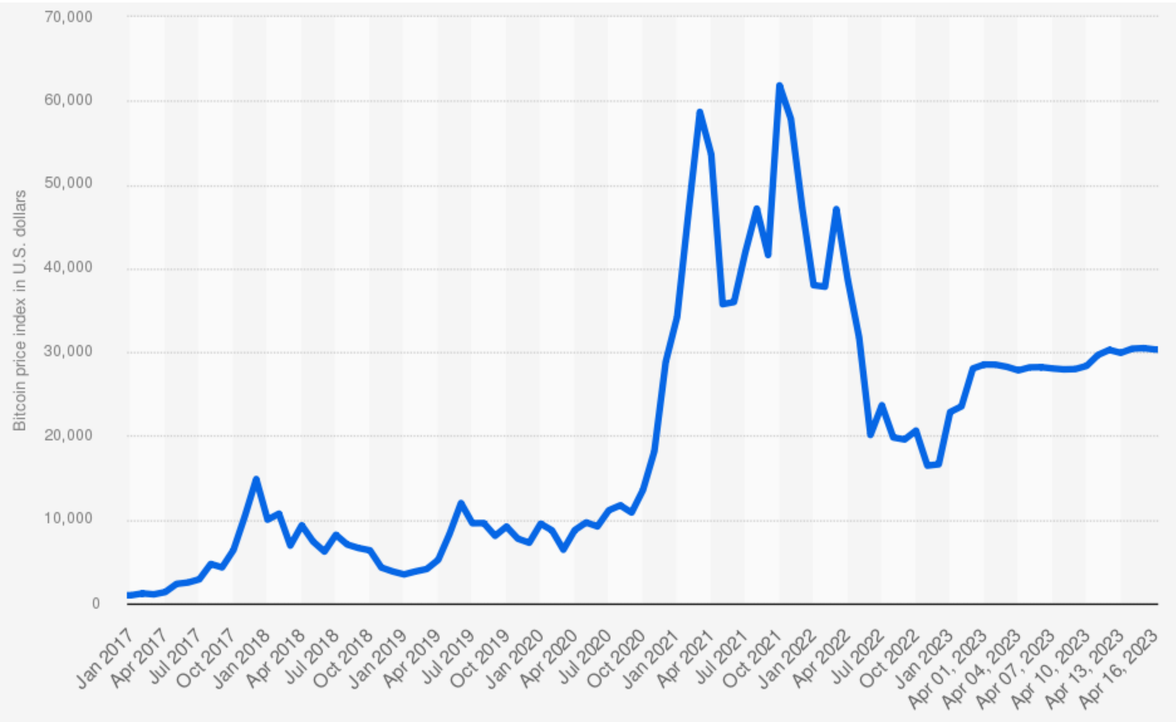
There is minimal proof that any crypto-asset is being used as a unit of account. The high volatility of exchange rates for crypto-assets makes it challenging to become a functional unit of account. For instance, the value of a Bitcoin compared to other traditional currencies varies significantly daily, forcing retailers to recalculate prices frequently, which can be confusing and costly. The uncertain market value of crypto-assets makes it tricky to use them as a reliable reference point for establishing consumer prices. Additionally, brokers and merchants often quote prices in three or more decimal places, which can be disconcerting for consumers, although it should not pose any mathematical difficulty (Gerba & Rubio, 2019). For example, as of today, 28 April 2023, \$10 equals $0.00034BTC$ (sign for Bitcoin).

Store of Value

Money is considered a store of value because it allows individuals to save money for future consumption. As a claim, it connects current and future times and is the most convenient way to claim goods and services. Because of this, many prefer to store their wealth as money instead of non-liquid assets such as stock shares or houses. Currency, or cash, is the most liquid form of an asset as it can be exchanged for goods and services cheaply and immediately. While other assets such as bonds, savings accounts, and real estate can serve as stores of value, they differ in liquidity.

To analyze the use of crypto-assets as a store of value, we must consider both the short and long term. In the long run, people's expectations about future supply and demand play a crucial role. While the supply of crypto-assets is assured due to their algorithmic production, demand, on the other hand, is uncertain. Public belief in the continued demand is vital for them to function as a store of value, which makes them perform this function questionably. However, in the short term, the high volatility of crypto-assets compared to traditional currencies makes them a poor store of value. Managing and ensuring security for digital wallets is also a significant issue for digital currencies as a store of value (Gerba & Rubio, 2019). While security is also concerned for traditional currencies such as the Euro, bank attacks and scams are less frequent. Also, in most cases, the bank ensures the safety of owners' assets. They compensate the loss if it is not the owners' fault, while an attack on a crypto exchange or its failure usually affects the asset owner directly. The following figure is a graph of Bitcoin price movement, showing its massive price fluctuations since January 2017.

Figure 5: Bitcoin (BTC) price per day from Jan 2017 - Apr 2023 in US dollars



Source: Statista (2023b).

2.3.2 Can Crypto-Assets be Classed as Currency?

Based on the analysis above, crypto-assets do not fully meet the criteria for functioning as money in the economy. It is unlikely that crypto-assets in their current form will become the main form of money in the economic system due to several issues, such as lack of familiarity with the technology, unfriendly user applications, safety concerns, and high volatility in exchange rates. Unlike traditional money, crypto-assets are not a central bank liability and can be considered a commodity, but they are intangible and only function with the user agreement. Although this difference is not an obstacle to functioning as money, it sets them apart from physical cash and notes (Gerba & Rubio, 2019).

2.4 Risks of Crypto-Assets

In examining entrance into a new market, it is crucial to evaluate its inherent risks and potential benefits carefully. This careful consideration is necessary to ensure that the investors' or traders' objectives align with the possible outcomes of the new investment environment. Understanding these factors places the potential investor in a powerful position to determine the appropriateness of expanding their investment portfolio into this emerging market. While presenting untapped potential, crypto-assets pose many risks to investors and traders.

Extreme Price Movements

Crypto-assets are highly speculative and subject to sudden and drastic price swings. Investors should carefully manage their risk exposure and be prepared for the possibility of losing a significant amount or even all of their invested money in a short period of time (EIOPA, 2022).

Misleading Information

Some crypto-assets and related products are advertised to the public using unclear, incomplete, inaccurate, or purposefully misleading information. Social media influencers may be biased in their communications, focusing primarily on the possibility of extreme gains and not focusing enough on the risk associated with the investment (EIOPA, 2022).

Absence of Protection

Many crypto-assets and related products or services are currently unregulated in the EU, so investors may not enjoy the same level of consumer rights and protections as they would with regulated financial services. That includes the lack of access to complaints or recourse mechanisms (EIOPA, 2022).

Fraud and Malicious Activities

Numerous fake crypto-assets and scams exist with the sole purpose of depriving an investor of their money using different techniques such as phishing. That is why investors must be highly cautious when entering the crypto-assets market to ensure they do not get involved with such scams (EIOPA, 2022).

Market Manipulation

Determining crypto-asset prices and executing transactions at exchanges can lack transparency, leading to market manipulation, low liquidity, and unequal treatment when buying or selling certain crypto-assets. In addition, holdings of some crypto-assets may be highly concentrated, further impacting prices or liquidity. Therefore, buyers and sellers of crypto-assets may face challenges in getting a fair price or treatment and may be unable to sell their assets quickly if there is no potential buyer. Market manipulation has been reported multiple times, highlighting the need for caution and diligence when dealing with crypto-assets (EIOPA, 2022).

Security Issues

Various issuers and service providers for crypto-assets, such as crypto exchanges and wallet providers, have encountered cyber-attacks and severe operational issues. Due to such attacks and disruptions, many consumers have lost their crypto-assets or suffered losses. Additionally, the loss of private keys used to access crypto-assets has caused people to lose their investments (EIOPA, 2022).

2.5 Benefits of Crypto-Assets

Despite the inherent hazards affiliated with crypto-assets, it is essential to recognize their prospective advantages, especially regarding investment or trading opportunities.

Decentralization

One of the primary benefits of crypto-assets is that they are decentralized, meaning they are not subject to the control of a central authority, such as a government or a financial institution. Thus, the possibility of a single point of failure is eliminated (Frankenfield, 2023a).

Accessibility

Anyone with an internet connection can access crypto-assets, allowing global market participation. Unlike traditional financial markets, which may be limited to specific geographic regions, the crypto-assets market is open to anyone worldwide (Frankenfield, 2023a).

Speed and Efficiency

Crypto-assets can offer faster and more efficient transactions than traditional financial systems. Transactions can be completed in minutes or even seconds, compared to the days or weeks it can take for traditional financial transactions to be processed. That is very convenient for individuals or institutions that need to transfer money quickly to another entity for whatever reason (Frankenfield, 2023a).

24/7 Trading Environment

An often overlooked benefit of cryptocurrencies is their trading environment, which is open every day of the week and never closes. While this may challenge some investors or traders, it allows everyone to participate in trading activities whenever they want. Because of this, there is no need to wait for any transfer of assets for any reason at any time (Nibley, 2022).

Lower Transaction Fees

Crypto-assets can (and usually do) offer lower transaction fees than traditional financial systems. That can be especially beneficial for individuals or institutions that make frequent or small transactions (Nibley, 2022).

Potential for High Returns

Crypto-assets can be highly volatile, which means they can also offer the potential for high returns for investors willing to take on the risks presented earlier (Nibley, 2022).

2.6 The Classification under Markets in Crypto-Assets (MiCA)

The crypto-assets market has grown in recent years, attracting investors and regulators alike. As mentioned in previous chapters, crypto-assets are a relatively new type of asset; thus, regulators have not yet reached a consensus on how to regulate the asset. That means subdividing the crypto-assets into different categories is still relatively undefined and changes from country to country. Furthermore, the crypto-assets market is still developing rapidly, and new types of assets are coming each year, making constructing a regulation framework extremely difficult. However, the European Union has proposed the Markets in Crypto-Assets (MiCA) regulation to establish a comprehensive regulatory framework for all crypto-assets. There has been a Plenary green light on 20 April 2023, with 517 votes in favor to 38 against and 18 abstentions, to new common rules on the supervision, consumer protection, and environmental safeguards of crypto-assets (European Parliament, 2023)

This chapter explains the classification of crypto-assets under the MiCA regulation, how it connects with the ECB definition of crypto-assets, and how it applies to Bitcoin. The regulation concerning Crypto-Assets Markets aims to address specific categories of crypto-assets that fall beyond the scope of existing regulations. That excludes non-fungible tokens

(NFTs) and security tokens that meet the requirements of financial instruments under the Markets in Financial Instruments Directive and Regulation (MiFID). The regulation also establishes a legal framework for providers of crypto-asset services and emphasizes consumer protection as a main priority (Boucheta & Joseph, 2023).

According to the European Central Bank (ECB), the definition of crypto-assets at the beginning of the chapter emphasizes that crypto-assets are not issued by any central authority or identifiable entity and are not backed by any underlying asset. The definition does not focus on the technology used for bookkeeping these assets. This perspective contrasts the European Commission's definition in the proposed Markets in Crypto-Assets (MiCA) regulation.

> **Definition**: "crypto-asset" means a digital representation of value or rights which may be transferred and stored electronically using distributed ledger technology or similar technology (European Commission, 2020).

The divergent definitions can be partially attributed to the MiCA definition, which encompasses only assets not yet encompassed within another regulatory framework. It also emphasizes someone's "right" instead of evaluating whether they serve as a financial claim.

The MiCA regulation proposes a classification of crypto-assets into three types:

1. Asset-Referenced Tokens
2. Electronic Money Tokens
3. Utility Tokens

Let us look at what these three types of crypto-assets mean, their main examples, and how we can classify the most known crypto-asset, Bitcoin, into these categories. The regulations will differ depending on which classification the crypto-asset will fall under. However, the regulations have become highly complicated, so we will not discuss them in detail.

2.6.2 Asset-Referenced Tokens (ART)

> **Definition**: 'asset-referenced token' means a type of crypto-asset that purports to maintain a stable value by referring to the value of several fiat currencies that are legal tender, one or several commodities or one or several crypto-assets, or a combination of such assets; (European Commission, 2020).

Asset-referenced tokens are tokens designed to maintain a stable value by referencing the value of several currencies, commodities, crypto-assets, or a combination of such assets. Examples of asset-referenced tokens include Tether (USDT), USD Coin (USDC), and Dai (DAI).

2.6.3 Electronic Money Tokens (EMT)

> **Definition**: "Electronic money token" or "e-money token" means a type of crypto-asset, the main purpose of which is to be used as a means of exchange and that purports to maintain a stable value by referring to the value of a fiat currency that is legal tender; (European Commission, 2020).

Electronic money tokens are tokens designed to be used as a means of payment, like traditional electronic money, and are accepted by entities other than the issuer. An example of an electronic money token is the e-money token at PayPal. For clarification, the currency is not technically transferred when making a payment through PayPal. Instead, users of PayPal obtain e-money tokens, which are then transmitted to the recipient. The recipient can then exchange this e-money token into currency (Deloitte, n. d.).

2.6.4 Utility Tokens

> **Definition**: 'Utility token' means a type of crypto-asset which is intended to provide digital access to a good or service, available on DLT, and is only accepted by the issuer of that token (European Commission, 2020).

Utility tokens are tokens that provide access to a product or service, either now or in the future, that is typically provided using distributed ledger technology. The Basic Attention Token (BAT) is an example of a utility token.

