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Central European Economic Journal

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Cryptocurrencies as an asset class in portfolio optimisation

Abstract

In this paper, cryptocurrencies are analysed as investment instruments. The study aims to verify whether they can be classified as an asset class and what kind of benefits they may bring to the investor's portfolio. We used 6 indices as proxies for the major asset classes, including the cryptocurrency index CRIX, for all cryptographic assets.
Cryptocurrencies relatively fully satisfied 7 asset class requirements, namely stable aggregation, investability, internal homogeneity, external heterogeneity, expected utility, selection skill and cost-effective access. It was found that crypto assets have diversification properties. Portfolio optimisation with the Modern Portfolio Theory showed an increase in the Sharpe ratio of tangency portfolios with the inclusion of CRIX. However, the Post-Modern Portfolio Theory identified significant deterioration of the downside risk and the Sortino ratio.

Keywords

cryptocurrencies | blockchain technology | asset class | portfolio optimisation | Modern Portfolio Theory | Post-Modern Portfolio Theory

JEL Codes

C61, G11, G12

1 Introduction

Cryptocurrencies are relatively new financial instruments; however, their usage has increased considerably since the introduction of Bitcoin in 2009. Simultaneously, Bitcoin has become a common payment tool for most kinds of online transactions. Nevertheless, there is still a controversial discussion on whether cryptocurrencies can be treated as an asset class or just a developing financial bubble.

Cryptocurrencies do not satisfy all the criteria of a traditional currency, according to David Yermack (2015). They fulfil the conditions only partially. Cryptocurrencies are not issued by any public institution, such as a government or a bank, meaning they are decentralised and, let us say, virtual. The only drivers of their prices are supply and demand; so cryptocurrencies show higher volatility compared to so-called hard currencies. All of these points, combined with the lack of any regulation, make them sensitive to speculation and financial bubble formation (Grinberg, 2011).

In recent years, the crypto market has matured significantly, having higher liquidity and narrowing bid–ask spread. Due to the development of trade platforms and exchanges with high level of automation, the problem of impracticality of quoting prices is disappearing. Regarding the intrinsic value, the increase in security of trading platforms and computers, as well as stabilised volatility, significantly lowers the risk of losing money and proves that cryptocurrencies are able to store a value.

From the investor's point of view, cryptocurrency may have a few significant benefits, such as no risk of being seized by government institutions, and transactions are usually tax free. Moreover, payments cannot be tracked, assuring a decent level of data protection and privacy. However, there are still risks involved, such as hacker attacks, crash of hard drives or viruses corrupting data. Apart from the technical issues, there might be regulatory factors that limit the usability of cryptocurrencies, such as a Chinese ban on Bitcoin trading in 2014.

There is still a debate whether cryptocurrencies can be considered as a new class of assets. Some authors, e.g., Brown (2018) and Kreuser and Sornette (2018), claim that this is an evident bubble. Nevertheless, most modern studies tend to maintain the idea that they are gradually evolving into a new distinct asset class.

The crypto market is in some way isolated from market-driven factors and external shocks. It implies that cryptocurrencies may be an effective diversification tool, offering a so-called "safe haven" for investors (Corbet, Lucey, Urquhart, & Yarovaya, 2019). As result, we can observe an idiosyncratic risk, which is related strictly to the crypto market and is difficult to hedge against.

As already mentioned, it is useful to look at cryptocurrencies as a diversification tool, as their levels of correlation with other assets tend to be 0 (Yermack, 2015). Baek and Elbeck (2015) found high volatility and a positive excess kurtosis, meaning there is a greater probability of extreme values compared to the stock market. Brière et al. (2015) found that addition of cryptocurrency to the investment portfolio brings risk–return benefits, which implies that cryptocurrencies may be treated as an asset class with good diversification and hedging properties. A similar conclusion was obtained by Chuen et al. (2017), who stated that incorporation of the cryptocurrency index significantly expands the efficient frontier of the traditional asset classes. Krueckeberg and Scholz., 2018 (2018) claimed that cryptocurrencies constitute a new distinct asset class and that adding even a 1% allocation to traditional portfolio structures leads to considerable and constant outperformance. Brauneis et al. (2018) were the first ones to find substantial potential for risk reduction when several cryptocurrencies are added, instead of 1 (typically Bitcoin), to a portfolio containing traditional asset classes. However, some studies are not that straightforward. For example, when Brière et al. (2015) analysed the Sharpe ratio and the adjusted Sharpe ratio in order to compare the risk–return performance, they discovered that the addition of Bitcoin provokes a significant increase in the Sharpe ratio, but a decline in the adjusted Sharpe ratio.

This paper aims to answer the question whether cryptocurrencies can be used as an asset class in portfolio optimisation and what kind of benefits an investor may obtain by adding these instruments to his/her portfolio. The topic is relevant currently due to the fast development of the crypto market and the numerous contradictions among researchers.

The paper comprises three parts. The first one, Literature Review, gives a theoretical background of crypto assets, blockchain technology, market and classification. In the second section, the choice of dataset and applied methodology are explained. The third section is dedicated to the empirical results of the research. The paper ends with discussions and conclusions.

2. Literature review

2.1. The technology behind cryptocurrency

Similar to any cutting-edge technology, blockchain, which underlies cryptocurrencies, meets both enthusiasm and resistance. While some people believe that blockchain is the beginning of a digital era of the future, their opponents argue that it is a developing financial bubble or a scheme for criminals and money launderers. There are arguments supporting both sides; however, 10 years of the growing usage of the blockchain technology, its implementation in public spheres and its involvement in daily transactions prove its practical application.

Cryptocurrencies have appeared as a pioneer generation of blockchain-based applications. The very first realisation of the technology was introduced by Satoshi Nakamoto in his article "Bitcoin: A Peer-to-Peer Electronic Cash System" (2008), where he stated as follows: "*What is needed is an electronic payment system based on cryptographic proof instead of trust, allowing any two willing parties to transact directly with each other without the need for a trusted third party*" (Nakamoto, 2008). In other words, blockchain is a decentralised tamper-resistant transaction system and data management solution, in which records are stored across numerous nodes connected in a chain. Another way to look at blockchain is as a distributed ledger spread across a network of multiple holders, locations or devices (Garriga, Arias, & De Renzis, 2018).

Blockchain contains a sequence of ordered back-linked blocks that keep details of transactions. Transactions inside each block are merged and hashed in the form of a binary tree, or Merkle tree, with the root (top) of the tree saved in each record (Nakamoto, 2008). Being in a chain, blocks preserve hashes of all the previous blocks and replay them from the origin of the chain. In case of modification of the original data, the hash is also altered and no longer matches the original fingerprint; so rehashing of all subsequent blocks would be needed. This ensures the integrity of the system as it is practically almost impossible to rewrite all the hashes and hence to manipulate the data inside the chain.

What makes blockchain technology unique is a set of three components, which allows one to create, update, verify and audit records across the system without third parties' intervention.

The first element is the **peer-to-peer (P2P) network** – a net of equally privileged computers (nodes) connected to each other within a common system (Garriga et al., 2018). The blockchain database is then distributed across multiple nodes, where all members of the network have access to the data. As result, there is no need to trust any intermediary party, as blockchain by itself is able to validate and maintain a permanent record-keeping process supporting privacy of personal data.

The second component, which ensures secure unaltered communication, is **cryptography**. The blockchain is secured against retrospective changes in records via a cryptographic hashing algorithm such as SHA-256 or some other, which serve as fingerprints when verifying the authenticity of the record. Once an initiator signs a transaction, it will be validated and distributed across the network of nodes until all nodes contain it in their blocks (Xu et al., 2017).

The third part is **consensus algorithm,** which maintains the consistency of the database each time when validation of a new transaction is needed. Proof-of-Work (PoW) is the most common consensus algorithm, underlying Bitcoin and Ethereum. To achieve consensus, PoW requires miners to solve a mathematical problem, usually a hash function, which demands high computational power and hence consumption of energy (Garriga et al., 2018).

The establishment of a decentralised autonomous organisation (DAO), which actually a public blockchain is, constitutes a shift from a socio-technical system to a techno-social system. The former controls the system through social relations, while the latter does this through autonomous technical mechanisms, avoiding social intervention. This has become a new era of economic relations.

2.2. Crypto market

Already, the crypto market has undergone 6 years of existence, although it has been activated only since 2017. A rapid jump in 2017 ended up with a peak of $836 billion market capitalisation on 7 January 2018. Since that time, the market cap has shown a constant downward trend and now amounts to $278 billion (as of 15.07.2019). In the meantime, the trading 24-hour volume has increased considerably in 2019, reaching higher volumes than in the period of the peak. Such tendency indicates a higher activity of traders and better liquidity characteristics of the market.

The structure of the market is defined by the market cap of cryptographic coins and tokens. Although Bitcoin remains the most valuable and popular cryptocurrency, the market of alternative implementations is growing rapidly. In early 2014, the numbers of altcoins and tokens amounted to 69 only and, since that time, have been increasing steadily. Currently, >2200 crypto assets are listed on Coinmarketcap, although many of them are still illiquid. Bitcoin's dominance has decreased from 95% in 2013 to 65% currently, while the fraction of new coins and tokens has risen; this signifies the growing potential and trust towards other blockchain-based assets.

To sum up, the market is still very small compared to traditional assets, and its internal structure is constantly in transformation. Market capitalisation is stabilising after drastic jumps in recent years. It is early to argue about the maturity of the crypto market, but the period 2018–2019 has shown a positive tendency.

