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Is the Bitcoin market efficient? A literature review[1]

¿El mercado de Bitcoin es eficiente? Una revisión de la literatura

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ABSTRACT

This paper presents a documentary research on the market behavior of Bitcoin with respect to market efficiency and the existence of speculative bubbles. To this end the paper analyses 25 journal articles to answer the following research question: Is the Bitcoin market efficient? Based on Eugene Fama´s Efficient Market Hypothesis (EMH), the selected articles are classified into two groups: the first group contains articles that support and potentially accept the EMH; the second group includes articles that refute or reject this hypothesis based on different empirical evidence of financial bubbles within the Bitcoin market. The two groups indicate that by 2021 there is no crystal-clear consensus among scholars and financial analysts in terms of efficiency. Nevertheless, far more articles reject the EMH than support it, concluding that the Bitcoin market is prone to develop speculative bubbles. Furthermore, due to the high volatility documented by both groups, users and future investors are advised to consider not only the potential financial gains that the most popular cryptocurrency may offer, but its numerous risks as well.
Keywords: Bitcoin; cryptocurrencies; financial bubbles; market efficiency.
JEL Classification: G14; G19.

RESUMEN

Este artículo presenta una investigación documental sobre el comportamiento del mercado de Bitcoin con respecto a la eficiencia del mercado y la existencia de burbujas especulativas. Con este fin, el documento analiza 25 artículos de revistas para responder a la siguiente pregunta de investigación: ¿es eficiente el mercado de Bitcoin? Con base en la Hipótesis de Mercado Eficiente (EMH) de Eugene Fama, los artículos seleccionados se clasifican en dos grupos: el primer grupo contiene

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artículos que potencialmente aceptan la EMH; mientras que el segundo grupo incluye artículos que refutan o rechazan esta hipótesis con base en distintas evidencias empíricas de burbujas financieras en el mercado del Bitcoin. Los dos grupos indican que para 2021 no existe un consenso claro entre los académicos y analistas financieros sobre si el mercado de Bitcoin es eficiente o no. Sin embargo, por cantidad, muchos más artículos rechazan la EMH de los que la apoyan, concluyendo que el mercado de Bitcoin es propenso a desarrollar burbujas especulativas. Además, debido a la alta volatilidad documentada por ambos grupos, se recomienda a los usuarios y futuros inversores que consideren no solo las posibles ganancias financieras que puede ofrecer la criptomoneda más popular, sino también sus numerosos riesgos.
Palabras Clave: Bitcoin; criptomonedas; burbujas financieras; eficiencia del mercado.
Clasificación JEL: G14; G19.

INTRODUCTION

Bitcoin has been a phenomenon since its inception in 2008 for several reasons. The iconic white paper of Satoshi Nakamoto (2008) laid out the principles and technical background to a new, peer-to-peer decentralized electronic cash payment system never seen before. Since then, the novel cryptocurrency Bitcoin, as it has been named, and soon its spinoffs have experienced a tremendous growth and popularity due their peculiar characteristics that make them attractive worldwide. Key characteristics include anonymity of the users, costless but irreversible transactions, flexibility, fungibility and less oversight of the authorities than other forms of payment (Böhme et al., 2015). The ability of Bitcoin to operate beyond the reach of central banks and the supervision of the state, makes it especially captivating for transactions that prefer to leave no trace behind, such as any illicit trading, and may have been one of the key reasons for early adoption. Other characteristics, for example its global coverage distinguishes it from other alternative decentralized currencies, such as social currencies which have a limited geographic reach and capacity (Gómez and Demmler, 2018).