2.6.5 Application of MiCA Regulation to Bitcoin

MiCA does not provide a specific definition for the term "token." However, a token can be understood as a digital representation of an interest that may hold value, a right to receive a benefit, perform specified functions, or not have a specified purpose or use. This broad understanding of tokens allows for other types of tokens beyond those that have been elaborated under the MiCA classification. For example, there could be a token that uses cryptography for security, provides digital access to a good or service, does not maintain a stable value, and is accepted by entities other than its issuer. This example shows that the categories defined under MiCA do not cover every possible aspect. With the token from the example, we do not know if it falls into MiCA regulation or not. Suppose such a token falls under the broad definition of crypto-assets and, at the same time, does not fall under any exclusions outlined in MiCA. In that case, it will be subject to MiCA's regulatory regime and otherwise not. The regulation of crypto-assets such as Bitcoin, which does not have an issuer or has a decentralized issuer, raises further questions on how MiCA will regulate such residual crypto-assets. (Tomczak, 2022)

The classification of Bitcoin and several other crypto-assets under the Markets in Crypto-Assets (MiCA) regulation is currently unclear. While the proposal provides definitions and criteria for classifying different types of crypto-assets, the final determination of how specific assets will be classified will depend on how those definitions and criteria are ultimately interpreted and applied. Additionally, the classification of Bitcoin under MiCA may also be influenced by other factors, such as their specific use cases and the overall regulatory landscape in the European Union. While Bitcoin is not pegged to a specific asset or currency, it can be considered an asset-referenced token because its value is derived from the underlying blockchain technology, the strength of the network, and the demand from users and investors. In that case, it may be more likely for Bitcoin to be classified as asset-referenced tokens under MiCA. On the other hand, if regulators view it primarily as a utility token, they may be subject to different regulatory requirements. Ultimately, the specific classification of Bitcoin and other crypto-assets under MiCA will likely depend on various factors, and it may take some time for regulators to reach a final decision.

3 ARBITRAGE ON CRYPTOCURRENCY EXCHANGES

After conducting an exhaustive analysis of crypto-assets and their related risks and benefits, we have observed that long-term investment in these assets may not be the most rational choice. According to the definition of crypto-assets and what they represent in most real-world scenarios, they do not carry any financial claim or liability linked to a specific identifiable entity. Thus, the anticipation of a future price increase becomes rather unreasonable, given that their worth is strictly contingent upon supply and demand. Still, we believe that crypto-assets supply many short-term trading opportunities due to their highly volatile nature. While long-term investment in crypto-assets from a traditional perspective is primarily centered on realizing financial gains from price inflations, measures like short selling and crypto-asset derivatives offer alternatives. These alternate strategies allow us to place bets on market demands – in line with or against them. Consequently, we attempt to surpass competitors in the market. Rather than simply hoping for another individual's willingness to pay higher for these assets, we employ statistical conclusions to predict market movements more accurately. By analyzing specific parameters, we endeavor to determine the direction the market is more likely to lean.

As an investment class, crypto-assets are inherently different from traditional assets such as stocks, bonds, and commodities since they have no source of revenue other than money provided by the investors. For example, stocks have dividends, commodities have customers who buy them for their utility, and bonds have legal bindings with a promise of redemption with interest. Crypto-assets have none of those things. Moreover, miners' fees make crypto-assets a negative sum game (Stolfi, 2018). A negative sum game refers to a situation where the total losses outweigh the total gains, resulting in an overall net loss for the participants. That is because the only source of revenue for crypto-assets is money provided by the investors, and fees are deducted for miners to operate a network. Therefore, we must have a trading edge over other participants to justify entering the market. We must construct a trading strategy that statistically confirms that we are more likely to profit than create a loss.

If we do not have statistical data, we can still enter the market to trade, but then trading is more similar to gambling. Thus, it makes sense to analyze the market movement and construct trading strategies before starting to trade to have a higher likelihood of profit than loss.

This research will analyze an **arbitrage trading strategy** to get an edge over other market participants and generate a profit.

This chapter will focus on understanding the arbitrage opportunities we want to analyze for further trading. It will initiate by defining arbitrage opportunities and explaining how to recognize them. Additionally, requirements and limitations will be provided to participate in trading these opportunities. A simplified theoretical and a real-life example of arbitrage between cryptocurrency exchanges will be shown, with calculations and an in-depth explanation.

3.1 What is an Arbitrage Trading Strategy?

An arbitrage trading strategy is a process through which an investor earns a profit without bearing any risk. In this context, that is meant as traditional investment risks, which refers to the potential for financial losses connected with factors such as market fluctuations, economic conditions, regulatory changes, credit defaults, and other uncertainties that can affect the value and returns of investments (CFI Team, n.d.a).

> **Definition**: Arbitrage is a trading strategy in which an investor simultaneously buys and sells an asset in different markets to take advantage of a price difference and generate a profit (Stobierski, 2021).

We see that arbitrage opportunities occur when an asset is priced differently on multiple markets simultaneously. By trading arbitrage, we profit by taking advantage of price inefficiencies in financial markets. Via taking advantage of the inefficiencies, arbitrageurs (individuals trading arbitrage) can earn risk-free profits because the financial assets traded are equivalent. Consequently, arbitrageur results in greater market efficiency, causing asset prices to converge.

The most basic type of arbitrage involves buying an asset in a market where its price is lower and simultaneously selling the same asset in a market where its price is higher. While the market price differences are usually minimal, this can still generate a significant return if exercised many times. In traditional finance, arbitrage opportunities are often short-lived and scarce, as financial instruments and markets are highly regulated and efficient. A significant role here is that global banks and other entities provide substantial liquidity to the market and exploit arbitrage opportunities. These entities contribute to the price discovery process, help mitigate price discrepancies, and improve market efficiency (Anderson et al., 2021). However, the arbitrage landscape differs in the crypto-asset decentralized world. Crypto-assets markets are highly fragmented and operate 24/7 without a central authority and often without strong regulatory oversight. As a result, crypto-asset prices can vary widely across multiple exchanges, where each exchange has its order books and liquidity. Nonetheless, the arbitrage landscape in any market is highly competitive, where profits can evaporate quickly due to market volatility, trading fees, network congestion, or technical issues.

While arbitrage opportunities can offer profit potential, they are not entirely risk-free. There are certain risks associated with arbitrage trading, including:

> **Connection Risk**: The risk of losing or experiencing disruptions in connection with a (cryptocurrency) exchange while trading. It may result in the inability to execute trades, access account information, or fill trades on time, potentially leading to missed opportunities or financial losses.

> **Regulatory and Legal Risks**: Arbitrage strategies may be subject to regulatory restrictions or limitations, and there is a risk of non-compliance with applicable laws and regulations.

Even though we will analyze trading “arbitrage” opportunities, in this research, we must also hold a portfolio of crypto-assets for trading them (which will be elaborated on later). Therefore, we put ourselves at another risk by holding a portfolio of highly volatile assets that have at least questionable backing in most cases.

> **Market Volatility Risk**: The risk associated with holding crypto-assets due to the high price volatility in the crypto-assets market. It can lead to substantial fluctuations in the portfolio's value and potential financial gains or losses for investors.

It is necessary for investors to carefully assess and manage these risks when engaging in arbitrage trading. While the strategy aims to exploit price inefficiencies, it does not eliminate all forms of risk.

3.1.1 Arbitrage in Our Context

In practice, there are many types of arbitrage; when discussing it, it can often become unclear which type of trading we are talking about. This research will discuss a specific type of arbitrage called *triangular arbitrage*.

> **Definition**: *Triangular arbitrage* is a process or strategy used in financial markets to exploit discrepancies in exchange rates across three (or more) different currencies to make a risk-free profit. It involves making three (or more) currency trades, hoping the result will yield more than the original amount (CFI Team, n.d.b).

We can look at these specific arbitrage types in crypto markets because we can exchange one crypto-asset for another just as in traditional currencies (Foreign Exchange market).

Furthermore, we rarely find arbitrage opportunities in practice as described in academic models. More often than not, the arbitrageur must provide some money to execute the trades and exploit arbitrage opportunities. We start talking about *risk arbitrage* as a consequence of providing money to execute trades (this can be simplest to imagine as money needed for purchasing futures contracts) (Shleifer & Vishny, 2012).

> **Definition**: *Risk arbitrage* is a strategy requiring an initial investment to exploit market inefficiencies with an acceptance of possible losses due to changing market conditions (Shleifer & Vishny, 2012).

This form of arbitrage implies that an arbitrageur will not always profit and might require significant financial resources to conduct his trades and offset potential losses. A considerable portion of real-world arbitrage transactions in bond and equity markets serve as instances of risk arbitrage in this context. Contrary to the academic model, *risk arbitrage* poses risks and necessitates capital allocation (Shleifer & Vishny, 2012).

> **Note**: Even though we will be using the term *arbitrage* throughout the research, we have to keep in mind that we are, in fact, talking about *triangular risk arbitrage*.

3.1.2 Arbitrage on Traditional Markets

The most commonly employed market for executing the arbitrage trading strategy detailed in this research, namely *triangular (risk) arbitrage*, is the Forex (Foreign Exchange) market. The primary rationale behind this choice is inherent in the characteristics of traditional currencies that can be exchanged directly for one another, analogous to crypto-asset trading. This direct exchange of currencies positions the Forex market uniquely for arbitrage, unlike stock, commodities, or bond markets, where securities can only be bought via currency and cannot be directly traded for other securities. In these markets, buying or selling assets is majorly done through currencies. Direct exchange of one company's stock for another is not commonplace, hence rendering this kind of arbitrage less feasible (Chen, 2023)

The decision to select the crypto-asset market as the centerpiece for this thesis instead of the traditional Forex market is strongly underpinned by two principal factors.

1. Firstly, the crypto-asset domain is characterized by increased data accessibility due to its superior quality of application programming interfaces (APIs). These digital tools facilitate the data extraction process, subsequently simplifying its analysis. That is crucial for comprehensively examining and understanding market trends, movements, and other relevant phenomena within the field. Moreover, the real-time data is provided for free and does not incur significant costs with data gathering. This feature offers a superior platform to delve into data exploration and research conclusively.

2. Secondly, the unique ecosystem of the crypto-asset market is largely unregulated, mainly with a high degree of volatility. This lack of comprehensive regulatory oversight and price instability captivates the interest of researchers and investors alike. This combination of instability and decentralization offers an attractive avenue for in-depth investigation and intrigue, making the crypto-asset market a compelling choice for this research.

In summary, while the Forex market often serves as the primary backdrop for triangular arbitrage due to direct currency exchanges and their volume, these strategies can likewise apply to crypto-asset markets. The structure of this market facilitates easier and cost-effective data gathering and more significant price fluctuations that can lead to more apparent arbitrage opportunities. Thus, this study aims to identify and "exploit" such opportunities in crypto markets, an area marked by constant evolution and increased data accessibility. By researching this domain, we boost our understanding of arbitrage strategies in the ever-growing field of crypto-assets.

3.2 How to Detect an Arbitrage?

In the trading process, orders are the fundamental building blocks, laying the foundation for potential trades. To detect an arbitrage on any given market, we must gather orders for the assets between which we want to look for arbitrage opportunities. It is essential to understand the concept of an **order book**, which displays **all open orders** for a specific financial instrument as posted by market makers and other participants. By studying the order books, traders can analyze the bid-ask spread, search for arbitrage, and assess market liquidity by examining bid and ask volumes.

Due to market participants' varying opinions regarding a financial instrument's fair price, there are active buy (bid) and sell (ask) orders on the order book at different price levels. The best **bid** represents the highest price a **buyer is willing to purchase** the instrument, while the best **ask** represents the lowest price a **seller is willing to sell**. The **bid-ask spread** denotes the difference between the best bid and the best ask price. **Bid volume** tells us the amount of an asset market participants are willing to buy at a quoted price, and **ask volume** tells us the amount of an asset market participants are willing to sell at a quoted price. Let us look at the following figure to visualize some of the concepts used (Optiver, 2023).

Figure 6: Order Book Example

Source: Adapted from Optiver (2023)

Let us assume that the order book in the upper figure is for $BTCUSD$ in 2013 (trading pair of Bitcoin and the United States dollar). In the $BTCUSD$ pair, BTC is the base asset (also known as the referenced asset or the asset being traded), and USD is the quote asset (also known as the currency used for valuation or the asset used to determine the price of the base asset). The volume quoted is always in the base asset. The best ask price, which is the best price we can buy Bitcoin at, is $\$44.62$, and there are 146 BTC available at this price. The best bid price is $\$44.60$, so we can sell Bitcoin at this price, and the market participants are willing to buy 122 BTC. The spread on this exchange is retrieved from calculating $bid - ask$ price, which is $\$44.62 - \$44.60 = \$0.02$.

In order to determine the best bid and best ask prices, it is necessary to gather all the prices and quantities at which market participants are willing to trade. All this information is typically consolidated in the order book, which contains a record of all outstanding limit orders posted by participants on an exchange. There are many possible types of orders. However, we will focus only on the two most important, the only ones we need for trading strategy.

> **Limit Order**: an order to buy or sell a financial instrument at a specified price or better, and if it is not immediately executed, it remains on the order book until it is matched or canceled.

With a limit order, investors specify a maximum price (for buying) or a minimum price (for selling) at which they are willing to transact. This order type helps mitigate the risk of unexpected prices. Unlike market orders, execution is not guaranteed immediately, and any unexecuted limit orders remain in the order book. With limit orders, we provide liquidity to the market.

> **Market Order**: an order to buy or sell a financial instrument at the best price currently available in the order book.