2.3. Classification of cryptocurrencies

Being too unconventional for financial markets, cryptocurrencies have not yet been classified by academics and investors. Some researchers tend to define them as currencies, while others argue about considering them a new asset class. Obviously, cryptographic assets cannot yet fully match all the commonly used criteria for either the first or the second group, at least those accepted by public institutions.

Traditional currency, as it is treated by Central Banks, should technically fulfil three functions to be considered as such: unit of account, store of value and medium of exchange. As a rule, high-cap cryptocurrencies show the potential to meet all the aforementioned requirements, while the remaining ones struggle to meet even a single one.

Unit of account is the first function of currency, which allows the measurement of the value in specific units and comparison among each other. Digital currencies are composed of identical, individual and measurable units of account. Until they are liquid, this function is satisfied, as the value is determined and comparable (Kim, Sarin, & Virdi, 2018). Thus, high-cap coins indeed behave like units of account.

Store of value implies retaining purchasing power in the future, so it can be more (or less or equally) useful and exchanged later on. It requires a certain degree of predictability of the future asset value, which can be pretty difficult with crypto assets due to their extreme volatility. For instance, both gold and digital coins are able to store the value, are detached from fiat money and provide a safe zone during crises; however, only gold preserves these features in the long run. Referring to Kim et al. (2018), daily exchanges of some digital assets, namely Bitcoin (BTC), Ethereum (ETH) and Litecoin (LTC), exceeded even the annual inflation rates of the countries in recession (such as Mexico and South Africa), meaning it is less risky to hold the Mexican Peso than hold top crypto coins. Due to such a degree of volatility and possible hacking attacks, the conformity of crypto assets to a safe store of value is questionable while the market is not stabilised.

Medium of exchange function requires an instrument to be widely accepted and exchangeable for all available goods and services. It has to behave like an intermediary and to avoid the limitations of the barter transactions. Nowadays, most of the cryptocurrencies cannot meet this condition, as they are not easily accessible for regular payments. BTC, LTC, ETH and United States dollar tether (USDT) provide access to other crypto assets and play the role of intermediaries between fiat money and crypto. Generally, cryptocurrencies can be treated as a medium of exchange of crypto assets (Kim et al., 2018), but this function is at the stage of development and is visible only for very top crypto-based coins, but not to the whole class.

Within governments, a common view on whether cryptocurrencies conform to the standards of actual money is still absent. The Bank of England refuses to consider cryptographic coins as money. Similarly, the European Central Bank has concluded that digital currencies could not be treated as money, but the nature and technology behind them may soon have a great impact on the economy, so virtual currencies should be actively monitored. The European Banking Authority rejects the term "currency" in the context of crypto assets and insists on their separation from payment activities due to high technological risks. At the same time, the European Supervisory Authorities published a warning for consumers about the risks of buying and holding virtual currencies. Most of the Central Banks in Europe do not treat crypto assets as a unit of account. However, the German Federal Financial Supervisory Authority accepted Bitcoin as a unit of account similar to a foreign exchange (although the Bitcoin does not satisfy the criteria to be a legal tender), but only as a kind of private means of payments. The French Authority rejects cryptocurrencies even for financial instruments. At the same time, in Italy, virtual currencies have been validated as a means of exchange. In China, in 2014, the mining industry was totally banned due to financial stability prospects. In the United States, cryptocurrencies are regulated simultaneously as a currency and as a security. The United States has not declared them officially as a legal tender, but they are not illegal.

Most studies agree that cryptographic coins and tokens cannot be considered as currencies but, more likely, can resemble speculative financial instruments (Demertzis and Wolff, 2018). The same derivation was obtained by Yermack (2015), stating that "currency" is a misnomer for Bitcoin and its derivative instruments, while a more appropriate nomination is "crypto assets". In this framework, we conduct further analysis of this topic.

According to the conducted literature review, some research works, such as those by Brown (2018) or Kreuser and Sornette (2018), claim that cryptographic assets are an obvious financial bubble. They built dedicated bubble models for cryptocurrencies, predicting their early burst. Nevertheless, most modern studies tend to maintain the idea that they are gradually evolving into a new asset class.

A dominant majority of authors is optimistic about the future of crypto assets, although uncertain regarding the current role of the latter. For example, Sontakke and Ghaisas (2017), Bianchi (2018), Trautman and Dorman (2018) and Corbet et al. (2019) support the idea that this is a future asset class that is currently at the stage of development and is obtaining the initial characteristics of a separate class. The key idea of these papers is the uncorrelated nature of cryptocurrencies.

In the meanwhile, Härdle, Chen and Overbeck (2017), Baur, Hong and Lee (2018) and Kurka (2019) have made a conditional conclusion regarding the readiness to form a distinct crypto asset class. They have proved a high dependence of the crypto market on shocks, speculations, hacker attacks and regulation changes; so such events are expected to define the future of crypto assets.

Nevertheless, there is already a group of academics who believe that cryptocurrencies are already showing the necessary characteristics to be defined as an asset class, regardless of current limitations and risks. Among them are Elendner, Trimborn, Ong and Lee (2018), Burniske and White (2017), Ankenbrand and Bieri (2018), Kim et al. (2018) and Krueckeberg and Scholz (2018). Such arguments as internal correlation among crypto assets, absence of correlation with external groups of assets, increasing liquidity, growing interest of public authorities, implementation into multiple industries and so on support the idea of the emergence of a new asset class.

3. Data and methodology

3.1. Data

3.1.1. Cryptocurrencies

In this research, cryptocurrencies are considered as an asset class; hence, we should test both internal structure of the crypto assets and their external relations with other asset classes.

Due to their very dynamic structure and extreme volatility, it is reasonable to use the cryptocurrency index instead of a few top currencies or Bitcoin only, whose dominance on the market is currently diminishing. According to research, the most comprehensive cryptocurrency index is the CRIX. Although it has appeared as an academic initiative and is not tradable, from the theoretical point of view, it effectively represents the market and is considered as a benchmark among both academics and traders. Additionally, it is adjusted to the specifics of the crypto market, among which are a very dynamic internal structure, the possibility of frequently vanishing and emerging coins and tokens, high volatility, necessity of constant monitoring, recalculation and so on. Consequently, CRIX perfectly fits the purpose of this paper.

The CRIX is computed and published on thecrix.de platform by the Humboldt University at Berlin in cooperation with the Singapore Management University. The index is a real-time benchmark computed following the Laspeyres derivation with regular rebalancing. In its calculation, a volume-weighting scheme is applied instead of simple market capitalisation weighting. The construction formula for the adjusted Laspeyres index is presented below:

$$\mathrm{CRIX}_t(k,\beta) = \frac{\sum_{i=1}^{k} \beta_{i,t_l^-} P_{it} Q_{i,t_l^-}}{Divisor(k)_{t_l^-}}, \tag{1}$$

$$Divisor(k,\beta)_0 = \frac{\sum_{i=1}^{k} \beta_{i0} P_{i0} Q_{i0}}{\text{starting value}}, \tag{2}$$

where P_{it} is the price of the asset i at time t, Q_{it} is the quantity of the asset i at time t, $\beta_{i,t}$ is the i-th asset's adjustment factor at time t, l is the adjustment factor and t_{-l} is the last time point of update (Trimborn and Härdle, 2018).

The constituents of the index are dynamic according to the liquidity rules. Crypto should fulfil at least 1 of 2 rules: have either high market capitalisation or high trading frequency. This makes only truly essential currencies eligible for CRIX.

The number of constituents in the index is also subject to change. While the indices of relatively stable markets usually have a fixed number of constituents, CRIX uses the Akaike Information Criterion (AIC) and the Bayesian Information Criterion (BIC) to identify the optimal one. When defined, each asset in the index is weighted according to its market capitalisation.

The key advantages of the index in the context of our study are as follows:

- The index has a dynamic number of constituents recalculated every 3 months. This catches the fast development of the market structure.
- Reallocation is conducted every month according to the market capitalisation. Shares inside the index are synchronised with the realised shares on the market.

Table 1: Asset classes and their proxies

Asset class	Proxy	Ticker	Details
Stocks	S&P500	^GSPC	The index represents stocks of 500 of the largest US companies.
Bonds	Vanguard Total Bond Market Index ETF	BND	ETF follows the Bloomberg Barclays US Aggregate Float Adjusted Index, which comprises corporate, government, international bonds, as well as mortgage- and asset-backed securities.
Foreign exchange	Dow Jones FXCM Dollar Index	USDOLLAR	The index tracks the performance of foreign exchange (FX) trading activity based on appreciation and depreciation of the dollar relative to EUR, GBP, AUD and JPY.
Commodities	Bloomberg Commodity Index	BCOM	The index reflects the changes in commodity futures prices. It contains 27 of the most significant and liquid commodities, including gold, silver, oil, gas, wheat, corn and so on.
Real estate	Dow Jones Real Estate Index	DJUSRE	The index reflects the performance of the real estate industry. It captures segments of the US market with large, medium and small capitalisation.

Source: Own work, computed in R.

– CRIX allows for a really high number of constituents as long as it is needed for adequate representation of the market.
– The index does not react on changes in the number of assets or initial coin offerings, but is only responsive to price fluctuations.
– In case the price of any coin is missing, the index is not affected.
– When any cryptocurrency stops functioning, as may often happen, the index is insensitive to this event and cancels the currency from the list on the reallocation date.