Bitcoin’s growth trajectory has not been without major setbacks, challenges, and serious concerns of the authorities. The stunning price increase of Bitcoin in late 2017 and the subsequent crash in early 2018 illustrated the volatility of the cryptocurrencies and casts serious doubt on its usefulness as unit of account and store of value. Nonetheless, despite this epic rise and fall, in early 2021 there are more than 8,400 cryptocurrencies registered on the online platform Coinmarketcap (Coinmarketcap, 2021), indicating a substantial growth in this market in which Bitcoin currently holds more than 60% of the market capitalization. Bitcoin’s price is once again on the rise, passing 49,000 USD for the first time in its history on February 14, 2021, surpassing the previously held all-time high price of 2017 when one Bitcoin cost 19,166.98 USD, on December 16, 2017 (Coindesk, 2021). With all the ups and downs of Bitcoin and cryptocurrency markets in general, a vivid debate within the international scientific community emerged in recent years about the efficiency of the Bitcoin market and its vulnerability to financial bubble tendencies. Hence, defining financial bubbles as one major empirical example of existing market inefficiencies, the question arises whether Bitcoin and broadly speaking all cryptocurrencies can be considered as an efficient or inefficient financial market.

The objective of this paper is to investigate the efficiency of the cryptocurrency market based on a documentary research of Bitcoin in particular, to determine whether it satisfies Fama´s hypothesis or that it contradicts the principles of the Efficient Market Hypothesis (EMH). The main conclusion of the article is that most of the literature reviewed reject the EMH than support it, even though there are some recent academic articles that support and potentially accept the efficiency of the Bitcoin market. Therefore, as of early 2021, no clear conclusion seems to emerge in the academic literature with respect of its market efficiency.

This paper is organized as follows: first, to give context, we present the key concepts of the EMH and summarize the historical data of Bitcoin’s price change within the EMH framework; second, we describe the methodology we used for selecting and classifying the articles we reviewed to evaluate Bitcoin's market efficiency; third, in the results and discussion section we present our key findings; finally, we discuss our conclusions along with recommendations for further research.

I. THEORETICAL AND CONTEXTUAL FRAMEWORK

Efficient Market Hypothesis and Asset Price Bubbles

According to the EMH, presented by the Nobel laureate economist Eugene Fama (1970), a market is efficient when the prices of any given asset reflect all available information and new information is quickly incorporated into market prices by rational investors. Hence, no one can outperform the market prices relying on the same information; it can occur only by chance, or as Fama called it, by random walks (Fama, 1991). As outlined in EMH, it is not possible for investors to systematically gain a higher return than the equilibrium market return using historical information (weak form efficiency), public information (semi-strong form efficiency) and insider information (strong form efficiency) (Fama, 1970). This implies that the market is efficient and reacts rapidly to any change or news related to the asset and the price reflects its fundamental value[2]. Based on this principle, no investor can outperform the others and cannot generate extraordinary profits for a prolonged time.

Essentially, according to the EMH financial markets follow a random walk as market prices only move because of new information which initially changes fundamental values and consequently also market prices. As the occurrence of new information is basically impossible to predict, market price changes should be randomly distributed, i.e. follow a random walk (Samuelson, 1965; Fama, 1965). According to the orthodox form of the random walk hypothesis, the future (uncertain) market price of an asset is the sum of the present market price and a random variable (normally distributed, expected value of 0). Hence, the best estimate of the future market price of an asset is its current market price as expected returns are 0 (martingale model) and consecutive market price changes are independent from one another, i.e. have an autocorrelation of 0 (Samuelson, 1965). Consequently, tests of the random walk hypothesis are essentially seen as tests of the EMH.

As one major consequence of the EMH, no asset bubble can form persistently as it would quickly be eliminated by rational market participants when asset price deviate from their fundamental values. This concept, one of the most influential theories in the financial literature, has been tested and heavily debated by several other scholars in the academic literature, such as other Nobel-prize awarded economist Robert Shiller (2015), who argued that asset bubbles do exist. He pointed out that during the 1990s in the technology sector there was a significant departure in stock prices from their fundamental value and used the term "irrational exuberance", coined by Alan Greenspan, to describe the investor spirit of this era (Shiller, 2015). Further, bubbles not only may be a result of economic euphoria, but they may be contagious from one market to another, crossing borders effortlessly (Kindleberger and Aliber, 2015).