Market orders are used by investors who want an immediate execution, although the specific price at which the trade is executed is not guaranteed. With market orders, we remove liquidity from the market. That is the type of order we will use in trading strategy, as we want to execute a trade as soon as we see profitable price discrepancies. Note that if we **buy** an asset with market orders, we will fill the **best ask price** since this is the lowest price at which market participants are willing to sell an asset. If we **sell** an asset with a market order, we will fill the **best bid price** since this is the highest price at which participants are willing to buy an asset.

An important aspect of trading is also order execution provided by the exchange. Price-time priority is a common mechanism used in order books to determine which orders get executed first. The best bid price in the example order book is $44.60, meaning it takes precedence regardless of arrival time. However, in cases where multiple orders share the same price, the order that arrived first is given priority for execution. When a buy order matches a sell order at the same price, a trade occurs, completing the transaction between the parties involved (Optiver, 2023).

3.2.1 Searching for Price Discrepancies

We focus on limit orders in analyzing order books for potential price discrepancies. These orders represent prices that are assuredly available in the market until either the order is canceled by the market participant or filled by others. To capitalize on price discrepancies, we decided to use market orders. While this could potentially result in less favorable prices than initially anticipated, it ensures that all orders are indeed executed. That is due to portfolio limitations, which will be explained later.

Suppose we are the first to execute the market order as we spot an arbitrage opportunity. Consequently, we will fill the best limit order in the order book, and arbitrage will be profitable. However, if someone executes an order faster than us or the limit order is canceled before our market order gets filled, we will be filled with the remaining limit orders in the order book. Because of the risk that we will not be the first to execute the order, we can define a benchmark of what the minimum profit we have to gain to trade arbitrage is. The higher this benchmark is set, the less likely we will create a loss.

For example, if there is arbitrage with only the best bid price in the order book, we will generate a loss if we do not fill this order. However, suppose imbalances are more significant, and the four best bid prices in the order book enable arbitrage. Then, even if we miss the first two and get filled by the third, we will still generate a profit, even though we got worse prices than anticipated. Interconnected with this is the volume for each price that arbitrage is possible for. If the volume for arbitrage is massive, then the likelihood we will not be filled on this price is smaller than if the volume is low, and it gets filled by only a few participants trading faster than us.

Theoretically, we could use limit orders to trade arbitrage. For it to be filled, we would specify the same price as the best possible price in the order book. However, a trade will not be executed if the order in the order book gets filled before our limit order gets through and the price moves in the opposite direction. Therefore, we could end up with too much of one asset and less of another asset since we bought the first one; however, our limit order for the second one was not executed (or vice versa).

3.2.2 Liquidity and Order Books

An important part of the financial market also plays liquidity. Liquidity refers to the ease with which a financial instrument can be bought or sold at a stable price. Various metrics are used to measure liquidity, and there is no single superior measure as each metric serves a different purpose. These metrics include the total volume traded or turnover, the volume of orders displayed on the order book at a specific time, and the bid-ask spread. While financial instruments are generally classified into liquidity categories ranging from highly liquid to highly illiquid, it is crucial to understand that liquidity is not stationary and can change over time due to shifts in market sentiment or specific events. Market makers, also known as liquidity providers, are crucial in enhancing market liquidity for a particular financial instrument. These market participants continuously quote both buying (bid) and selling (ask) orders, thereby supplying liquidity to the market.

It is not unusual for liquidity to vary between different listings of the same asset. For example, consider a medium-sized Slovenian company with a primary listing on the Slovenian market and a secondary listing on a foreign exchange. The primary listing typically exhibits high liquidity and substantial average daily trading volume, with numerous active participants. Conversely, the foreign exchange may have limited trading activity, with few participants actively trading the instrument. On certain days, trading activity may be extremely low or even non-existent. This lack of liquidity on the foreign exchange increases the risk for participants trading in that market, as they may be compelled to execute trades at unfavorable prices (Optiver, 2020). That plays a significant role in the crypto-asset market since liquidity can often be an issue on smaller cryptocurrency exchanges. That is one of the reasons the order books on different exchanges are not synced, which brings us to arbitrage opportunities if the differences between exchange rates are greater than the fees paid for trade executions.

3.2.3 Arbitrage Detection in Order Books

To detect an arbitrage, we must gather the order books for the assets between which we want to look for arbitrage opportunities. To get order books from exchanges, we have to set up a connection with them that allows us to communicate. Once the connection is established, we can send requests to them to provide us with all kinds of data, including order books. Since order books can be updated in milliseconds, we must ensure a stable connection to the exchange server to gather new data as soon as possible. Once we have acquired order books from exchanges, we can start looking to see if there are arbitrage opportunities.

Suppose the profit from the price discrepancy between order books exceeds the fees incurred during the trade executions. In that case, it indicates the presence of an arbitrage opportunity in the market.

By thoroughly analyzing the order books and identifying arbitrage *cycles*, we can systematically conduct a series of trades to exploit these price discrepancies and generate profit. A *cycle* refers to a sequence of trades involving multiple crypto-assets, resulting in a net profit when executed in a specific order. That sequence of trades always has the same starting and ending asset. If we start the arbitrage cycles with Bitcoin (BTC), we want to increase the amount of BTC at the end of the sequence while not changing the amount of other assets. We differentiate the same assets in the cycles if positioned on different exchanges. Thus, if we started with BTC on exchange A, we want to increase BTC on exchange A at the end of the sequence. Therefore, the name cycle.

Since calculations for these cycles are increasingly time-consuming for each additional trade, the algorithm limits itself to arbitrage cycles of a maximum length of 7 and a maximum of 2 withdrawals. That means there are at most seven different trades included in arbitrage detection. That length limitation is given as an input to the algorithm due to the increasing time complexity of calculations of longer cycles (which requires enormous computer capabilities to perform calculations). Also note that some cryptocurrency exchanges allow the holding of fiat currencies such as EUR and USD, which we will include in arbitrage detection. However, they usually do not provide fiat to fiat currency trading pairs like $EURUSD$.

The process for identifying arbitrage cycles starts by scanning the order books of different exchanges to identify situations where crypto-assets prices are imbalanced. For instance, consider a scenario involving three crypto-assets: Bitcoin (BTC), Ethereum (ETH), and Theter ($USDT$), and two exchanges: A and B. We systematically analyze the prices of these assets across these exchanges and search for price imbalances to identify potential cycles. It is important to note that for arbitrage strategy to be viable, the price imbalances must exceed the trading fees imposed by the exchanges. That ensures that the potential profits outweigh the costs of executing the trades. Suppose the maximum profit may occur if we execute a cycle as follows:

1. Sell BTC for $USDT$ on exchange A
2. Transfer $USDT$ from exchange A to exchange B
3. Buy ETH with $USDT$ on exchange B
4. Transfer ETH from exchange B to exchange A
5. Buy BTC with ETH on exchange A

To take advantage of this arbitrage opportunity, we **must hold** approximately the same value of $\boldsymbol{BTC}$**,** $\boldsymbol{ETH}$**, and** $\boldsymbol{USDT}$ on both exchanges and **take these trades simultaneously ***. If we do not, we expose ourselves to a risk that before the first trade is completed, the conditions on the market will change. Consequently, there may be no more arbitrage opportunities, and we will incur a loss. In this example, if we read order books correctly and have performed trades on time, we end up with slightly more BTC on exchange A and the same amount of BTC on exchange B, whereas the amounts of ETH and $USDT$ stayed the same on both exchanges.

> **Note ***: The term *simultaneously* does not necessarily imply that all trades happen in the exact same nanosecond. Rather, the execution is done automatically in rapid succession, using an algorithm where each order execution is independent of other orders. An algorithm does not wait for any responses from the exchanges; instead, all orders are sent instantly when the opportunity is detected.

3.3 Requirements for Trading Arbitrage

The previous example shows that specific requirements must be met to participate in trading arbitrage and exploit price inefficiencies in the crypto-assets market. These requirements ensure that the trading strategy is executed effectively and profitably. The following are the essential requirements for trading arbitrage efficiently.

Portfolio of Crypto-Assets

As mentioned, trading arbitrage involves simultaneously buying and selling assets in different markets to capitalize on price differences. Therefore, *holding a portfolio* of crypto-assets between which the arbitrage trades will be performed is essential. With that, we ensure that all trades can be executed immediately and that the market conditions do not change between trades. Hence, sufficient trading capital is required to execute arbitrage trades effectively. The amount of capital will depend on the size of the trades and the number of crypto-assets held. The choice of crypto-assets in the portfolio depends on the specific arbitrage opportunities being pursued and the market conditions.

Access to Multiple Exchanges

Access to multiple cryptocurrency exchanges is necessary to identify and execute arbitrage opportunities. We must establish accounts and connections with these exchanges to execute trades and manage portfolios. It also allows us to gather necessary order books.

Simultaneous Execution of Trades

All trades in the arbitrage cycle must be executed simultaneously. That means buying and selling assets across multiple exchanges should coincide. In more mechanical terms, the algorithm sends orders independent of one another simultaneously (even though there can be some delay – think nanoseconds – between executing orders on the arbitrage trader side). However, the trader does not affect the time it takes the exchange to execute the order on their part, so if it does not meet his criteria, it can simply move to another exchange with lower latency.

Simultaneous execution helps to ensure that the price differences identified for arbitrage are effectively capitalized upon and minimizes the risk of market movements affecting the strategy's profitability.

Real-Time Market Data

Timeliness is crucial in arbitrage trading as price inefficiencies can be short-lived. We need access to real-time market data, including order books and trade history, to identify and analyze potential arbitrage opportunities. This data is obtained through connections with exchanges.

Technological Infrastructure

A robust technological infrastructure is necessary to support the requirements of arbitrage trading. A stable and fast trading platform is essential for efficiently executing arbitrage trades. The platform should provide reliable connectivity to exchanges and low latency for order placement and execution. We have to ensure that infrastructure can handle the demands of real-time data analysis and trade execution. That includes reliable internet connectivity, high-speed computers or servers, and efficient data processing capabilities.

We can enhance the chances of executing profitable arbitrage trades in crypto-asset markets by meeting these requirements. It is important to note that trading arbitrage is a dynamic and competitive field, and traders should adapt their strategies and requirements based on market conditions or other changes affecting them.

3.4 Limitations for Trading

In addition to understanding the requirements for trading arbitrage, it is crucial to know the limitations that may affect trading activities. Before trading, we must first decide which arbitrages are worth pursuing and which are not (because of connection or some other risk).

3.4.1 Profit Benchmark

To avoid pursuing opportunities that do not yield enough return and are therefore too risky to take, we can define a *Profit Benchmark.*

> **Definition**: A *Profit Benchmark* is a predetermined measure indicating the intended growth in the initial asset's amount, achieved through the execution of arbitrage trades.

For example, we can set a Profit Benchmark to increase the amount of the starting asset in the arbitrage by at least 0.2% to count it as a viable option. That is because we realize that trades may not be executed with the prices we used to calculate arbitrage opportunities. That can happen for several reasons, such as too slow trade execution and connectivity issues with the exchange. Therefore, as soon as we calculate arbitrage opportunity with a Profit Benchmark exceeding 0.2%, we execute all necessary trades.

3.4.2 First In Principle

First In Principle is a mechanism for determining which arbitrage opportunities to execute and which should stay "in the waiting line." When there are more arbitrage opportunities simultaneously, we first trade the first one we calculated. While waiting for the execution of the first arbitrage we took, we can trade only arbitrage opportunities between the assets not included in the first arbitrage until we get a response from the exchanges that all orders were executed and we get updated balances. Once the response with the updated balance is received, we can trade the next arbitrage opportunity in the line (if it is still available). So, if the arbitrage cycle does not overlap, we can simultaneously trade several arbitrages; however, if the cycle overlaps, we must wait until we get responses from the exchanges.

3.4.3 Minimal Crypto Asset

One of the crucial considerations in trading arbitrage is maintaining a balanced portfolio of crypto-assets. A balanced portfolio means that all assets have approximately the same value. With that, we ensure enough of each asset is available to execute trades and take advantage of arbitrage opportunities while accounting for potential fees. However, the portfolio will rarely be fully balanced as exchange rates constantly change, affecting asset values.

Definition: The *Minimal Crypto Asset* in the arbitrage cycle is the asset with the smallest USD value in the portfolio.

We could measure it in any asset; however, we will use the latter since most transactions are done in USD. If there is not this possibility because of an unexistent order book for quote asset in USD, we will clarify in which asset we measure the value or use an order book from a different exchange. The asset with a minimum USD value limits us in arbitrage opportunity since we cannot trade a larger volume than the volume of the asset with a minimum balance minus the fee of its trade.

For example, suppose we have a portfolio with $\$10{,}000$ worth of BTC, $\$10{,}000$ worth of ETH and $\$50$ worth of $USDT$. Suppose an arbitrage opportunity involves all three crypto-assets, BTC, ETH, and $USDT$, with an order book volume greater than $\$10{,}000$ for each asset. As trades must be exercised simultaneously, the maximum value we can trade is still approximately $\$50$ worth of each. That is, since we can maximally buy $\$50$ of $USDT$ worth of another asset. In this case, the $USDT$ is the *Minimal Crypto Asset*. To make a balanced portfolio, we should sell some BTC and ETH and buy $USDT$. We would strive for a balanced portfolio of around $\$6600$ for each asset to use most of the portfolio for arbitrage and maximize gains, as the combined value of the portfolio is $\$20{,}050$. In a balanced portfolio scenario, arbitrage trade volume would be approximately $\$6600$ (per trade) instead of the $\$50$ (in the case of $USDT$ trade). In a case of 1% profit (an increase of starting asset) from arbitrage, we would earn $\$66$ instead of $\$0.5$ (with the same value of the portfolio, only differently positioned).