In order to analyse the internal structure of the crypto asset class, the dataset of the top 20 cryptocurrencies are used according to their market capitalisation. High, low, open and closed modes; market capitalisation; as well as the trading volume compose a set for analysis. We use the data from 01.08.2014 to 17.07.2019 with daily frequency.

3.1.2. Traditional assets

Following Krueckeberg and Scholz., 2018 (2018), there are 5 key asset classes: stocks, fixed income, commodities, foreign exchange and real estate (Table 1). In order to represent the whole class, a corresponding index or exchange-traded fund (ETF) is used in this study. Further analysis is based on the US market in order to avoid any misclassifications in representation of the asset classes on a global scale. The analysed period is the same as for the CRIX index – from 01.08.2014 to 17.07.2019. The data frequency is respectively daily.

3.2. Methodology

3.2.1. Asset class requirements

The first question is whether cryptocurrencies can be considered as a distinct asset class. A common methodology to test this hypothesis is subjective. The most general definition was given by Sharpe (1992) in his Asset Class Factor Model. Three requirements were proposed: mutual exclusivity among other classes, exhaustiveness within the class itself and meaningful difference in returns compared to other assets. In practice, it means that any asset may be included strictly in 1 asset class; the asset class should be capable of including as many assets of similar nature as needed; the returns of the asset in 1 class have either really low correlation or different level of volatility with other classes (Sharpe, 1992).

A more advanced definition, which covers both traditional and alternative assets, was proposed by Kinlaw, Kritzman, Turkington, and Markowitz (2017). According to their book, “an asset class is a stable aggregation of investable units that is internally homogeneous and externally heterogeneous, that when added to a portfolio raises its expected utility without benefit of selection skill, and which can be accessed cost effectively in size”. Following this definition, there are 7 essential criteria that should be satisfied by cryptocurrencies for them to be considered as a distinct asset class.

1. Stable aggregation

It refers to the stability of the class composition. To be treated as an asset class, the structure of the cryptocurrency market should not be too volatile in terms of the nature of its constituents; otherwise, constant rebalancing, misclassifications and monitoring of the new elements may be overly expensive. Market capitalisation of individual assets may be changeable due to price movements, while the nature, statistical properties, purpose of the usage and so on should remain stable. In case the composition depends on external factors that highly vary in time, the assets would not be stable and, thus, would not be qualified as a class. For cryptocurrencies, this criterion can be checked via qualitative analysis.

2. Investability

The assets should be directly investable. If, to expose the performance of the asset, an investor has to create a replicating portfolio, it cannot be treated as an asset class. Replication generates additional costs to maintain a proper structure and is sensible to outer events; so, that cannot truly mimic the behaviour of the underlying asset. To test the investability of the cryptocurrencies, we need to prove easy access to channels of direct investing for this class.

3. Internal homogeneity

It is assumed that all constituents of the class have similar characteristics for the investor. Internal homogeneity means similarity inside the class. There can be several groups with different characteristics within 1 class, although, together, all have the same characteristics compared to other classes.

In order to perform a quantitative analysis, we download the close prices of the top 20 cryptocurrencies with the highest market capitalisation. This number is assumed to have enough representative power due to its relative stability compared to the remainder of the market structure. As inputs, we take daily returns. Next, the normality of each time series should be tested with Shapiro–Wilk or Lilliefors normality test. Then, correlation analysis of the internal dependencies between cryptocurrencies should be done. We use three correlation coefficients, both parametric and non-parametric, and compare the correlation matrices for reliability: a parametric product-moment **Pearson's r,** a non-parametric rank **Kendall's** τ and a non-parametric rank **Spearman's r.** An internal homogeneity of the asset class can be proved when assets are positively correlated. Therefore, we expect correlation coefficients to be positive from 0 to 1 (Krueckeberg and Scholz., 2018).

4. External heterogeneity

As opposed to the internally homogeneous structure of the class, externally, assets must be heterogeneous. Significant dissimilarities with other classes are beneficial for an investor; otherwise, the class may be simply redundant on the market. A comparison of asset classes should be based on their representation as a whole. Thus, to test the heterogeneity, we use proxies, namely indices, which represent the overall performance of the class. The CRIX, which is the proxy for cryptocurrencies, is suitable due to its dynamic structure and monthly rebalancing.

The analysis comprises 3 steps: an analysis of statistical properties of the asset classes, comparison of their profiles and correlation matrix analysis. Statistical profiles comprise daily mean, standard deviation, trimmed mean, median, median absolute deviation (MAD), minimum, maximum, skewness, kurtosis and standard error; the profiles show how asset returns are distributed. To satisfy the heterogeneity criterion, the statistical properties of the asset class have to differ from already existing ones. The correlation matrix is computed on the basis of Spearman's coefficient, which fits the cryptocurrencies' properties the most, as it is not limited to linear relation only. In statistical terms, heterogeneity implies absence of correlation with other classes.

5. Expected utility

When an asset is included into an investment portfolio, it should increase an expected utility of this portfolio, which means either to raise the return or reduce the risk. This may be reached in two cases: when the asset has relatively high return and low risk; or when the asset is highly heterogeneous, i.e. it is uncorrelated with other classes. In other words, we want to get a diversification benefit from its inclusion. The rise of the expected utility sometimes depends on the market conditions and may occur in periods of crises, while it is not observed during a period of economic growth.

The second and third hypotheses are derived exactly from this property of an asset class. To check whether they hold, Modern and Post-Modern Portfolio Theories are used.

6. Selection skill

An investor is not supposed to have any special skills to pick a proper unit from an asset class to add an expected utility to his/her portfolio. This requirement is supported by the internal homogeneity of the asset class, so any unit of the class brings relatively similar exposure. Introduction of indices usually decreases the need for selection. Analysis of existing indices and internal homogeneity will serve as the test for this criterion.

7. Cost-effective access

Transaction fees, spread, opportunity costs and liquidity level play a crucial role when deciding whether to invest or not. The expected utility of inclusion of the asset to the portfolio also depends on them. Consequently, the asset class should be available at reasonable costs. Due to the necessity of permanent rebalancing of the portfolio, the mentioned trading costs should not impair profitability and liquidity of the portfolio (Frazzini, Israel, & Moskowitz, 2018). In order to verify this feature of cryptocurrencies, an analysis of bid–ask spread, transaction fees and liquidity is conducted.

Cryptocurrencies with the highest market cap are analysed here. For each of them, the following parameters are calculated:

1. **Bid–ask spread** – the difference between the bid (the highest price a buyer wants to pay) and the ask (the lowest price a seller is ready to sell). Spread is usually determined by demand, supply and liquidity of the asset traded. A narrow spread is common for the most liquid instruments with balanced levels of supply and demand. This measure shows the hidden costs for a trader, which is especially important when trading frequency is high, as in the case of cryptographic assets.

2. **Spread percentage** – the bid–ask spread presented as a percentage of the close price. It indicates the relative measure of spread and is more applicable for our analysis due to its comparability.

$$Spread\ percentage = \frac{Ask\ price - Bid\ price}{Closing\ price} * 100\%. \quad (3)$$

3. **Turnover ratio** – a measure of the liquidity of the asset on the market. Higher values imply better liquidity of the instrument. In other words, this ratio shows how easily we can obtain or get rid of the asset. It can be calculated as the total value of the asset traded over a certain period by the total value of assets outstanding for the same period (Frazzini et al., 2018). As inputs, we use the daily trading volume and daily market capitalisation.

$$Turnover\ ratio = \frac{Volume}{Market\ capitalisation}. \quad (4)$$

4. **Close ratio** – a measure of completion of the orders. This ratio can be expressed as a percentage of the closed orders to the total number of orders made over a certain period of time (Kelly, 2015). It also indicates the liquidity and shows which part of the transactions has been proceeded with over the period, a day in our case.

$$Closing\ ratio = \frac{Closed\ orders}{Total\ number\ of\ orders}. \quad (5)$$

Additionally, an analysis of the transaction fees on the main exchanges should be conducted and compared with the fees on trading traditional assets.

3.2.2. Modern Portfolio Theory optimisation

The Modern Portfolio Theory (MPT), or Markowitz model, was introduced in 1952. Using mean and variance as proxies for return and risk, it considers financial assets as diversifiers and assesses them by their contribution to the risk–return profile of the portfolio. MPT aims to determine the optimal weights for assets in the portfolio in order to maximise the return and simultaneously minimise the level of risk (Markowitz, 1952).

The key assumption of the MPT is risk aversion of the investor. Consequently, a portfolio with higher level of risk may be chosen only when it provides higher return. And vice versa, if an investor wants to receive higher return, he/she should expect higher risk.

Portfolio return of the portfolio is calculated as the sum of proportionally weighted assets' returns, as follows:

$$E(R_p) = \sum_i w_i E(R_i), \tag{6}$$

where R_p – the portfolio return, R_i – return of asset i, w_i – an individual asset's weight and i – the number of assets in the portfolio.

Portfolio variance is expressed as a function of the correlation coefficients of each asset pair in the portfolio, their individual volatilities and weights (Markowitz, 1952), as shown in Eq. (7):

$$\sigma_p^2 = \sum_i w_i^2 \sigma_i^2 + \sum_i \sum_{j \neq i} w_i w_j \sigma_i \sigma_j \rho_{ij}, \tag{7}$$

where s$_i$ – an individual asset's standard deviation, r$_{ij}$ – a correlation coefficient between returns on a pair of assets *i* and *j*.