We can define a *Portfolio Balance Benchmark* to avoid substantial limitations because of an unbalanced portfolio.

Definition: The *Portfolio Balance Benchmark* is a predetermined value representing the maximum allowable difference in worth between the assets held in a portfolio.

For instance, if the Portfolio Balance Benchmark is set at 20%, no individual asset's worth may be less or more than 20% of any other held asset's worth in the portfolio. The Portfolio Balance Benchmark aims to mitigate limitations due to an unbalanced portfolio. However, applying the Portfolio Balance Benchmark requires continuous monitoring and rebalancing of the portfolio. That can be due to arbitrage trading or the constant fluctuation of exchange rates affecting the value of each asset. By appropriately setting a *Portfolio Balance Benchmark*, we can mitigate the risk of being unable to execute trades due to insufficient funds or leaving significant parts of the portfolio unused.

The problem of an unbalanced portfolio can happen for two reasons.

1. If arbitrage always occurs with BTC as the starting asset, then we will only increase the value of BTC. That means much of this BTC will be left unused (as explained in

the example) in the portfolio for trading. We should rebalance the portfolio and exchange some of this BTC for other assets between which we look for arbitrage.

2. If one asset appreciates or depreciates significantly compared to others, the balance gets ruined. Then, we have to sell some of it and acquire more other assets to have as much of an active portfolio for trading as possible (or vice versa).

As explained before, all arbitrage trades we analyze are cycles. That means that buying and selling activity will be exactly the same no matter the starting asset of the cycle. That is because we use the same bid and ask orders in the cycle, and for trade execution, it is irrelevant which asset we choose as the starting one. The only aspect that the starting asset has an effect on is which of the assets in the arbitrage trade we will be increasing. Therefore, to avoid rebalancing fees and try to keep the portfolio as balanced as possible at every moment, we can smartly choose the starting asset for every arbitrage trade. For starting assets in the cycle, we should always choose the *Minimal Crypto Asset* of the cycle (the asset with the smallest USD value in the portfolio). With that, we eliminate the first cause for an unbalanced portfolio since we will always increase the value of the assets that deviate the most from the portfolio into the negative side. However, that may not be the case if we follow some other portfolio optimization and do not try to minimize the rebalancing fees by keeping the portfolio as balanced as possible.

3.4.4 Maximum Order Volume

When engaging in trading arbitrage, it is vital to consider the maximum order volume that can be traded within the order books. The *Maximum Order Volume,* within the context of trading arbitrage, is determined by the volume available on the exchange for the best price, used to calculate arbitrage opportunity.

> **Definition**: *Maximum Order Volume* refers to the minimum order volume in the order books of all assets included in the arbitrage cycle at the optimal prices.

A higher volume level allows trading larger amounts without impacting the market price, thus enabling more significant arbitrage profits. When calculating the maximum volume we can trade for the arbitrage, we must consider the volumes of all crypto-assets included in the cycle. Once the cycle is calculated, we know all the prices (bid or ask) necessary for arbitrage to generate a profit. Alongside those prices, we also gain volumes for each price. We have to look at the minimum volume of all those assets, as this volume limits the amount we can trade in arbitrage. That minimum volume in the cycle's order books of crypto-assets tells us the maximum volume we can trade and, therefore, the *Maximum Order Volume* for that trade. If we trade with a larger volume, we will change the price in the order book, and part of our order will be filled with a worse price, resulting in a loss (or at least a lower profit) – for the part of the order that was filled with the worse price.

3.5 A Simple Example of Arbitrage

Understanding the landscape of arbitrage trading becomes complex due to the various requirements, limitations, and definitions involved. Let us explore a simplified theoretical example of an arbitrage opportunity to provide a more precise understanding. This example will serve as a foundation for discussing real-life scenarios later on. It will help us to clarify the requirements and limitations we face when we seek to trade these kinds of arbitrage.

Suppose we connect the trading platform to two exchanges, A and B. Both exchanges offer the same trading pairs with their order books. Trading pairs are one of the most popular; however, exchange rates will be entirely made up for simplification. Both exchanges charge a 1% fee for the withdrawal but do not charge fees for executing trades and depositing. As we stated before, we want to perform all trades simultaneously to fulfill all orders of the arbitrage cycle as soon as we calculate an arbitrage opportunity. Therefore, we have to hold a portfolio of crypto-assets (or even currencies if the exchanges allow us to, and we seek to trade arbitrage among them). We will construct an approximately balanced portfolio based on the exchange rates in the order books to minimize the *Minimal Crypto Asset* limitation. Therefore, we set the *Portfolio Balance Benchmark* to 20%, meaning no asset should be worth less or more than 20% of any other asset we hold. That should be true for any asset on any of the exchanges between which we trade arbitrage. This benchmark will only affect us in the example with the initial portfolio selection since we will perform only one arbitrage. However, we perform many arbitrages over time in real life, so portfolio rebalancing would occasionally be needed. We also set a *Profit Benchmark* of 1% to count arbitrage opportunities as a viable option.

To meet the requirements of the 20% *Portfolio Balance Benchmark*, we create a portfolio with a $2\ BTC$ and $20\ ETH$ positioned as follows :

1. Exchange A
    a. $1\ BTC$
    b. $10\ ETH$
2. Exchange B
    a. $1\ BTC$
    b. $10\ ETH$

Both exchanges offer the same trading pair $ETHBTC$ with the following order books. The order books only state the best bid and ask prices with the corresponding volume for each price. Volume is the amount of the base asset (the first element of the symbol, in this case, ETH) that participants are willing to buy or sell at a specified price. As we can see, holdings' values are in a 20% deviation based on the exchange rates provided by the exchanges (it does not matter if we measure the value in ETH or BTC).

Table 1: Order Book for Example

Exchange A			
Bid Volume	$ETHBTC$	Ask Volume	
	0.1	11	Ask price
11	0.09		Bid Price

Source: Own work

Table 2: Order Book for Example

Exchange B			
Bid Volume	$ETHBTC$	Ask Volume	
	0.08	11	Ask price
11	0.07		Bid Price

Source: Own work

> **Note**: Such massive price discrepancies are (practically) never presented in real-life trading. However, the numbers are chosen to make it easy to see discrepancies and understand the principles used.

We must remember that we must perform market orders to execute trades. That is crucial since the best price we can be filled at is stated in the order books. If we **buy** an asset with market orders, we will get executed with the **best ask price**, and if we **sell** an asset with a market order, we will get executed with the **best bid price**.

Now, let us examine if there is an arbitrage opportunity on the market. To check for arbitrage, we must consider all possible cycles between the assets in the portfolio. Remember, the starting and ending asset has to be the same in the arbitrage cycle. We can go even one step further and make it mandatory to have the same starting and ending asset on the same exchange in the cycle (which is what we want). Possible arbitrage cycles between assets we can hold on the exchanges are:

1. $BTC - ETH - BTC$
2. $ETH - BTC - ETH$

In the first example, we start with BTC, exchange it for ETH, and then exchange ETH for BTC. In the second, we start with ETH, exchange it for BTC, and then exchange BTC for ETH.

To check every possibility for these two cycles, we have to consider all options:

1. We search for arbitrage solely on exchange A
2. We search for arbitrage solely on exchange B
3. We search for arbitrage between A and B

We denote a trade differently depending on the exchange where the asset is positioned and the order we have to execute. First, we denote on which exchange we are positioned with the asset. With underwritten text, we tell what kind of order we perform, ask, bid, or withdrawal (deposit is implicitly included in withdrawal notation). In the end, we specify the trading symbol, which tells us, together with the order type, which asset we exchanged for another. All possible notation are as follows:

> A_{ask} $BTCUSDT$ … BTC sold on exchange A for $USDT$ (filled the best bid price). It also implicitly tells us the starting asset, which is BTC.
>
> A_{bid} $ETHBTC$ … ETH bought on exchange A with BTC (filled the best ask price). It also implicitly tells us the starting asset, which is BTC.
>
> $A_{withdrawl}$ BTC … BTC withdrawn from exchange A. It implicitly assumes that it was deposited on the exchange with which the cycle continues – or where the cycle began if there are no further trades.

If we follow the new denotation we used, the cycle BTC – ETH – BTC becomes denoted as the following possibilities.

If we are trading solely on exchange A:

$$A_{bid}\ ETHBTC - A_{ask}\ ETHBTC \tag{1}$$

If we are trading solely on Exchange B:

$$B_{bid}\ ETHBTC - B_{ask}\ ETHBTC \tag{2}$$

If we are trading between exchanges A and B:

$$A_{bid}\ ETHBTC - A_{withdrawl}\ ETH - \ B_{ask}\ ETHBTC - B_{withdrawl}\ BTC \tag{3}$$

$$B_{bid}\ ETHBTC - B_{withdrawl}\ ETH - \ A_{ask}\ ETHBTC - A_{withdrawl}\ BTC \tag{4}$$

The logic shown in (1), (2), (3) and (4) will be used from now on. We will show how to analyze only the cycle BTC – ETH – BTC possibilities, as it is the same for any other two asset cycles. If more assets are in the cycle, the logic stays the same; however, analyzing all necessary aspects becomes much more complex. Now, let us look at these examples and scan for arbitrage opportunities.

3.5.1 Arbitrage on exchange A

The arbitrage cycle starts with BTC that we hold on exchange. On exchange A, we hold a portfolio of 1 BTC and 10 ETH. If we check for arbitrage between BTC and ETH, starting the cycle with BTC, we write it as:

$$A_{bid}\ ETHBTC - A_{ask}\ ETHBTC \quad (5)$$

The arbitrage (calculation) would go as follows:

1. Buy for 1 BTC worth of ETH.
   a. Use the best ask price from $ETHBTC$ order book since this is the best price we can buy ETH with BTC. (1 $ETH = 0.1$ BTC).
   b. $1\ BTC * \frac{1\ ETH}{0{,}1\ BTC} = 10\ ETH$ (6)
2. Sell 10 ETH for BTC.
   a. Use the best bid price from $ETHBTC$ order book since this is the best price we can sell ETH for BTC. (1 $ETH = 0.09$ BTC).
   b. $10\ ETH * \frac{0.09\ BTC}{1\ ETH} = 0.9\ BTC$ (7)

As we can see in this scenario, we have 10 ETH and 0.9 BTC in the end, resulting in a loss of 0.1 BTC instead of creating a profit. That shows that there is no arbitrage opportunity in this cycle on exchange A.

3.5.2 Arbitrage on exchange B

On exchange B, we also hold a portfolio of 1 BTC and 10 ETH. As before, the arbitrage cycle starts with BTC that we hold on the exchange.

$$B_{bid}\ ETHBTC - B_{ask}\ ETHBTC \quad (8)$$

The arbitrage (calculation) would go as follows:

1. Try to buy for 1 BTC worth of ETH.
   a. Use the best ask price from $ETHBTC$. (1 $ETH = 0.08$ BTC).
   b. $1\ BTC * \frac{1\ ETH}{0.08\ BTC} = 12.5\ ETH$ (9)

As seen above, we would want to buy 12.5 ETH. However, the *Maximum Order Volume* is 11 ETH. Meaning we can, at most, buy 11 ETH. Nevertheless, in the portfolio on the exchange, we hold only 10 ETH. So even if we buy 11 ETH, we cannot sell that many for BTC (when simultaneously trading). That means the *Minimal Crypto Asset* limits us to buy at most 10 ETH.

   c. So the actual amount we can trade (and should if we want to take full advantage of arbitrage) is retrieved from solving the equation for X:
   d. $10\ ETH = X\ BTC * \frac{1\ ETH}{0.08\ BTC}$ (10)
   e. Therefore, we want to buy 0.8 BTC worth of ETH: $0.8\ BTC * \frac{1\ ETH}{0.08\ BTC} = 10\ ETH$. The rest of the BTC we leave on exchange B (0.2 BTC).
2. Sell 10 ETH for BTC.

a. Use the best bid price from $ETHBTC$. ($1\ ETH\ =\ 0.07\ BTC$).

b. $10\ ETH * \frac{0.07\ BTC}{1\ ETH} = 0.7\ BTC$ (11)

As we can see in this scenario, we have 10 ETH and 0.9 BTC in the end, resulting in a loss of 0.1 BTC instead of creating a profit. That shows there is also no arbitrage opportunity in this cycle on exchange B.

3.5.3 Arbitrage between exchanges A and B

We hold a portfolio of 1 BTC and 10 ETH on both exchanges. As before, the arbitrage cycle starts with an initial portfolio value of BTC that we hold on the exchange. However, we must consider which exchange we start the arbitrage cycle with this time. For withdrawals, both exchanges charge a fee of 1%.

3.5.3.1 Arbitrage with starting asset on exchange A

The arbitrage cycle that starts with BTC that we hold on the exchange A is denoted as:

$$A_{bid}\ ETHBTC - A_{withdrawl}\ ETH - \ B_{ask}\ ETHBTC - B_{withdrawl}\ BTC \qquad (12)$$

The arbitrage (calculation) would go as follows:

1. Buy 1 BTC worth of ETH on exchange A.
   a. Use the best ask price from $ETHBTC$. ($1\ ETH\ =\ 0.1\ BTC$).
   b. $1\ BTC * \frac{1\ ETH}{0.1\ BTC} = 10\ ETH$ (13)
2. Transfer 10 ETH from exchange A to exchange B. We pay a fee of 1%. Therefore, the transacted amount is equal to 9,9 ETH.
3. Sell 9,9 ETH for BTC on exchange B.
   a. Use the best bid price from $ETHBTC$. ($1\ ETH\ =\ 0.07\ BTC$).
   b. $9.9\ ETH * \frac{0.07\ BTC}{1\ ETH} = 0.693\ BTC$ (14)
4. Transfer 0.693 BTC from exchange B to exchange A. We pay a fee of 1%. Therefore, the transacted amount is equal to approximately 0.686 BTC. With this, we complete the cycle.

As we can see in this scenario, we have in the end 10 ETH on both exchanges, 1 BTC on exchange B, and 0.686 BTC on exchange A, resulting in a loss of 0.314 BTC. That shows us that there is no arbitrage opportunity in this cycle between both exchanges.

3.5.3.2 Arbitrage with starting asset on exchange B

The arbitrage cycle that starts with BTC that we hold on exchange B is denoted as:

$$B_{bid}\,ETHBTC - B_{withdrawl}\,ETH - \ A_{ask}\,ETHBTC - A_{withdrawl}\,BTC \qquad (15)$$

The arbitrage (calculation) would go as follows:

1. Try to buy 1 BTC worth of ETH on exchange B.
   a. Use the best ask price from $ETHBTC$. (1 $ETH\ =\ 0.08\ BTC$).
   b. $1\ BTC * \frac{1\ ETH}{0.08\ BTC} = 12.5\ ETH \qquad (16)$

However, the *Maximum Order Volume* is 11 ETH. Meaning we can, at most, buy 11 ETH. Nevertheless, in the portfolio on the exchange, we have only 10 ETH. So even if we buy 11 ETH, we cannot sell that many for BTC (when simultaneously trading). That means the *Minimal Crypto Asset* limits us to buy at most 10 ETH plus the fee we will have to pay for withdrawal.

   c. So, the actual amount we can trade (and should if we want to take full advantage of arbitrage) is retrieved from solving the equation for X. The $(1 - 0{,}01)$ is used because of the 1% fee paid for transferring this asset to another exchange.
   d. $10\ ETH = X\ BTC * \frac{1\ ETH}{0.08\ BTC} * (1 - 0.01) \qquad (17)$
   e. Therefore, we want to buy $0.808\ BTC$ worth of ETH: $0.808\ BTC * \frac{1\ ETH}{0.08\ BTC} = 10.1\ ETH$. The rest of the BTC we leave on exchange B ($0.192\ BTC$).
2. Transfer $10.1\ ETH$ from exchange B to exchange A. We pay a fee of 1%. Therefore, the transacted amount is equal to $9.999\ ETH$.
3. Sell $9.999\ ETH$ for BTC on exchange A.
   a. Use the best bid price from $ETHBTC$. (1 $ETH\ =\ 0.09\ BTC$).
   b. $9.999\ ETH * \frac{0.09\ BTC}{1\ ETH} \cong 0.9\ BTC \qquad (18)$
4. Transfer $0.9\ BTC$ from exchange A to exchange B. We pay a fee of 1%. Therefore, the transacted amount is equal to $0.891\ BTC$. With this, we complete the cycle.

As we can see in this scenario, we have in the end 10 ETH on both exchanges, 1 BTC on exchange B, and 1.083 BTC on exchange A, resulting in a profit of 0.083 BTC (or 8.3% increase of starting asset). That shows us that there is an arbitrage opportunity in this cycle between both exchanges. It also meets the requirements of the *Profit Benchmark*, which requires growth in the initial asset's amount greater than 1%. Therefore, it fulfills all the requirements for an arbitrage opportunity we intend to capitalize on through trading.

In conclusion, trading arbitrage has limitations that must be considered to ensure successful and efficient trading. By carefully evaluating these limitations, we can enhance trading strategies and improve the overall profitability of arbitrage activities. Understanding the maximum amount that can be traded within the order book and maintaining a reasonable minimum balance of crypto-assets are vital aspects of managing and optimizing arbitrage opportunities.

3.6 A Real Example of an Arbitrage Opportunity

After exploring a theoretical example of arbitrage, let us delve into a real-life scenario that unveils the true potential of this trading strategy. We will show an arbitrage opportunity in the crypto-assets market, demonstrating how traders can harness market inefficiencies for financial gain. This real-life example shows firsthand how market inefficiencies can manifest, enabling traders to capitalize on the price discrepancies between trading pairs. There are numerous examples on the market, yet we will provide an example of arbitrage on the same exchange to show that having a connection to more than one crypto exchange is not mandatory. Furthermore, we will not discuss *Minimal Crypto Balance* in this example, as it is irrelevant in this context since it does not affect the arbitrage opportunity itself. However, we will look at *Maximum Order Volume*, as these market conditions limit arbitrage opportunities on the market.

The data used in this example is actual data received from the crypto exchange Bitstamp through a "WebSocket" connection. Bitstamp is recognized as one of the most trustworthy cryptocurrency exchanges. It reported a daily trading volume of $120 million on its platform as of November 24th, 2023, catering to 4 million customers globally. Bitstamp has established itself as a trusted entity, facilitating users in acquiring, selling, and securing digital asset storage (CoinMarketCap, n.d.b).

On the 9th of November, 2023, we analyzed arbitrage opportunities on Bitsamp (in the cycle denoted as "*Bit*"). Fees on this date for market takers (market orders) have been 0.40% per trade (Bitstamp, n. d.). We have been gathering data for several trading pairs, including $XRPEUR$, $BTCEUR$, $BTCUSD$, and $XRPUSD$ for which we identified the following arbitrage cycle (19):

$$Bit_{bid}BTCUSD - Bit_{ask}BTCEUR - Bit_{bid}XRPEUR - Bit_{ask}XRPUSD \qquad (19)$$

For these pairs, we have received the following best bid and best ask price in order books in a span of 100 milliseconds. These orders are part of "the latest order book" published by the exchange for each pair. Remember, if we buy an asset with market orders, we will get executed with the best ask price, and if we sell an asset with a market order, we will get executed with the best bid price.

Table 3: Real Example Order Book

Bitstamp			
Symbol	Time in milliseconds	Ask price	Volume
$BTCUSD$	1699547824710	35943	2.15140853

Source: Own work

Table 4: Real Example Order Book

Bitstamp			
Symbol	Time in milliseconds	Bid price	Volume
$BTCEUR$	1699547824643	33942	0.0223

Source: Own work

Table 5: Real Example Order Book

Bitstamp			
Symbol	Time in milliseconds	Ask price	Volume
$XRPEUR$	1699547824742	0.59878	4660.38731918

Source: Own work

Table 6: Real Example Order Book

Bitstamp			
Symbol	Time in milliseconds	Bid price	Volume
$XRPUSD$	1699547824743	0.65083	16885.49773366

Source: Own work

If the algorithm calculates that arbitrage cycle fast enough to execute orders before the volume available in the order book is filled, we can yield a profit on that arbitrage opportunity. However, we must consider this arbitrage opportunity's *Maximum Order Volume* limitation. It turns out that the limitation arises from trading pair $BTCEUR$, which allows us to trade 0.0223 BTC. That equals $33942€ * 0.0223 = 756.9€$, smaller than the quoted volumes for any other pair included in the cycle.

To find the starting amount of USD needed to take the maximum advantage of this arbitrage opportunity, we calculate:

$$BTC\ volume * USD\ exchange\ rate * (1 + fee) =$$

$$0.0223\ BTC * 35943\ USD\ /\ 1\ BTC * 1.004 \cong 804.73\ USD \tag{20}$$

If orders were sent to exchange after receiving updated order books fast enough, the arbitrage trade calculation would go as follows:

1. Buy BTC with USD
   a. $804.73\ USD * \frac{1\ BTC}{35943\ USD} * (0.996) \cong 0.0222995\ BTC$ (21)

2. Sell BTC for EUR
    a. $0.0222995\ BTC * \frac{33942\ EUR}{1\ BTC} * (0.996) \cong 753.86\ EUR$ (22)
3. Buy XRP with EUR
    a. $753.86\ EUR * \frac{1\ XRP}{0.59878\ EUR} * (0.996) = 1253.957313\ XRP$ (23)
4. Sell XRP for USD
    a. $1253.957313\ XRP * \frac{0.65083\ USD}{1\ XRP} * (0.996) \cong 812.84\ USD$ (24)

For all calculations, we have used floor rounding, the most probable method exchanges use for actual trading. As we can see, we started with $804.73\ USD$ and ended with $812.84\ USD$ if everything went as expected and we filled in these orders. Thus, we have increased the amount of our starting asset for $\left(\frac{812.84}{804.73} - 1\right) * 100 = 1.00779\%$. Of course, we would trade as much as possible with such a lucrative opportunity; however, we see how the trading volume limits us to trade a small amount.

Do not forget that to execute this arbitrage trade, it is necessary to hold a portfolio on the Bitstamp that exceeds $0.0223\ BTC$, $754\ EUR$, $1{,}254\ XRP$, and $805\ USD$ and execute all trades simultaneously.

As arbitrage opportunity in this example arises on the same exchange, one can doubt the reliability of the exchange's data. That is because one would expect major exchanges to take advantage of these price discrepancies on their own. Nonetheless, the data received is the same for all market participants wishing to trade on Bitstamp, so even if the data is unreliable, it is unreliable for all market participants competing in trading arbitrage (except maybe for the exchange itself).

Furthermore, it is essential to state that when an opportunity arises, it is most important to be one of the first traders to send in the order before the orders in the order books are filled. That is extremely difficult as we do not compete only with other arbitrage traders but also traders who execute orders for other reasons and can fill in the orders as soon as we receive the updated order book (or even sooner, as they do not trade based on received order books).

4 MEASURING THE EFFICIENCY OF THE ARBITRAGE ALGORITHM

In the previous chapter, we explored the concept of arbitrage and how it can be a profitable trading strategy. We learned about the calculations for identifying arbitrage opportunities and executing trades to capitalize on market price imbalances. Now, as we delve deeper into the exploration of arbitrage trading strategy, we shift focus to measuring the efficiency of the arbitrage algorithm. While it is crucial to identify and seize arbitrage opportunities, it is equally important to evaluate the trading strategy's success objectively. However, traditional metrics may not fully capture the efficiency of trading algorithms, as they often fail to isolate the gains made solely through arbitrage trading from the broader market movement. To address this limitation, we will develop a novel metric tailored to measure the success of arbitrage trading strategy's success while removing the market movement's influence. By considering only the gains derived from arbitrage trading and excluding the impact of general market movements, we can better understand the algorithm's actual efficiency.

This chapter will present and explain this new metric in detail. We will outline its components and the reasoning behind its design, demonstrating how it provides a more accurate representation of the algorithm's performance. Additionally, we will construct a fictional portfolio with which we will "trade" arbitrage opportunities found on the market. We will look at its performance and measure it with the new metric. By incorporating this specialized metric into the evaluation process, we aim to gain deeper insights into the efficiency of the arbitrage algorithm. That will enable us to make informed decisions, refine trading strategies, and enhance trading performance.

4.1 Weighted Arbitrage Growth Index (WAGI)

The *Weighted Arbitrage Growth Index* (WAGI) is a specialized performance metric designed to measure the efficiency of an arbitrage trading strategy by isolating the gains derived solely from these trades while excluding influence from broader market movements. The proposed metric is designed to capture the weighted return on investment (ROI) for each arbitrage trade as the strategy progresses from one stage to another. It follows the logic of the time-weighted performance method.

The Weighted Arbitrage Growth Index (WAGI) is defined with the following formula:

$$WAGI = \prod_{j=1}^{m} \sum_{i=1}^{n} \frac{B_{i,j_{updated}}}{B_{i,j}} W\left(B_{i,j}\right) - 1 \tag{25}$$

Where:

1. n … Number of assets we hold.
2. m … Number of stages in the period we analyze (the number of arbitrage cycles traded in a given period).
3. $B_{i,j}$ … Balance of asset i at the stage j, representing the quantity of the asset held in the portfolio at a specific stage.
4. $W\left(B_{i,j}\right)$ … Weight of the asset i in the portfolio at the stage j. It is calculated as the balance of the asset multiplied by its value in USD, divided by the portfolio's total USD value. The weight emphasizes the relative importance of each asset in the portfolio, ensuring that the measurement accurately reflects the actual contribution of each asset to the overall return on investment.
5. Stage j … The moment we calculate the arbitrage opportunity, we decide to trade. In any stage j, we gather order books; with them, we have defined prices on each

exchange for each asset. Thus, the asset's price $P(B_{i,j})$ in stage j is uniquely defined on each exchange (as the best bid price – since this is the best price for which we can sell the asset), as are corresponding balances $B_{i,j}$. If we want to be extremely precise, we can use all the best bid prices until we fill the whole volume we hold on the exchange and create a weighted average for the asset's price.

6. Stage $j_{updated}$ … The next instance after stage j, at which we receive updated balances of assets after the arbitrage trade. In this stage $j_{updated}$ we are interested only in the updated balance of assets, while all the other calculations and readings are done in stage j.

The weight of an asset is calculated as follows:

$$W(B_{i,j}) = \frac{B_{i,j} * P(B_{i,j})}{\sum_{k=1}^{n} B_{k,j} * P(B_{k,j})} \tag{26}$$

Where:

1. $P(B_{i,j})$ … Price of asset i at the stage j in USD.
2. $\sum_{i=1}^{n} W(B_{i,j}) = 1$ … The weights sum to 1, as the sum of all balance values must equal the whole portfolio value.