Portfolio volatility, or risk, is calculated as follows:

$$\sigma_p = \sqrt{\sigma_p^2}. \tag{8}$$

The variance of the whole portfolio depends on the covariance between individual assets. The higher the covariance between an asset pair is, the higher is the volatility of the portfolio. This relation allows obtaining **diversification** benefits using uncorrelated assets.

A plot of each possible composition of the portfolio on the risk–return space defines an **efficient frontier**. Combinations along the upper boundary of the obtained parabola are equivalent to portfolios without risk-free assets and with the highest return for a given level of risk. The point on the frontier with the lowest volatility is named the minimum-variance portfolio. The introduction of the risk-free tangent line from the point of this rate on the *y*-axis to the upper bound of the efficient frontier determines the capital allocation line, which becomes a new efficient frontier. The tangency portfolio is a combination of assets without risk-free returns, and it has the highest Sharpe ratio, which can be computed using the following formula:

$$S_a = \frac{E[R_a - R_b]}{\sigma_a} = \frac{E[R_a - R_b]}{\sqrt{\text{var}[R_a - R_b]}}, \tag{9}$$

where R_a – the portfolio return, R_b – risk-free or benchmark return, s$_a$ – the volatility of the asset's excess return. A higher Sharpe ratio indicates better return on the unit of risk (Sharpe, 1992).

In this paper, portfolio optimisation is conducted within the framework of the discussed MPT. First, statistics and risk–return profiles of the asset classes are checked. To obtain a wider look at the topic, we test 4 cases of portfolio construction with and without crypto and short positions.

Minimum-variance portfolio offers the investor the lowest possible level of risk. It can be formulated as a minimisation problem:

$$\begin{aligned} \min \quad & \sigma_P^2 = \frac{1}{2} w^T \Sigma w \\ s.t. \quad & w^T \mu = \rho \quad , \\ & w^T 1_n = 1 \end{aligned} \tag{10}$$

where s^2 is the variance of the return w^Tm, m – vector of returns and w – a vector of portfolio weights. The first constraint defines a minimum rate of return, although it can be omitted, as we did. The second constraint forces to invest all the money, so that all weights sum up to 1.

Tangency portfolio provides the highest Sharpe ratio for the investor and hence can be expressed as the following maximisation model:

$$w_{MSR}^* = arg \max_w \frac{w^T(\mu - r_f)}{\sqrt{w^T \Sigma w}} \quad s.t. \quad w^T 1_n = 1, \tag{11}$$

where r_f – a risk-free rate, and the maximum Sharpe ratio (MSR) is a market portfolio. When the risk-free rate is equal to 0, the MSR becomes identical to the tangent portfolio.

For each case, we build an efficient frontier, construct the minimum variance and tangency portfolios, examine the weights of portfolios and calculate performance measures, including the Sharpe ratio. There are several assumptions to the model, which have to be mentioned:

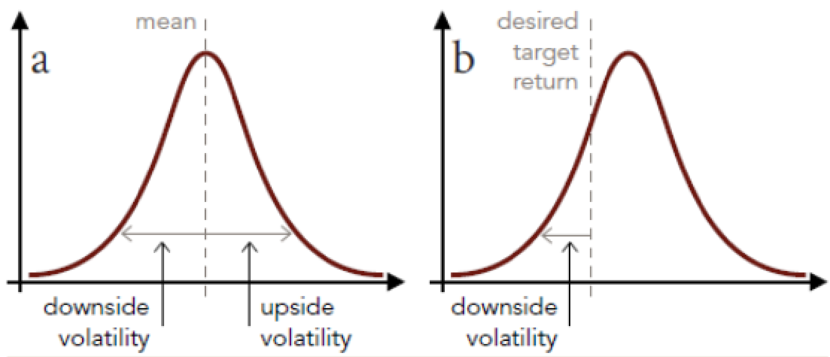

Fig. 1. Downside risk on the bell curve. *Source*: Rollinge and Hoffman (2013).

1. The indices are representative for the whole asset class. According to their methodology, they are rebalanced on a regular basis.
2. The risk-free rate is equal to 0.
3. There are no transaction costs.
4. The maximum weight for a single asset in a portfolio does not exceed 60% to avoid dominance of a single asset class.

3.2.3. Post-Modern Portfolio Theory (PMPT)

Although Markowitz's MPT is the most popular and widely used mathematical technique for portfolio management and asset allocation, it has significant limitations, which lay mainly in its initial assumptions. The first is the statement that investment risk can be correctly measured by the variance of historical returns and expected return – by their mean. The second one states that the whole universe of asset classes, investment instruments and portfolios has returns distributed normally. This assumption makes the model sensitive to the assets with non-normal distribution of returns, which is a crucial feature of cryptocurrencies.

According to the PMPT, true risk appears only when returns fall below some target level, while positive movements above this level are preferable for an investor and does not constitute a risk for him. The weights for the loss are more than for the gain, which implies asymmetry of the distribution. MPT thus becomes just a symmetric case of PMPT. There are two distinguishing measures: downside risk and the Sortino ratio (Rom and Ferguson, 1994).

Downside risk plays the role of standard deviation (Figure 1). It is calculated as the annualised standard deviation of asset returns that fall below the minimum acceptable level defined by the investor. In other words, it is target semi-deviation. Downside risk is also expressed in percentage, and so, it is comparable to standard deviation (Sortino and Van Der Meer, 1991).

$$d = \sqrt{\int_{-\infty}^{t} (t-r)^2 f(r) dr}, \tag{12}$$

where d – downside risk or deviation, t – the minimum acceptable return (MAR) or target return, r – the random return, f(r) – the function of distribution of annual returns, usually lognormal. We assume that MAR is equal to the risk-free rate, which is 0 in our case.

The **Sortino ratio** was developed within the framework of PMPT in order to replace the Sharpe ratio as a representative of risk-adjusted return. It uses the downside risk measure (instead of standard deviation) and the target return (instead of risk-free rate) (Sortino and Price, 1994). The formula is as follows:

$$Sortino\,ratio = \frac{r-t}{d}, \tag{13}$$

where r – annual return, t – MAR or target return and d – downside risk. The Sortino ratio usually provides significantly different results, compared to the Sharpe ratio, when ranking investments according to profitability against the risk (Rollinge and Hoffman, 2013).

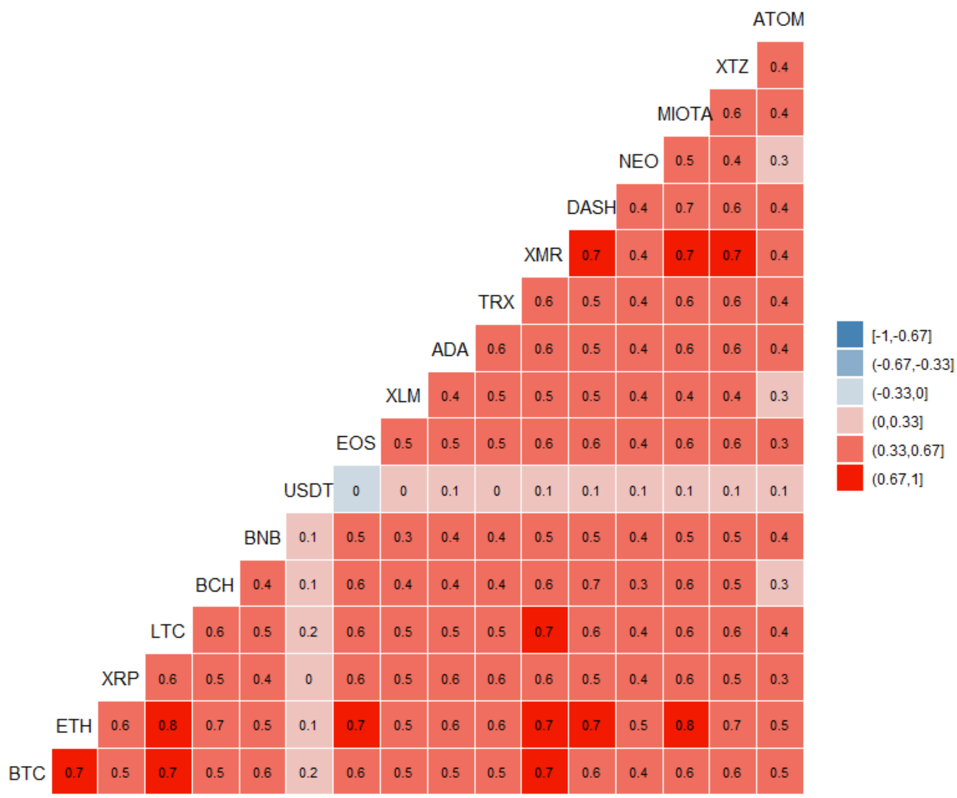

Fig. 2. Correlation matrices of cryptocurrencies based on Pearson's correlation coefficient. *Source:* Own work, computed in R.

As cryptocurrencies are highly volatile, these measures are used to test the reliability of results of portfolio improvement due to inclusion of the crypto asset class. We calculate the downside risk and the Sortino ratio for each portfolio constructed with MPT optimisation. This allows one to check whether addition of cryptocurrencies indeed brings diversification benefits and increases portfolio performance regardless of their high volatility.