The values of the WAGI can fall anywhere in the interval $[-1, \infty)$. If we get a value of -1, we have lost a complete portfolio and do not have any holdings left on the exchanges. If the value is smaller or equal to 0, it means we have generated a loss (or at least not a profit) with arbitrage trading, and there has to be a critical flaw in the algorithm for trading. If the value is greater than 0, the arbitrage strategy is profitable, and we have increased portfolio holdings by trading. With measuring values, as stated above, we do not have a problem when we decide to pay out a part of a portfolio or when we decide to rebalance a portfolio. That is because if we sell or buy assets outside of arbitrage trading, that is not noted as a new stage, and changes do not affect any part of the measurement. That is because when we move to the next stage (by trading new arbitrage) after profit payout or rebalancing, we look only at a weighted change of portfolio from balances that we owned at the moment when we calculated arbitrage opportunity (which is already updated).

Note: When considering assets in WAGI, the BTC on exchange A is a different asset from the BTC on exchange B. That is because prices of BTC can be (and usually are) different on exchanges. With this, we eliminate the problem of which price to use for BTC. The same goes for all other assets and exchanges.

4.1.1 The Rationale for the Metric

In arbitrage trading, we look to increase the holdings of assets and not necessarily the monetary value of the portfolio. With WAGI, we measure only the percentage increase of the portfolio holdings due to arbitrage trading. Since there is always more than one asset included in arbitrage, and we have to hold a portfolio of these assets, we want to weigh how much portfolio holdings increased – if we look at the portfolio as a whole. That is why every holding in the portfolio gets a weight, which tells us how much of the portfolio it represents. Then, we take a look at how holdings changed after the arbitrage. We look at every asset held because there can be a problem with execution with trades, and even though we may increase the amount of the first asset we hold, we may have decreased the amount of some other asset in the cycle. That can be due to the execution of a trade being too slow or some other problem. With that knowledge, we can calculate each arbitrage trade's weighted return on investment. To get the compound return over several stages, each stage (arbitrage) return is multiplied and subtracted by 1. The components of the metric are as follows:

1. $\sum_{i=1}^{n} \frac{B_{i,j_{updated}}}{B_{i,j}} W\left(B_{i,j}\right)$ … The sum of the weighted returns of the n assets in the portfolio at a given stage.
2. $\prod_{j=0}^{m}(SUM) - 1$ … Represents the multiplication of the returns for all m stages (arbitrages), capturing the overall ROI across them. The product part accumulates the returns from each stage as the strategy moves from the initial stage to the final stage.

WAGI offers a more accurate reflection of an algorithm's performance executing arbitrage trades by focusing on weighted return on investment for each arbitrage trade. Another benefit of WAGI is its consideration of varying asset weights within the portfolio. This aspect is essential for evaluating arbitrage strategies, as different assets may contribute differently to the overall portfolio value. By assigning appropriate weights to each asset, WAGI can provide a more precise and comprehensive assessment of the arbitrage strategy's success across all assets involved in the trades. This level of detail enables investors to make more informed decisions regarding their arbitrage trades, identifying areas for improvement and optimizing the strategy for maximum returns. Moreover, the metric can be used to compare the performance of different arbitrage strategies.

For example, we hold 20 assets with the same USD value, and with arbitrage trade, we increase the amount of starting assets in the cycle by 10% while the amounts of other assets stay the same. The return on investment of this arbitrage trade is, in reality, $\frac{0.1}{20}$, as this is how much of the portfolio it represents. That is because we must hold all 20 assets in the portfolio as an investment to generate that return by taking advantage of arbitrage opportunities. However, if we hold a portfolio of only four assets and find the same opportunity resulting in a 10% initial asset increase, the gain is $\frac{0.1}{4}$. Therefore, we must consider how many assets we hold and what kind of returns we can generate (historically) with those assets. Therefore, by employing WAGI measurement, we can detect which arbitrage strategy provides the highest arbitrage trading return.

Furthermore, suppose we trade many arbitrages at the beginning of the analysis period with minimal profits, always with the same starting asset. If the starting asset has a significant price increase, the portfolio will incur a significant value increase. This portfolio may beat another with a better algorithm applied as the price increases did not affect it as much. Thus, the need for a better metric for measuring arbitrage algorithm efficiency arises.

However, note that even if we have a high positive value of WAGI, that does not necessarily mean we are increasing the value of the arbitrage portfolio. We can earn a profit with arbitrage trading, but if the assets we hold are losing value rapidly, we can still generate a significant loss. Nevertheless, this is not a concern, since WAGI is constructed only to measure the efficiency of the arbitrage algorithm. For complete optimization of the portfolio, we would have to consider many other aspects in-depth, which we will not cover in this research.

4.2 Example usage of WAGI

Here, we present a simplified example to illustrate the practical implementation of the Weighted Arbitrage Growth Index (WAGI) in evaluating the performance of an arbitrage trading strategy. Through a hypothetical scenario, we will demonstrate how WAGI can effectively measure the success of arbitrage trades while considering the weighted returns on investment and the varying asset weights within a portfolio. This example aims to understand how WAGI works in practice. While the example is simplified for illustrative purposes, it serves as a valuable starting point for understanding the mechanics and potential benefits of WAGI in real-world applications. In this example, we will analyze the WAGI measurement across two stages.

Suppose we are trading on only one exchange, called A; there are no fees on the market, and exchange A offers several trading pairs: $BTCUSD$, $ETHUSD$, $ETHBTC$, $XRPBTC$, and $XRPUSD$. We use a *Portfolio Balance Benchmark* of 50% for portfolio values to avoid paying too many theoretical rebalancing fees.

4.2.1 Stage 1

We have an initial portfolio of:

1. Exchange A
    a. $B_{1,1} = 1\ (BTC)$
    b. $B_{2,1} = 10\ (ETH)$

c. $B_{3,1} = 26.000\ (XRP)$
d. $B_{4,1} = 26.000\ (USD)$

We will not overly complicate the examples with order books and their spread. Instead, we will use a unified price defined for ask and bid orders, with unlimited volume supporting it in that stage. Suppose at the beginning (Stage 1), holdings in the portfolio have the following exchange rates:

1. $1\ BTC\ =\ 26000\ USD$
2. $1\ ETH\ =\ 2600\ USD$
3. $1\ ETH\ =\ 0.08\ BTC$
4. $1\ XRP\ =\ 1\ USD$
5. $1\ XRP\ = \frac{1}{26000}\ BTC$

We see that with these prices, there is an arbitrage opportunity on the market that we decide to trade. The arbitrage cycle is $ETHBTC_{bid} - ETHUSD_{ask} - BTCUSD_{bid}$ and for starting asset, we can take any asset since all USD values of holdings are the same. Here, we will choose BTC as a starting asset. So, for stage 1, we do the following calculations.

1. Calculate the corresponding weights of the assets in the portfolio.

   Total portfolio value:

$$\sum_{k=1}^{4} B_{k,j} * P\left(B_{k,j}\right)\ = 1\ *\ 26000\ +\ 10\ *\ 2600\ +\ 26000\ *\ 1\ + 1 * 26000 =$$

$$26000\ +\ 26000\ +\ 26000 +\ 26000\ =\ 104000\ USD \tag{27}$$

   Now, we calculate the weights for each asset:

$$W\left(B_{1,1}\right) = \frac{B_{i,j}*P\left(B_{i,j}\right)}{\sum_{k=1}^{3} B_{k,j}*P\left(B_{k,j}\right)} = \frac{(1 * 26000)}{104000} = \frac{1}{4} \tag{28}$$

$$W\left(B_{2,1}\right) = \frac{(10 * 2600)}{104000} = \frac{1}{4} \tag{29}$$

$$W\left(B_{3,1}\right) = \frac{(26000 * 1)}{104000} = \frac{1}{4} \tag{30}$$

$$W\left(B_{4,1}\right) = \frac{(26000 * 1)}{104000} = \frac{1}{4} \tag{31}$$

As expected, the sum of weights equals 1.

2. At the same time, we execute trades for arbitrage simultaneously:
   a. Buy ETH with BTC.

i. Use the price from $ETHBTC$ ($1\ ETH\ =\ 0.08\ BTC$).
ii. The amount we can trade is retrieved from solving the equation for X.
iii. $10\ ETH = X\ BTC * \frac{1\ ETH}{0.08\ BTC}$. (32)
iv. Therefore, we want to buy 0.8 BTC worth of ETH: $0.8\ BTC * \frac{1\ ETH}{0.08\ BTC} = 10\ ETH$. We leave the rest of the BTC on exchange ($0.2\ BTC$).

b. Sell $10\ ETH$ for USD.
i. Use the price ask price from $ETHUSD$ ($1\ ETH\ =\ 2600\ USD$).
ii. $10\ ETH * \frac{2600\ USD}{1\ ETH} = 26000\ USD$. (33)

c. Buy for 26000 USD worth of BTC.
i. Use the ask price from $BTCUSD$ ($1\ BTC\ =\ 26000\ USD$).
ii. $26000\ USD * \frac{1\ BTC}{26000\ USD} = 1\ BTC$. (34)

After executing all trades, we get updated portfolio balances on exchange A. These are:

1. $B_{1,1_{updated}} =\ 1.2\ (BTC)$
2. $B_{2,1_{updated}} = 10\ (ETH)$
3. $B_{3,1_{updated}} = 26000\ (XRP)$
4. $B_{4,1_{updated}} = 26000\ (USD)$

Now, we can calculate the WAGI for Stage 1:

$$WAGI_1\ = \prod_{j=1}^{1}\sum_{i=1}^{4}\frac{B_{i,j_{updated}}}{B_{i,j}}W(B_{i,j}) - 1 =$$

$$\left(\frac{B_{1,1_{updated}}}{B_{1,1}}\ *\ W(B_{1,1})\ + \frac{B_{2,1_{updated}}}{B_{2,1}}\ *\ W(B_{2,1})\ + \frac{B_{3,1_{updated}}}{B_{3,1}} * W(B_{3,1}) + \frac{B_{4,1_{updated}}}{B_{4,1}} * W(B_{4,1})\right) - 1 =$$

$$= \left(\frac{1.2}{1}\ * \frac{1}{4}\ + \frac{10}{10}\ * \frac{1}{4}\ + \frac{26000}{26000} * \frac{1}{4} + \frac{26000}{26000} * \frac{1}{4}\right) - 1 = \frac{21}{20} - 1 = \frac{1}{20} =\ 0.05 \qquad (35)$$

The WAGI measurement for Stage 1 is 0.05, indicating a positive return on investment of 5% due to the BTC arbitrage trade. If prices do not change after arbitrage (given that we have unlimited volume trading at these prices for bid and ask), that is also the portfolio value increase since $\frac{109200\ USD}{104000\ USD}\ = \frac{21}{20}\ =\ 1.05$.

4.2.2 Stage 2

In stage 2, we operate with updated values from stage 1 in the portfolio, meaning the holdings are equal to the following:

1. $B_{1,2} = 1.2\ (BTC)$
2. $B_{2,2} = 10\ (ETH)$
3. $B_{3,2} = 26000\ (XRP)$
4. $B_{4,2} = 26000\ (USD)$

Suppose there has been a significant period of time between stage 1 and current stage 2. In that period the price changed significantly to the following levels.

1. $1\,BTC = 20000\,USD$
2. $1\,ETH = 2000\,USD$
3. $1\,ETH = 0.1\,BTC$
4. $1\,XRP = 0.45\,USD$
5. 1 XRP $= \frac{1}{40000}\,BTC$

Because XRP is the asset worth the least in USD value, we will choose it as a starting asset if it is included in the arbitrage opportunity. Based on the prices provided, we can see that there is arbitrage opportunity $XRPBTC_{ask} - BTCUSD_{ask} - XRPUSD_{bid}$.

1. Calculate the corresponding weights of the assets in the portfolio.

   Total portfolio value:

$$\sum_{k=1}^{4} B_{k,j} * P(B_{k,j}) = 1.2 * 20000 + 10 * 2000 + 26000 * 0.45 + 26000 * 1 = 81700\,USD. \tag{36}$$

   Now, we calculate the weights for each asset:

$$W(B_{1,2}) = \frac{B_{i,j} * P(B_{i,j})}{\sum_{k=1}^{3} B_{k,j} * P(B_{k,j})} = \frac{(1.2 * 20000)}{81700} = \frac{240}{817} \tag{37}$$

$$W(B_{2,2}) = \frac{(10 * 2000)}{81700} = \frac{200}{817} \tag{38}$$

$$W(B_{3,2}) = \frac{(26000 * 0.45)}{81700} = \frac{117}{817} \tag{39}$$

$$W(B_{4,2}) = \frac{(26000 * 1)}{81700} = \frac{260}{817} \tag{40}$$

As expected, the sum of weights equals 1.