4. Empirical results

4.1. Conformity of cryptocurrencies to the asset class requirements

1. Stable aggregation

The technology itself makes the composition of the crypto asset class relatively stable. There are two types of cryptographic assets: coins and tokens. They have emerged together with the cryptographic technology, and the whole network is working due to their existence. Under these conditions, the aggregation of the assets is stable. Additionally, there are three features that make cryptocurrencies unique: P2P network exchange; purely electronic nature; not being the liability of anyone. Such characteristics are maintained solely by cryptographic coins and tokens; there are no other groups of assets that can also be included into the class. However, one can argue that due to lack of regulation, too many new coins and tokens have been created and too many have failed. This may cause changes in the internal structure, and this is indeed true although it does not have a harmful influence on composition, which is still stable while aggregating coins and tokens, both new and old ones (Hileman and Rauchs, 2017). As result, the first condition of the asset class is satisfied.

2. Investability

A distinct asset class is supposed to have direct access to investment. Currently, there is a wide range of channels for investment in the cryptocurrency market. The spectrum of direct financial services is broad enough as well. Currently, the total number of exchanges is >250, with the total trading volume in the range of 60–90 million/day. The versatility of

Table 2: Descriptive statistics of the asset's daily returns, for the period from August 2014 to July 2019

Asset class	Mean	SD	Median	MAD	Maximum	Minimum	Range	Skew	Kurtosis
CRIX	0.00119	0.04127	0.00241	0.02220	−0.25334	0.19854	0.45188	−0.73932	6.06653
Stocks	0.00035	0.00845	0.00042	0.00544	−0.04184	0.04840	0.09025	−0.44359	3.74452
Bonds	0.00001	0.00203	0.00012	0.00188	−0.00994	0.00693	0.01686	−0.36463	1.01629
Commodities	−0.00038	0.00807	−0.00014	0.00722	−0.03945	0.02989	0.06934	−0.11117	1.02663
FX	0.00012	0.00286	0.00013	0.00257	−0.01184	0.01743	0.02927	0.00864	2.00035
Real estate	0.00018	0.00887	0.00061	0.00737	−0.04703	0.03393	0.08097	−0.57110	2.05658

Source: Own work computed in R.

exchange services lies in the different verification procedures, geographical locations, trading pairs, limits, analytical tools, transaction fees, payment methods and so on.

More important is the fact that some financial institutions have started to offer cryptocurrencies as a financial instrument to invest in. Currently, some banks accept Bitcoin and Ethereum, although only a few allow direct investments in them. There are also some examples of indirect investments through banks, such as derivatives, tracking certificates or contracts for difference. The initial coin offerings (ICOs), another way to invest in crypto assets, require an investor to have Bitcoin or Ethereum; therefore, this channel also cannot be considered as direct.

Summing up, specialised exchanges are currently the only way for direct investment into the cryptocurrency market, but they require having an intermediary cryptocurrency to buy the others. Financial institutions are still reluctant to use them as financial instruments and offer only limited indirect investment services. Compared to traditional regulated assets, cryptocurrencies cannot fully meet the criteria of investability. However, being decentralised, there are already plenty of opportunities to invest in the crypto market even faster and easier than in traditional markets. Thus, we assume a decent level of investability at this stage of development.

3. Internal homogeneity

We find that 95% of the units in the selected crypto sample are not normally distributed. The *P*-values usually tend to 0, rejecting the null hypothesis about normality. In further correlation analysis, 17 cryptocurrencies are used according to market cap. Due to the discovered non-normality of the analysed time series, we use three different correlation coefficients. The correlation matrices of Pearson's, Kendall's and Spearman's measures were calculated.

As expected, although the coefficients differ from each other, all of them unanimously identify significant positive correlation among the titles inside the class (Figure 2). The highest results are obtained by Spearman's measure where the correlation coefficients reach 0.8. This means that cryptocurrencies display internal homogeneity, which is one of the crucial features needed for an asset class; so the third criterion is met.

4. External heterogeneity

The descriptive statistics of the proxies of all asset classes is summarised in Table 2. Cryptocurrencies, as an asset class, produce the highest level of each analysed parameter. The mean, or expected daily return, accounts for 0.12%, exceeding stocks' average return more than 3 times.

Volatility measures, such as standard deviation, MAD and range, are, respectively, 4.8, 4 and 5 times higher than the corresponding stock characteristics. At the same time, the crypto asset class has the highest deviation from normal distribution. CRIX's bell curve is negatively skewed, so the left tail is longer and fatter, while the mean and median are to the left from the mode. The kurtosis, equal to 6, indicates a leptokurtic distribution, with heavy tails and extreme values. Such distribution of returns is considered to bear a high risk level.

Relationships between asset classes are presented in Figure 3. While the correlation between the traditional asset classes is still preserved, the cryptocurrency index is the most uncorrelated

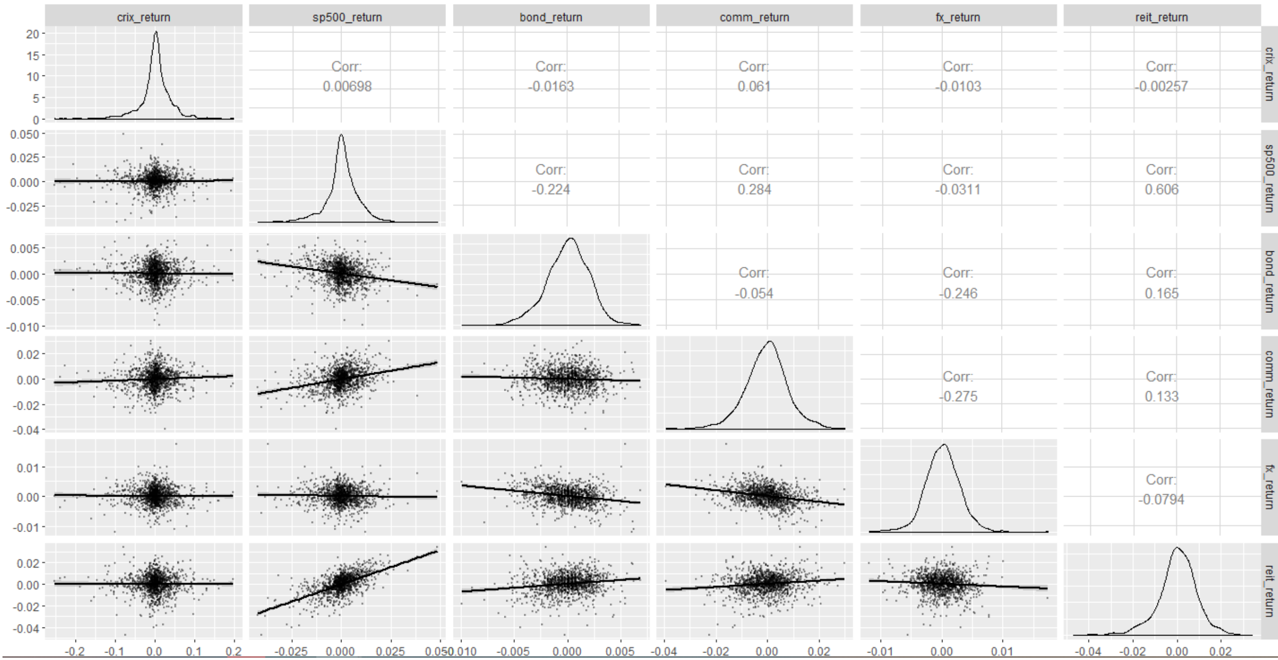

Fig. 3. Correlation matrix between returns of the asset classes based on Spearman's coefficient, for the period from August 2014 to July 2019. *Source:* Own work, computed in R.

class. In our case, Spearman's coefficient reveals no correlation between CRIX and other asset classes, although it catches a wider range of dependencies and usually shows higher values than other measures. This tendency can be clearly seen in the graphs, where the slopes of the regression lines between CRIX and other classes are nearly 0.

Our findings prove the external heterogeneity of cryptocurrencies as a coherent whole, which is the fourth necessary criterion.

5. Expected utility

The next section 4.2 is devoted to the problem of portfolio optimisation with cryptocurrencies and justifies this feature in detail.

6. Selection skill

As discussed in the Methodology section, this requirement means that an investor should not need special skills to select the asset. Due to external heterogeneity and internal homogeneity of the class, even Bitcoin itself may bring diversification benefits to an investor. However, the possibility of extreme volatility imposes on the investor too high a level of risk and may diminish the Sharpe ratio of the portfolio. The previous analysis showed that use of the cryptocurrency index helps to avoid the problem of picking specific coins. A properly constructed index or an ETF is sufficient to avoid the problem of selection. This also removes the necessity of active monitoring and asset management. Currently, there are plenty of crypto indices and ETFs on the market, among which are CMC Crypto 200 Index, CMC Crypto 200 Ex Bitcoin Index, Bloomberg Galaxy Crypto Index, Bloomberg Galaxy Crypto Index, Crypto Market Index 10, Major Crypto Index, All Crypto Index and so on. Therefore, we consider this requirement to be proved.