2. At the same time, we execute trades for arbitrage simultaneously:
    d. Sell XRP for BTC.
        i. Use the ask price from $XRPBTC$ ($1\ XRP\ = \frac{1}{40000}\ BTC$).
        ii. $26000\ XRP\ * \frac{1\ BTC}{40000\ XRP} = \frac{13}{20} BTC$ (41)
    e. Sell $\frac{13}{20}\ BTC$ for USD.
        i. Use the bid price from $ETHBTC$ ($1\ BTC\ =\ 20000\ USD$)
        ii. $\frac{13}{20}\ BTC * \frac{20000\ USD}{1\ BTC} = 13000\ USD$ (42)
    f. Buy for 13000 USD worth of XRP.
        i. Use the ask price from $BTCUSD$ ($1\ XRP\ =\ 0.45\ USD$)
        ii. $13000\ USD * \frac{1\ XRP}{0.45\ USD} = 28888.9\ XRP$ (43)

After executing all trades, we get updated portfolio balances on exchange A. However, as we executed trades (all trades explained above are made simultaneously), there was a problem with execution when selling BTC for USD. Instead of the price in the order book, we were filled (possibly because of too slow execution) with a price of $1\ BTC\ =\ 19000\ USD$. So instead of $13000\ USD$, we bought only $12350\ USD$ with BTC in trade e. Therefore, the updated balances are as follows:

1. $B_{1,2_{updated}}\ =\ 1.2\ (BTC)$
2. $B_{2,2_{updated}} = 10\ (ETH)$
3. $B_{3,2_{updated}} = 28888.9\ (XRP)$
4. $B_{4,2_{updated}} = 25350\ (USD)$

Now, we can calculate the WAGI for Stage 2:

$$WAGI_2\ = \prod_{j=2}^{2}\sum_{i=1}^{4}\frac{B_{i,j_{updated}}}{B_{i,j}} W(B_{i,j}) - 1 =$$

$$\left(\frac{1.2}{1.2} * \frac{240}{817} + \frac{10}{10} * \frac{200}{817} + \frac{28888.9}{26000} * \frac{117}{817} + \frac{25350}{26000} * \frac{260}{817}\right) - 1 \cong$$

$$\cong 1.00796 - 1 = 0.00796 \tag{44}$$

The WAGI measurement for Stage 2 is 0.00796, indicating a positive return on investment of 0.796% due to the XRP arbitrage trade. Even though there was a problem with one of the trades, the algorithm still generated a profit with this trade. Yet, the profit generated is not equal to the increase in XRP holding ($\frac{28888.9}{26000}\ \cong 1.11$) even though this was the "goal." Since we have "lost" some other assets in the arbitrage process, we must adjust profit generation for the loss we have incurred correspondingly. That is precisely what we do with WAGI. If prices do not change, the portfolio value will increase for the same amount as the calculated WAGI return of the second arbitrage trade since $\frac{82350.05\ USD}{81700\ USD} \cong 1.00796$.

4.2.3 Results

The example showcased two arbitrage trades, both resulting in positive returns on investment. The first stage returned a WAGI of 0.05, indicating a 5% return on investment due to the BTC arbitrage trade. The second stage had a WAGI of 0.00796, which translates to a 0.796% return on investment, emerging from the XRP arbitrage trade. Overall WAGI over this period is equal to:

$$WAGI = \prod_{j=1}^{2}\sum_{i=1}^{4}\frac{B_{i,j_{updated}}}{B_{i,j}}W\left(B_{i,j}\right) - 1 = (WAGI_1 + 1) * (WAGI_2 + 1) - 1$$

$$= 1.05 * 1.00796 - 1 \cong 0.05836 \quad (45)$$

The overall WAGI combining both stages was 0.05836, indicating a total positive compound return on investment of 5.836%. Through two stages of arbitrage trades, this example illustrates the capacity of WAGI to measure the performance of an arbitrage trading strategy effectively. Moreover, the example showcases the necessity of adjusting profit generation to account for potential losses incurred during the arbitrage process. This aspect of WAGI's calculation accurately assesses an arbitrage trade's performance and underlying dynamics.

Even though we had a successful arbitrage trading and the algorithm was profitable (although we had an error in stage 2), we still lost money. Since we have to hold a portfolio of assets we trade, we are greatly influenced by the market movement. We started with a portfolio worth $104{,}000\ USD$ and ended up with a portfolio worth $82{,}350\ USD$. That equals a loss of around 20.8%. However, due to the successful algorithm, we outperformed the passive portfolio of only holding these assets, as it would decrease more than the active portfolio did. If we did not trade arbitrage and would passively manage the portfolio (meaning initial balances would not change), the value at the end of stage 2 would be $77{,}700\ USD$, which equals a loss of 25.3%. Thus, we generated a loss of 4.5 percentage points less by actively managing the portfolio. With WAGI, we see that the algorithm for trading arbitrage is efficient, and we can generate a positive return with it (in the example). However, we also have to consider other optimizations of positioning assets to be less exposed to market movement since we still generated a loss.

Nevertheless, by incorporating WAGI measurement, we can see how profitable and efficient the algorithm is, even though we may be losing money in the crypto-assets market in the long term. If that is the case, one can consider entering another market where the portfolio is not so exposed to market movement yet still has arbitrage opportunities. Alternatively, change the structure of their portfolio.

In this example, we demonstrated how the Weighted Arbitrage Growth Index (WAGI) could be applied to measure the performance of arbitrage trading strategies and how it offers a more comprehensive assessment than simply examining the asset's value increases. We see that WAGI effectively adapts to the changes in asset weights as the portfolio evolves, ensuring an accurate representation of performance across different stages of the trading process. Moreover, the example also highlights WAGI's ability to capture the details of the trade execution process. In stage 2, the execution faced a problem resulting in a lower USD return from selling BTC, yet WAGI still recorded a profit. WAGI’s calculation allowed for the adjustment of profit generation in relation to the loss incurred, accurately reflecting the trade's performance. This example ultimately serves as a testament to the importance of utilizing WAGI to optimize arbitrage trading strategies. By capturing the dynamics of trading strategies, adapting to changes, and accounting for issues during execution, WAGI provides a comprehensive performance measurement that enables traders and investors to make informed decisions and adjustments.

4.2.4 Real-World Applications

While the example provided is simplified for illustrative purposes, WAGI's potential extends beyond this scenario. WAGI can be utilized across multiple trading pairs and exchanges in real-world applications. As the WAGI metric provides a more comprehensive assessment of arbitrage trading performance, it can be employed to compare different strategies and identify the most effective one for specific market conditions. That ensures better-informed decision-making and can potentially lead to increased returns.

4.3 The Generality of the Arbitrage Strategy Used

This section will clarify how the trading exchanges were selected for the following analysis. That is a critical aspect as it informs the extent to which the arbitrage strategy example presented can be considered a 'general' case. Furthermore, we will analyze the generalisability of this example, examining whether the principles and methods applied could be transposed to other financial markets, such as the FX market.

4.3.1 Choice of Exchanges and Generality of the Analysis

In choosing which trading exchanges to analyze for this thesis, three primary factors were considered:

1. the comprehensiveness of the API documentation,
2. the CoinMarketCap Score, and, in some instances,

3. their origin and personal preferences.

Exchanges with robust and detailed API documentation, such as Bitfinex, Bitstamp, and Binance, were favored because they facilitate easier data extraction and manipulation, which is crucial to the research's effectiveness. The CoinMarketCap Score, a reliable indicator of an exchange's credibility, transparency, and security, also played a significant role in the selection process. Bitstamp and Binance, for instance, are highly rated in this aspect. Personal preferences also influenced the choice, especially for native exchanges like Bitfinex. Comparatively, these chosen exchanges share many similarities with other top-perceived crypto exchanges, and we could choose any one of them to perform the analysis. Nevertheless, looking at the cross-section of trading pairs these exchanges offer is also crucial due to the optimization of finding the most arbitrage cycles with the lowest number of assets held.

Because all chosen exchanges feature various trading pairs, maintain high liquidity, and are extensively adopted, they are appropriate for evaluating arbitrage opportunities in cryptocurrency markets. So, we can look at this analysis as a »general« representation of the crypto-assets market, as the exchanges used are among the most prominent. However, significant differences exist between the volume traded on exchanges and their liquidity (even though all can be classed as high liquidity). Thus, for any new exchange, an analysis must be done to see its characteristics and which assets offer a possibility (if any) for arbitrage trading. Nevertheless, because the algorithm is generalized, the calculations can be done for any exchange if only we can access live data and transform it into the correct »format. «

4.3.2 Is this Aritrage Strategy applicable in the FX Market?

As discussed earlier in the previous chapter, the characteristics of the crypto-assets markets are, in principle, the same as those of the foreign exchange (FX) market when looking at the *triangular arbitrage*. As the solution for searching arbitrage opportunities is generalized, we could perform these calculations on any market with properties for triangular arbitrage if we have access to live data. Thus, with connection to some of the »exchanges« for the FX, we could search for the same type of opportunities. However, more often than not, access to FX data is costly, and (in personal experience) the API documentation to establish a connection with the exchanges is less detailed and understandable. Thus, operating with the crypto-assets market for research makes more sense.

4.3.3 Counterparty Risk

By trading on crypto exchanges, we expose ourselves to risks similar to those we expose ourselves to when trading on any other financial market. Counterparty risk is the likelihood or probability that one of those involved in a transaction might default on its contractual obligation (Murphy, 2023). We cannot eliminate these risks entirely when striving for arbitrage trading on the crypto exchanges. There were many cases when very well-perceived exchanges failed to meet their obligations (such as the *Futures Exchange* (*FTX*)), and many investors lost high quantities of assets. However, we can strive to minimize these risks.

Initially, we should opt for crypto exchanges governed by strict regulatory standards and committed to high levels of security and open business practices. This step is essential to safeguard funds and minimize the risk of losing investments because of other parties' failure. Nevertheless, we can meet these requirements only to some extent in the crypto-assets market. Furthermore, performing comprehensive due diligence on all counterparties we decide to work with is crucial. That includes evaluating their financial health and overall standing in the industry – which is what CoinMarketCap Score achieves to some extent. Detailed analysis and investigation into digital asset history can shed light on these entities' dependability and past performance. However, we must find the right balance between doing this kind of analysis and accepting the risks connected to the market we are entering.

By positioning our assets on more than one exchange, one of the key factors for arbitrage trading strategy (but by no means a necessary one, as arbitrage can exist on a single exchange), we reduce exposure to the risks discussed above. Even if one of the exchanges fails to meet its obligations, »initial investment« is safe on other exchanges. Thus, the more trustworthy crypto exchanges we include in trading strategy, the better it is. However, this does come with some downsides, for example, a decreased *Minimal Crypto Balance* for the strategy (considering the same initial investment).

4.4 Portfolio WAGI Measurement

With a comprehensive understanding of WAGI, we can discuss its applicability in real-life trading on the crypto-assets market. We will perform empirical analysis with some assumptions, which allow us to analyze market conditions without trading. In this subchapter, we will analyze the performance of three distinct portfolios:

1. Arbitrage Strategy 1 … (AS1)
2. Arbitrage Strategy 2 … (AS2)
3. Passive Portfolio … (PP)

The first two are active portfolios utilizing arbitrage trading with different sets of requirements for trading. The third one is a passive buy-and-hold portfolio that is a reference for the portfolio we must hold to trade arbitrage opportunities with the other two. This analysis aims to provide empirical evidence demonstrating the effectiveness and usefulness of the WAGI metric in a real-life context.

To analyze growth and calculate WAGI, we will program an algorithm not added to this research for its complexity. As has already been, some of its logic will be explained along the way.

> **Note**: The analysis done in this chapter is not an analysis of actual trading. It is merely an entry point for anyone wishing to try trading arbitrage opportunities and wants to analyze the market before entering a crypto-asset market. Alternatively, it can be seen as a framework for backtesting and analyzing how the arbitrage algorithm works.

4.4.1 Inputs for Analysis

The analysis uses actual data from crypto exchanges on which calculations are done. However, since the execution of orders can be flawed in actual trading, or the volatility is too high to get filled by the orders used to calculate arbitrage opportunity, monitoring trading activities when trading in practice is crucial.

This analysis shows how many opportunities are on the market and what kind of return we can theoretically generate if we trade it ideally. The requirements and assumptions for this analysis are the following:

1. ***Profit Benchmark*** (for portfolio AS1) … For arbitrage to be considered valid, the profit benchmark is set to 0.3% (the calculated increase of the starting asset has to be greater than 0.3%)
2. ***Profit Benchmark*** (for portfolio AS2)… For arbitrage to be considered valid, the profit benchmark is set to 0.5%
3. ***Fees*** (for both) … Are actual and **are included**.
4. ***Time difference*** (for both) … Order books must be up to 0.1 seconds old to be considered for the arbitrage.
5. ***Maximum Order Volume*** (for both) … The minimum amount we are willing to trade is $1000\ USD$.
6. ***Uniqueness*** (for both) … Two arbitrage opportunities cannot have the same order (in the order books) even if the volume is high enough.
7. ***Response delay*** (for both) … To simulate a real-life scenario, we must wait 20 seconds after performing an arbitrage before trading another. That is to simulate the time needed for the exchange to provide confirmation of orders and updated balances on the account. Thus, the "fastest" we can trade is one arbitrage per 20 seconds, even though there can be hundreds of opportunities in time slots.
8. ***There are no flaws*** (for both) … Every calculated arbitrage is also filled with prices used for finding arbitrage with zero errors.

The algorithm uses two inputs:

1. order books from exchanges and,
2. arbitrage cycles.

Thus, the algorithm knows in which time slots look at specific arbitrage cycles (symbols and exchanges). The reason to give the algorithm arbitrage cycles is due to the time complexity of calculations. With this, we significantly decrease the analysis time by feeding only the relevant order books into the algorithm. Then, it stimulates the market by feeding relevant order books (correct exchanges and symbols) to the "agent," which calculates profit with the order books "on the market." If the calculated profit meets the Profit Benchmark and other requirements are fulfilled, the agent "trades" the arbitrage and saves the results.

The exchanges used in the analysis are:

1. Bitfinex
2. Bitstamp
3. Binance

Furthermore, we are searching for arbitrage between the following trading symbols. Note that not all symbols are necessarily presented on all exchanges:

1. $BTCUSD$
2. $BTCEUR$
3. $ETHUSD$
4. $ETHEUR$
5. $ETHBTC$
6. $XRPUSD$
7. $XRPEUR$
8. $XRPBTC$
9. $LTCUSD$
10. $LTCEUR$
11. $LTCBTC$

4.4.2 Initial Portfolio Setup

We will analyze the Passive Portfolio (PP) value increase and the actively managed portfolios (AS1 and AS2) value increase in the given period. Furthermore, the calculation of the corresponding WAGI for the actively managed portfolios will be made, while for the passively managed portfolio, WAGI is undefined.

All portfolios started with the same initial balance on all exchanges consisting of the following assets.

Bitstamp:

- $B_{1,1} = 1\ (BTC)$
- $B_{2,1} = 10\ (ETH)$
- $B_{3,1} = 60000\ (XRP)$
- $B_{4,1} = 30000\ (USD)$
- $B_{5,1} = 30000\ (EUR)$

- $B_{6,1} = 500\ (LTC)$

Bitfinex:

- $B_{7,1} = 1\ (BTC)$
- $B_{8,1} = 10\ (ETH)$
- $B_{9,1} = 60000\ (XRP)$
- $B_{10,1} = 30000\ (USD)$
- $B_{11,1} = 30000\ (EUR)$
- $B_{12,1} = 500\ (LTC)$

Binance:

- $B_{13,1} = 1\ (BTC)$
- $B_{14,1} = 10\ (ETH)$
- $B_{15,1} = 60000\ (XRP)$
- $B_{16,1} = 30000\ (USD)$
- $B_{17,1} = 30000\ (EUR)$
- $B_{18,1} = 500\ (LTC)$

That holds true for portfolios PP, AS1, and AS2. The value of the portfolios is derived from the actual order books from the exchanges at the beginning of the analyzing period.

4.4.3 Trading Strategy Analysis

The data set for the analysis was retrieved for two days, which were 9.11.2023 and 4.12.2023. Both days are analyzed from 00:01 to 23:59. There were no portfolio changes between those two days. Thus, the analysis period starts on 9.11.2023 at 00:01 and ends on 12.04.2023 at 23:59, with trades happening only on these dates. The decision to use given days for this example arises from calculation power limitation and a wish to showcase the possible number of arbitrage opportunities. However, it is essential to acknowledge that days can be significantly different in almost all aspects from the day chosen for the analysis. We also cannot claim how likely a day of this type happens, as we do not possess those statistics.

Considering balances in our portfolio, our initial portfolio value equals $\$582991.54$ as per prices on the exchanges on 9.11.2023 at 00:01. After running the analysis, we gathered the following statistics for all three portfolios.

Arbitrage Strategy 1 ($\mathbf{0.5\%}$)

- Number of trades: 56
- Starting portfolio value: \$582,991.54
- Ending portfolio value: \$602,251.49
- Portfolio profit: \$19,259.95
- Portfolio percentage profit: 3.30%
- WAGI: 0.009039

Arbitrage Strategy 2 ($\mathbf{0.3\%}$)

- Number of trades: 84
- Starting portfolio value: \$582,991.54
- Ending portfolio value: \$603,800.98
- Portfolio profit: \$20,809.44
- Portfolio percentage profit: 3.56%
- WAGI: 0.010262

Passive Portfolio (no change of balances)

- Starting portfolio value: \$582,991.54
- Ending portfolio value: \$600,885.17
- Portfolio profit: \$17,893.63
- Portfolio percentage profit: 3.06%

As the logic for choosing the starting assets is the same for AS1 and AS2, the portfolio with higher WAGI also has higher portfolio profit (in USD), even though that is not necessarily always the case. If the strategies take different starting assets when trading, their value in USD affects the portfolio value differently as their prices move individually.

By trading arbitrage opportunities on the market with AS2, we have generated a return of 0.5 percentage points higher than holding only a passive portfolio. We can see analog results with AS1. Even though we have applied extreme requirements of waiting for 20 seconds between arbitrage opportunities, this results in a significant profit for two trading days (in theory). This limitation greatly affects our trading, as arbitrage opportunities do not arise often, yet when they do, there can be hundreds of opportunities, and trading speed is essential.

After the trading period, the amount of assets held in the portfolio for each arbitrage strategy are as follows.

Arbitrage Strategy 1

Binance:

- BTC: 1
- ETH: 10.016859
- EUR: 30,000
- LTC: 500
- USD: 30,000
- XRP: 60,009.672

Bitfinex:

- BTC: 1
- ETH: 10.054422
- EUR: 30,230.94
- LTC: 500
- USD: 30,319.339
- XRP: 60,020.166

Bitstamp:

- BTC: 1
- ETH: 10.083761
- EUR: 30,196.32
- LTC: 500.46053
- USD: 30,191.66
- XRP: 60,000

Arbitrage Strategy 2

Binance:

- BTC: 1
- ETH: 10.046018
- EUR: 30,000
- LTC: 500.29434
- USD: 30,000
- XRP: 60,197.795

Bitfinex:

- BTC: 1
- ETH: 10.144573
- EUR: 30,397.26
- LTC: 500
- USD: 30,668.67
- XRP: 60,040.332

Bitstamp:

- BTC: 1
- ETH: 10.164166
- EUR: 30,395.58
- LTC: 500.72484
- USD: 30,379.30
- XRP: 60,006.648

The overall WAGI for both actively managed portfolios on this day is retrieved from the following calculations:

$$WAGI_{AS1} = \prod_{j=1}^{56} \sum_{i=1}^{18} \frac{B_{i,j_{updated}}}{B_{i,j}} W(B_{i,j}) - 1$$

$$= (WAGI_1 + 1) * (WAGI_2 + 1) * \ldots * (WAGI_{78} + 1) - 1$$

$$= 1.0000828 * 1.0000553 * \ldots * 1.0001208 - 1 \cong 0.009039 \quad (46)$$

$$WAGI_{AS2} = \prod_{j=1}^{84} \sum_{i=1}^{18} \frac{B_{i,j_{updated}}}{B_{i,j}} W(B_{i,j}) - 1$$

$$= (WAGI_1 + 1) * (WAGI_2 + 1) * \ldots * (WAGI_{84} + 1) - 1$$

$$= 1.0000824 * 1.0001509 * \ldots * 1.0000470 - 1 \cong 0.010262 \quad (47)$$

The portfolio with the more successful arbitrage strategy (AS2) also created a more considerable financial gain. However, remember that even though a financial gain can be more significant for a particular portfolio, it does not mean that the arbitrage algorithm applied to the portfolio is the most efficient. For further trading, we would employ an arbitrage strategy AS2 as it results in a higher WAGI value for the analyzing period. Yet, we have to be cautious as, in practice, it could happen that because of small profit requirements, we often create a loss (because of slow trading or other problems) instead of a profit, which may not be the case when following AS1. Thus, it is imperative to remember that trading is not a stationary endeavor, and we have to continuously analyze trading activity and adjust the parameters for the algorithm based on market circumstances.

That analysis is a testament to the fact that traders can take advantage of lucrative arbitrage opportunities on the crypto-asset market if they have their trading infrastructure set up correctly.

4.5 Now What - Should We Go Trading Arbitrage?

As shown here, we could take advantage of very lucrative trading opportunities on the market in theory. Thus, one should have questioned why there are no traders (institutional or retail) on the market who take advantage of these opportunities. Unfortunately, we cannot give a straight answer to this question. The reality is that there are most likely some big players already taking advantage of these opportunities. Nevertheless, data of this kind is not publicly accessible, so we cannot claim anything with certainty.

However, do not let this analysis give us a false feeling that these kinds of arbitrage are relatively straightforward to exploit. Developing an algorithm, as in this thesis, which is more similar to backtesting and is looking solely for the "existence of arbitrage opportunities," is way easier than developing an actual trading algorithm that could take advantage of these opportunities in real-time. For example, we assumed we could trade everything perfectly and fill the "arbitrage prices" at desired levels. However, in reality, we do not know how long these opportunities last and how likely it is to develop a trading algorithm that will be able to take advantage of them. We would have to create a whole new analysis to gain this knowledge. The markets are in constant price movement; thus, an actual application of high-frequency trading should be applied to exploit these price discrepancies.

So, to answer why no one (or rarely anyone) is taking advantage of these arbitrary opportunities, is because it is a very advanced technical programming problem requiring much financial knowledge and resources. Unfortunately, it is not one of those "getting rich schemes," as developing such an algorithm would take a team of people familiar with necessary tools much more time than it seems at first glance reading this master thesis.

5 CONCLUSIONS

The thesis explained cryptocurrency as an asset class, discussing its definition, characteristics, and the fundamental role of money. It explains the use of the term crypto-assets instead of cryptocurrency and its rationale. The risks and benefits associated with crypto-assets were examined to highlight the importance of thoroughly understanding these factors when engaging in arbitrage trading. Furthermore, we focused on the intricacies of arbitrage trading on cryptocurrency exchanges, including detecting (triangular risk) arbitrage opportunities and the requirements for successful trading. Limitations that may impact trading activities, such as the "First In Principle," “Minimal Crypto-assets,” and “Maximum Order Book Volume,” were identified as crucial considerations for implementing a robust arbitrage trading strategy.

The study aimed to measure the arbitrage algorithm's efficiency and evaluate its performance objectively, considering the gains derived solely from arbitrage trading while excluding the influence of broader market movements. A novel metric, the Weighted Arbitrage Growth Index (WAGI), was introduced to address this challenge. Throughout the research, a comprehensive explanation of the WAGI metric was provided, including its components, calculation formulas, and rationale. The metric's application was demonstrated through a fictional portfolio, where arbitrage opportunities identified by the algorithm were executed and evaluated using WAGI. The results obtained from applying WAGI showcased its ability to measure the success of the arbitrage trading strategy while isolating the gains derived solely from arbitrage trading. The metric effectively removes the influence of general market movements, allowing for a more accurate assessment of the algorithm's efficiency. It is important to note that while WAGI provides a valuable tool for evaluating the performance of the arbitrage algorithm, it focuses solely on the percentage increase of the portfolio holdings due to arbitrage trading. Factors such as asset depreciation or appreciation are not directly considered within the metric. By incorporating this metric into the evaluation framework, investors can make informed decisions, refine their trading strategies, and enhance their overall trading performance in the crypto-asset market.

Further research and analysis are recommended to explore additional aspects of portfolio optimization and comprehensive performance evaluation beyond the scope of this research. By incorporating various factors and considering broader market dynamics, investors can better understand their arbitrage trading strategies and enhance their outcomes. Overall, this research contributes to the existing body of knowledge in arbitrage trading and provides a valuable framework for evaluating the efficiency of arbitrage algorithms using the Weighted Arbitrage Growth Index (WAGI).

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APPENDIX

Appendix 1: Povzetek (Summary in Slovene language)

V magistrski nalogi smo si ogledali kripto valute kot naložbeni razred, jih definirali in razložili njihove značilnosti ter analizirali kako dobro zadostijo pogojem za vlogo denarja. Poleg tega smo utemeljili nadaljnjo uporabo izraza kripto sredstva (Crypto-Assets) namesto kripto valute in razložili, zakaj je ta izbira imena za naložbeni razred primernejša. Pogledali smo si tveganja in koristi povezana s kripto sredstvi ter poudarili pomembnost temeljitega razumevanja tveganj in koristi za kvalitetno arbitražno trgovanje na trgu kripto sredstev.

Arbitraža, ki smo jo obravnavali v magistrski nalogi je *triangularna tvegana arbitraža* (triangular risk arbitrage), kljub temu, da se skozi celotno nalogo uporablja le termin arbitraža. Poleg tega smo se osredotočili na praktično vse vidike arbitražnega trgovanja na kripto valutnih borzah, vključno z odkrivanjem priložnosti za arbitražo in zahtevami za uspešno trgovanje. Kot bistvene vidike za izvajanje kvalitetne arbitražne trgovalne strategije smo prepoznali omejitve, ki lahko vplivajo na trgovalno dejavnost, kot so "First In Principle", “Minimal Crypto-assets” in “Maximum Order Book Volume”.

V nalogi smo želeli izmeriti učinkovitost arbitražnega algoritma in objektivno oceniti njegovo uspešnost. Pri tem smo želeli upoštevali le dobičke, pridobljene izključno iz arbitražnega trgovanja in hkrati izključiti vplive širših tržnih gibanj. Za reševanje izziva je bila predstavljena nova mera WAGI (Weighted Arbitrage Growth Index). Podali smo obsežen opis mere WAGI, vključno s potrebnimi parametri, formulo za izračun in utemeljitvijo. Uporaba WAGI je bila prikazana skozi fiktivna portfelja, na katerima so bile trgovane arbitraže. Rezultati, pridobljeni z uporabo WAGI, so pokazali sposobnost merjenja uspešnosti arbitražne trgovalne strategije, pri čemer smo obravnavali le dobičke pridobljene izključno iz arbitražnega trgovanja. Mera učinkovito odstrani vpliv splošnih tržnih gibanj, kar omogoča natančnejšo oceno učinkovitosti arbitražnega algoritma. Pomembno je opozoriti, da čeprav WAGI zagotavlja orodje za ocenjevanje uspešnosti arbitražnega algoritma, se osredotoča izključno na odstotno povečanje sredstev v portfelju zaradi arbitražnega trgovanja. Dejavniki, kot so padec ali rast vrednosti sredstev, niso neposredno upoštevani znotraj te mere. Z uporabo WAGI za ocenjevanje arbitražnih strategij lahko vlagatelji sprejemajo informirane odločitve, izpopolnjujejo svoje trgovalne strategije in izboljšajo svoje splošne trgovalne rezultate.