7. Cost-effective access

The last criterion inspects trading costs and liquidity. Table 3 contains the consolidated data of three key measures. Bid–ask spread percentages of the top cryptocurrencies are very volatile. In most cases, the relative spread has decreased over the past years compared to the early stages of development of the technology, i.e. the adoption period, although there may still occur extreme values, such as 60% of the close price. This is provoked by frequent speculative attacks, which are common for the cryptocurrency market, and the lack of regulation of price movement. As a rule, the average daily bid–ask spread percentage

Table 3: Spread percentage, turnover and close ratio of the top cryptocurrencies with the highest market capitalisation (average over the period from August 2014 to July 2019)

Cryptocurrency	Spread percentage [%]	Turnover ratio	Close ratio
BTC	4.0992	0.0952	0.5276
ETH	5.8820	0.2185	0.4906
XRP	6.0555	0.0577	0.4726
LTC	6.4739	0.3513	0.4966
BCH	7.8009	0.1525	0.4820
BNB	6.3621	0.0548	0.5439
EOS	6.7004	0.3292	0.5277
BSV	8.9249	0.1136	0.4495
TRX	0.8114	0.1802	0.4890
Total market	-	0.1649	-

Source: Own work, computed in R.

over the past year lies within the range of 4%–8% of the price, which is significantly higher than for traditional assets, for which this measure accounts for about 1%–3% on average.

Dynamics of the turnover ratio are positive for most of the coins. An upward trend tells about the growing daily turnover of the cryptocurrencies, with a turnover ratio of about 16% for the total market and up to 35% for single assets. It signifies high liquidity level, comparable to traditional asset classes.

The close ratio fluctuates a lot over the analysed period, although, on average, it accounts for around 50% for all top coins, meaning that every day, half of the total number of orders is closed. Therefore, the speed of transactions is also high enough to prove sufficient level of liquidity.

The transaction fees depend on an exchange and have a significant influence on portfolio performance. Currently, there is a wide range of exchanges with their own fee structures and discount systems. In the Appendix, the most significant exchanges according to market capitalisation are analysed. Trading fees fluctuate in the range from 0.1% to >1%. Considering the fees on the trading of traditional assets, cryptocurrency exchanges fees are pretty low. For instance, trading stocks require 0.1%–5% of the investment amount, options require 0%–5%, bonds involve 0.01%–3%, certificates of deposit (CDs) require 0.1%–5% and foreign currency exchange needs 0.2%–1% in fees (Nishide & Tian, 2019). Additionally, most crypto exchanges offer discounts on volume and do not charge fees on deposits; however, they usually have fees on withdrawals from the platform. As a result, trading fees on cryptocurrencies are on the same level as on traditional assets. This supports the last feature of an asset class.

4.2. Mean-variance portfolio analysis within MPT

As the first step, the risk–return profiles of each asset class are analysed. Table 4 contains the key performance measures annual return, volatility, Sharpe ratio and maximum drawdown (DD). Return of the CRIX index is almost identical to stocks return, both >8% per annum. However, standard deviation of the crypto assets exceeds the volatility of stocks and real estate by 5 times or that of bonds and foreign exchange by >10 times. Thus, the Sharpe ratio of cryptocurrencies is much lower than that of stocks, foreign exchange and real estate, but higher than that for bonds and commodities. Obviously, cryptocurrencies display the highest maximum DD due to the extreme fall of Bitcoin in 2018.

The visualisation in Figure 4 shows the daily risk–return profiles. It is clear that CRIX significantly differs from the traditional assets: it has at least 4 times higher daily volatility and 3 times higher daily returns compared to other classes. This is another piece of evidence that cryptocurrencies are externally heterogeneous. Within the portfolio optimisation framework, such a difference indicates the possibility

Table 4: Risk–return profiles of the asset classes, for the period from August 2014 to July 2019

Risk-return measuremets	CRIX	Stocks	Bonds	Commodities	FX	Real estate
Annualised return	0.0816	0.0828	0.0017	−0.0977	0.0295	0.0373
Annualised standard deviation	0.6551	0.1342	0.0323	0.1281	0.0453	0.1408
Annualised Sharpe ratio (*R*f=0%)	0.1245	0.6172	0.0516	−0.7625	0.6511	0.2649
Maximum DD	0.4519	0.0801	0.0162	0.0573	0.0276	0.0702

Source: Own work, computed in R.

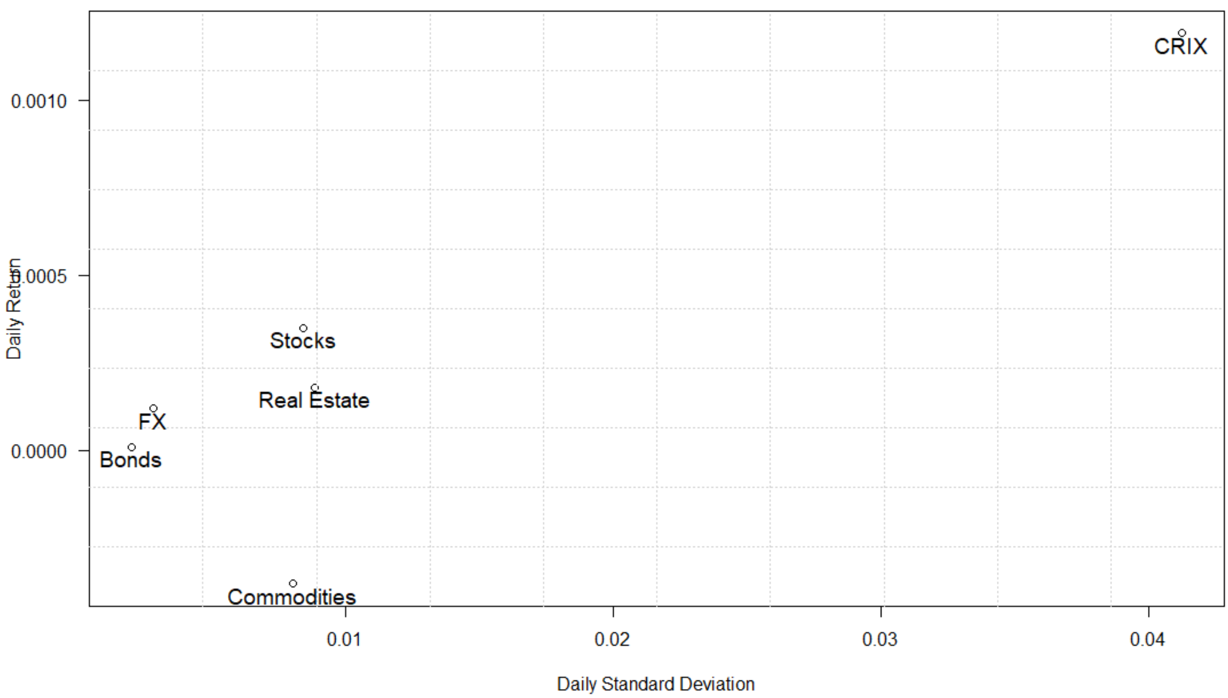

Fig. 4. Daily risk–return profiles of the asset classes. *Source:* Own work, computed in R.

of increasing both return and risk, which is not always optimal in relative terms.

In Table 5, the results of portfolio optimisation for all 4 cases are presented. What is notable from the portfolio construction is that cryptocurrencies are added automatically to all portfolios, even though we did not add any constraint on the minimum weights. When building the minimum-variance portfolio, it is not advisable to use crypto assets, as they significantly deteriorate the level of risk. However, in the tangency portfolio, their weights are already considerable: 1.9% in portfolios with long positions only, and 2.8% in portfolios with both long and short positions. Addition of the cryptocurrency index indeed improves the performance measures of the portfolios. Total return and risk have increased in all cases. Considering the long positions only, the Sharpe ratio of the minimum-variance portfolio has increased by 3%, while that of the tangency portfolio increases by 10%, from 1.04 to 1.14. As for portfolios with short position, the Sharpe ratio has improved by 3% and 7%, respectively. Maximum DD has significantly deteriorated with the inclusion of CRIX, namely 2–3 times. As result, the effect of Sharpe ratio improvement diminishes considering such a risk level.

The presented empirical results (Figures 5-8) prove that crypto assets indeed provide diversification benefit for an investor due to the distinguishing risk/return profile and absence of correlation with other asset classes. Moreover, adding a small fraction of cryptocurrency to the investment portfolio leads to risk-adjusted outperformance. The relative

Table 5: Consolidated results of portfolio optimisation

	Annual return	Annual standard deviation	Annual Sharpe ratio	Maximum DD	Asset allocation (weights)					
					CRIX	Stocks	Bonds	Commodities	FX	Real estate
Portfolio without cryptocurrencies, only long position allowed										
MinVar	0.0102	0.0202	0.5057	0.1263	–	0.0421	0.5619	0.0534	0.3427	0.0000
Tangency	0.0291	0.0280	1.0372	0.1565	–	0.1577	0.3673	0.0000	0.4749	0.0000
Portfolio without cryptocurrencies, long and short positions allowed										
MinVar	0.0108	0.0197	0.5471	0.1320	–	0.0694	0.5932	0.0491	0.3286	−0.0403
Tangency	0.0632	0.0478	1.3226	0.2300	–	0.3343	0.5519	−0.2440	0.4459	−0.0881
Portfolio with inclusion of cryptocurrencies, only long position allowed										
MinVar	0.0105	0.0202	0.5212	0.3295	0.0010	0.0421	0.5617	0.0530	0.3423	0.0000
Tangency	0.0339	0.0298	1.1371	0.3366	0.0187	0.1528	0.3637	0.0000	0.4648	0.0000
Portfolio with inclusion of cryptocurrencies, long and short positions allowed										
MinVar	0.0111	0.0198	0.5624	0.3356	0.0009	0.0694	0.5930	0.0487	0.3283	−0.0403
Tangency	0.0707	0.0499	1.4189	0.4163	0.0276	0.3271	0.5453	−0.2465	0.4322	−0.0858

Source: Own work, computed in R.

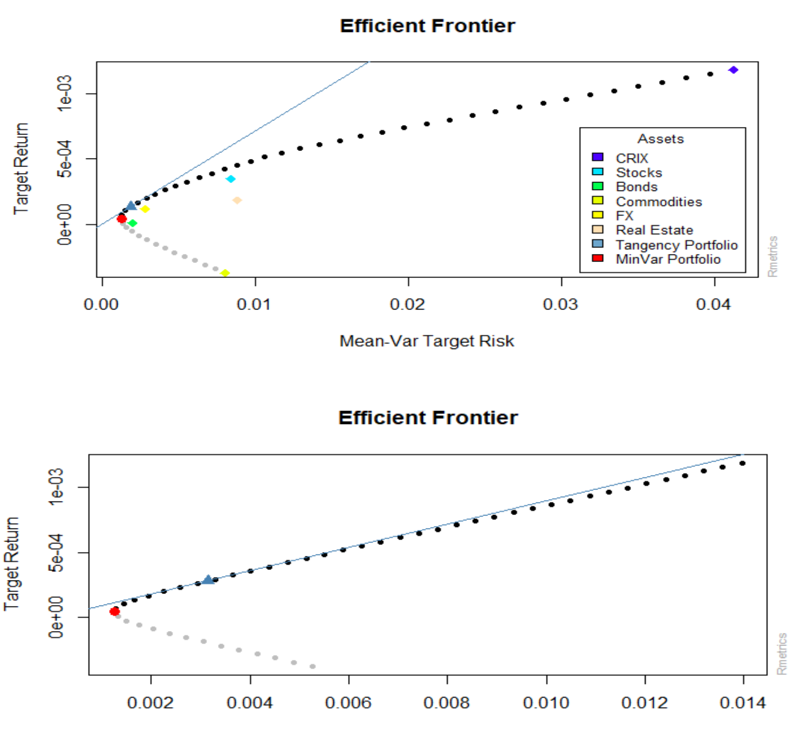

Fig. 5. Efficient frontier of portfolios with inclusion of cryptocurrencies, only long positions allowed versus long and short positions allowed. *Source:* Own work, computed in R.

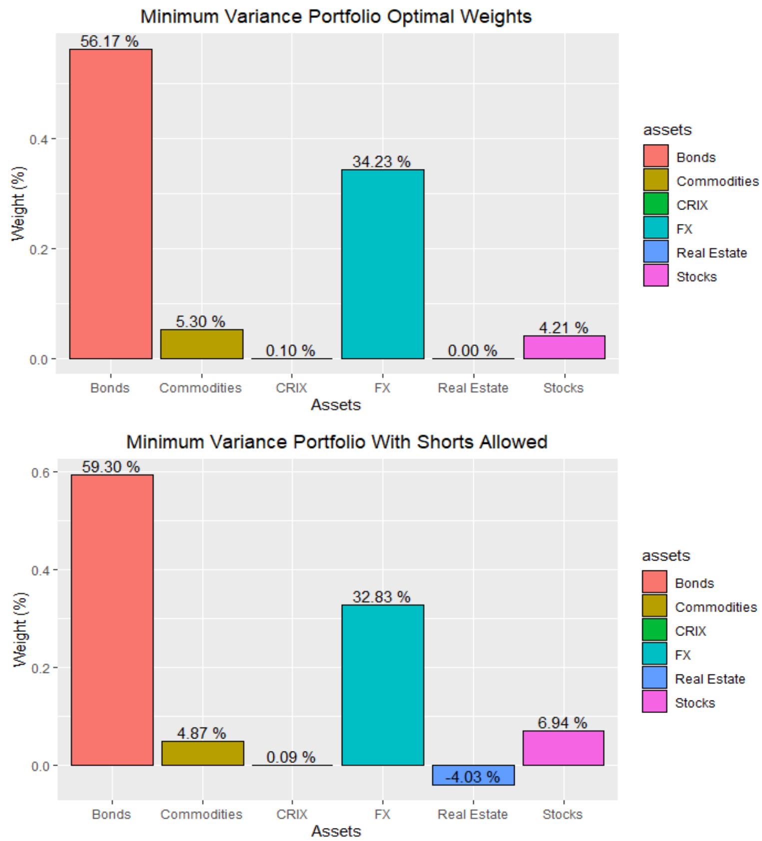

Fig. 6. Minimum-variance portfolio optimal weights with inclusion of cryptocurrencies, only long positions allowed versus long and short positions allowed. *Source:* Own work, computed in R.

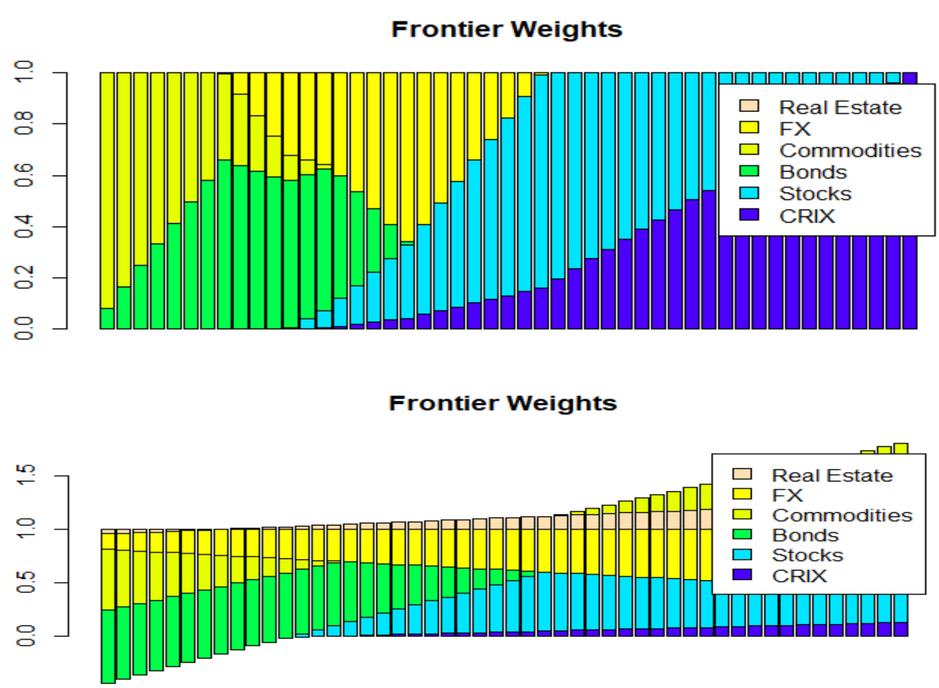

Fig. 7. Weights of portfolios of efficient frontier with inclusion of cryptocurrencies, only long positions allowed versus long and short positions allowed. *Source:* Own work, computed in R.

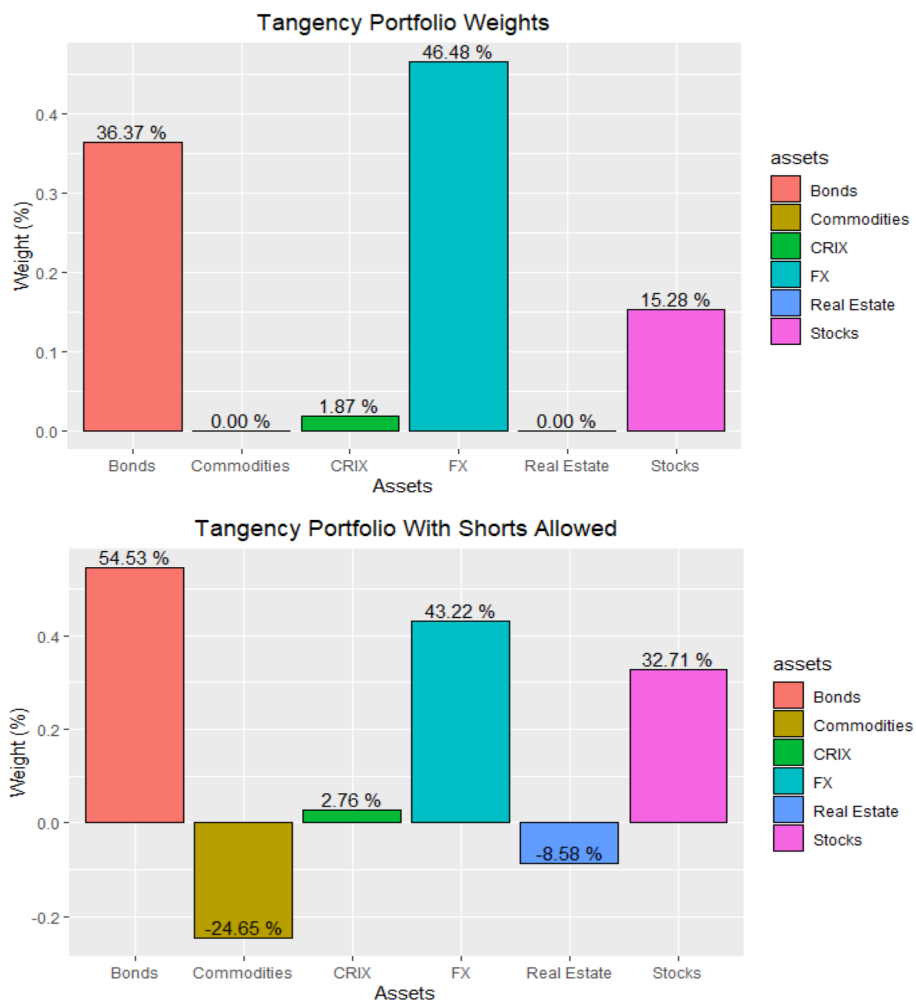

Fig. 8. Tangency portfolio optimal weights with inclusion of cryptocurrencies, only long positions allowed versus long and short positions allowed. *Source:* Own work, computed in R.

improvement would be pretty satisfactory: a 7%–10% increase of Sharpe ratio gained with the inclusion of 2%–3% of cryptocurrencies; however, the increased maximum DD measure brings about doubts and requires the application of another approach.

4.3. Application of the PMPT

In Table 6, the performance measures of the PMPT are analysed. We compare the changes in the Sharpe and Sortino ratios of portfolios with and without cryptocurrencies. According to the last column, adding even a small fraction of cryptocurrencies raises the downside risk more than 2 times. This can be explained by a large downward trend in the Bitcoin price in 2018. Similar tendency is observed with maximum DD, which went up to twice the original. Consequently, it influences the performance ratio. The Sortino ratio of minimum-variance portfolios practically did not change, as expected. However, more important observations come from the tangency portfolios. When only the long position is allowed, the ratio decreases from 1.4 to 0.7 (by 47%) after inclusion of the crypto index. In case shorting is allowed as well, this change constitutes 43%. Such results contradict with the MPT, where the Sharpe ratio increases when cryptocurrencies are added.

To summarise, following MPT, we support that cryptocurrencies bring diversification benefits and increase portfolio performance. However, PMPT gives the opposite results. Due to the extreme volatility of crypto assets, especially the downside risk, performance measures have deteriorated, meaning that both hypotheses are rejected.

Nevertheless, the market of cryptocurrencies is developing fast, and there is a broad field for future

Table 6: Portfolio performance analysis within the framework of PMPT

	Annual return	Maximum DD	Sharpe ratio	Sortino ratio	Downside volatility (%)
Portfolio without cryptocurrencies, only long position allowed					
MinVar	0.0102	0.1263	0.5057	0.7910	5.63
Tangency	**0.0291**	**0.1565**	**1.0372**	**1.3989**	5.26
Portfolio without cryptocurrencies, long and short positions allowed					
MinVar	0.0108	0.1320	0.5471	0.8761	5.78
Tangency	**0.0632**	**0.2300**	**1.3226**	**1.9041**	6.71
Portfolio with inclusion of cryptocurrencies, only long position allowed					
MinVar	0.0105	0.3295	0.5212	0.7916	12.92
Tangency	**0.0339**	**0.3366**	**1.1371**	**0.7396**	12.73
Portfolio with inclusion of cryptocurrencies, long and short positions allowed					
MinVar	0.0111	0.3356	0.5625	0.8744	13.26
Tangency	**0.0707**	**0.4163**	**1.4189**	**1.0839**	15.99

Source: Own work, computed in R.

research. Application of more advanced portfolio optimisation tools, inclusion of the rebalancing mechanism, usage of other indices and time frames may considerably improve performance and prove the hypothesis.

5. Conclusions

This study answers the question whether cryptocurrencies can be treated as a distinct asset class in portfolio optimisation and what benefits they bring to the investor's portfolio.

The literature review on this topic showed that, compared to traditional asset classes, cryptocurrencies are indeed distinctive due to their nature. What makes crypto assets unique is the blockchain technology. Such elements as P2P network, cryptography and consensus algorithm make them decentralised and secured, which is often argued to be a new era of economic relations. Blockchain technology, being a DAO, is the first step in switching the privacy model from a socio-technical to a techno-social one.

The crypto market contains two kinds of assets: coins and tokens. Its internal structure is developing very fast with the introduction of new assets, replacement of non-liquid ones, implementation of the technology in further economic and social areas and so on. Still, the market is volatile and highly dependent on Bitcoin trends, which is an argument against its maturity.

According to the research, cryptographic assets are not yet classified. They do not fully satisfy the conditions to be a currency, while having more similarities with an asset class. Seven criteria of the asset class were analysed with qualitative and quantitative techniques. Most of the features were satisfied, among which are stable aggregation, internal homogeneity, external heterogeneity, selection skill and cost-effective access. However, there are two criteria that were not fully proved, such as expected utility and investability. The first one depends a lot on methodology, period and technical properties of the analysis; the second one is more common for traditional classes and may rather be proved for such technology as blockchain. So at this stage, we accept the hypothesis that cryptocurrencies form a new asset class.

Statistical analysis of the cryptocurrency index (CRIX), as a proxy of the class, showed that it is indeed a coherent whole, i.e. internally homogeneous, as well as uncorrelated with other asset classes, i.e. externally heterogeneous. CRIX has no common trends with traditional assets and is not influenced by global economic events. Its statistical properties, such as high mean and high standard deviation, are distinguishing among other asset classes. Therefore, we can also prove the second hypothesis: “Crypto assets provide diversification benefits to the portfolio of traditional assets.”

The third hypothesis within the framework of the MPT, the statement that adding a small fraction of cryptocurrencies to the investment portfolio leads to risk-adjusted outperformance, was proved. The optimisation mechanism added 1.9% of cryptocurrencies to portfolios with long positions only and 2.8% to portfolios with both long and short positions. There was an increase in the performance measures after inclusion of the cryptocurrency index to the portfolio of traditional assets. Considering long positions only, the Sharpe ratio of the minimum-variance portfolio increased by 3%, while that of the tangency portfolio increased by 10%. For portfolios with both long and short positions, the Sharpe ratio increased by 3% and 7%, respectively.

Nevertheless, application of the PMPT to the mean-variance analysis of the constructed portfolios brought about contradictions. It was discovered that if one were to use the downside risk measures and the Sortino ratio instead of the Sharpe ratio, the results would be the opposite. Inclusion of cryptocurrencies boosted the downside risk >2 times in all cases, from 5%–6% to 12%–15%. Consequently, we obtained a decrease of performance by 47% for the tangency portfolio with long positions and a decrease by 43% for the tangency portfolio with short positions allowed as well. This is explained by a large fall in the Bitcoin’s price in 2018, which affected the statistical characteristics, especially downside risk, of the CRIX.

Overall, we support the idea that cryptocurrencies can be readily used by private investors as an asset class.

This study showed that portfolio optimisation with MPT is sensitive to frequency of data, historical period, risk measures and model assumptions. The results would differ a lot if we take another period for the analysis, instead of 5 years. In further studies, it is advisable to experiment with other conditions and assumptions to check the sensitivity of the model. Other methodological approaches in portfolio management and optimisation may give more reliable and unambiguous results, so these are worth testing in a further research.

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Appendix

Table: Transaction fees on top cryptocurrency exchanges

Exchange	Trading Fees			Funding Fees		Discounts	
	Maker	Taker	Spread	Deposits	Withdrawals	Exchange Token Discount	Volume Discount
Bibox	0.1%	0.1%	No	No	Yes	Yes	No
Binance	0.1%	0.1%	No	No	Yes	Yes	Yes
Bitfinex	0.1%	0.2%	No	Yes (<$1k)	Yes	No	Yes
Bitsane	0.1%	0.2%	No	Yes	Yes	No	Yes
Bitstamp	0.25%	0.25%	No	No	No	No	Yes
Bittrex	0.25%	0.25%	No	No	No	No	No
BTCMarkets	0.22%-0.85%	0.22%-0.85%	No	No	Yes (AUD free)	No	Yes
CEX.IO	0.16%	0.25%	No	No	Yes	No	Yes
Coinbase	N/A	1.49% or fixed fee	0.5% fiat 1.00% crypto	No	No	No	Yes
Coinbase Pro	0.15%	0.25%	No	No	No	No	Yes
CoinSpot	0.1%	0.1%	No	Yes	No	No	No
Coss	0.14%	0.2%	No	Yes	Yes	Yes	Yes
Cryptopia	0.2%	0.2%	No	No	No	No	No
Gate.io	0.2%	0.2%	No	No	Yes	No	Yes
Gemini	1.00%	1.00%	No	No	No	No	Yes
HitBTC	0.1%	0.2%	No	No	No	No	No
Huboi	0.2%	0.2%	No	No	No	Yes	Yes
IDEX	0.1%	0.2%	No	No	No	Yes	No
Kraken	0.16%	0.26%	No	No	No	No	Yes
Kucoin	0.1%	0.1%	No	No	No	No	Yes
Livecoin	0.18%	0.18%	No	Yes	Yes	No	Yes
Liquid	0.1%	0.1%	No	No	Yes	Yes	Yes
Poloniex	0.08%	0.2%	No	No	Yes	No	Yes
Shakepay	0.75%	0.75%	No	No	Yes	No	No
Uphold	0.65%-1.95%	0.65%-1.95%	No	No	Yes	No	No

Source: Stone, Sam (2019, May 2). 2019 Crypto-Exchange Fee Comparison. Medium. Retrieved August 5, 2019, from https://medium.com