The term asset bubble refers precisely to this phenomenon, when the price of any asset departs significantly from its fundamental value and the subsequent process is characterized by dramatic increase in market prices that is later followed by a collapse, as Brunnenmeier (2008) summarized it. The author groups the asset price bubbles into four categories, according to the explanations offered for their formations: 1) rational bubbles under symmetric information, the least likely and accepted explanation, as not all investors are rational, nor do they possess the same information simultaneously; 2) rational bubbles under asymmetric information in which rational investors do not have the same information regarding the asset therefore they price it differently; 3) bubbles due to limits to arbitrage that result from different risks

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[2] The calculation of the asset´s fundamental value is based on its expected risk-adjusted future returns (Demmler, 2017).

such as the existence of irrational noise traders or the costs of arbitrage; 4) heterogeneous beliefs of investors about the existence of bubbles in which investors differ in their judgement of the asset price, therefore prices may vary.

Despite that many academic articles that empirically documented the existence of asset bubbles and the circumstances of when and how they form, economists still hold differing views on asset bubbles. Most importantly, investors often behave rationally but then other times irrationally when pricing, buying, and selling assets. Several studies documented the psychological factors of investment strategies and behavior, such as herd behavior, the "sell to the greater fool" behavior, the over-confidence of investors or the positive feedback loop that may exacerbate an initially moderate optimistic investor sentiment and lead to major price increases, among other factors (Shiller, 2015; Demmler, 2017).

Consequently, financial markets cannot be expected to behave solely rationally, but rather, bubbles are bound to occur under certain conditions which create a fertile environment for over-enthusiastic investment. One of these conditions is often related to the spread of a new technology that creates an optimistic investor sentiment in the financial market. Such was the case in the 1960s, at the appearance of the new "tronics" firms, or in 1990s with the emergence of "tech-firms", as Baker & Wurgler (2006) have documented it. Another factor can be the availability of cheap financing, when the interest rates are low for a prolonged time, such as in the early 2000s (Shiller, 2015) at the emergence of the subprime bubble in the US housing market. In addition to these circumstances, the authors Froot & Obstfeld (1991) have provided empirical evidence for the existence of "intrinsic bubbles" which means that asset bubbles are frequent and inevitable elements of financial markets and they may grow exponentially before they burst. Even more troublesome is the finding that not only do bubbles occur, but they may persist for a prolonged period, as the scholars Dhar and Goetzmann have observed: ″A bubble can be sustained some time by investment sentiment and feedback trading despite a widespread awareness that assets are mis-valued″. (Dhar and Goetzmann, 2006, p. 4). Based on these market characteristics, it is not surprising to see the stellar boom and bust events that have occurred in the cryptocurrency markets since 2017.

It is important to note that there are several other examples of market inefficiencies in addition to the appearance of speculative financial bubbles. Other factors may include the predictability of future asset prices, calendar anomalies (predictable price changes on certain days of the week), overreaction and underreaction to public announcements in connection with an asset or the issuing company, among others (Demmler, 2017). Nonetheless, considering that the most common and frequently studied phenomenon in the Bitcoin market is the emergence of bubbles, this feature is considered for the analysis of market efficiency/inefficiency in the present study.

Bitcoin (BTC)

Among the existing cryptocurrencies, Bitcoin is the most popular by far. Its popularity stems from various factors, documented by various authors (Böhme et al., 2015; Frisby, 2014; Metha et al., 2019). For one, it was the first virtual cryptocurrency on the market that appeared and therefore there is more trust and experience accumulated with its use than with its peers. Second, its total future quantity is capped at 21 million BTC; in other words, it is not prone to foment inflation due to its limited availability. Third, the technology behind it – decentralized digital blockchain – is considered revolutionary and it is expected to spread to other areas beyond finance for widespread use, for example, registering ownership titles, diplomas, including public and private blockchains; most recently, for tracking COVID-19 vaccines (Korin, 2020). Another positive aspect of BTC lies in its democratizing nature, as it is easily accessible to everyone in the world with a smartphone and internet access, including millions of people who have no bank account - the "unbanked" – and have been left out and are unattended by the traditional financial sector. In fact, another key factor of the rise in BTC and the other alternative digital coins (altcoins) popularity can be attributed to the disenchantment with the financial sector´s monopolistic and reckless behavior that became all too evident during the 2007 and 2008 financial crisis. (Mehta et al., 2019).

Despite its numerous virtues, Bitcoin faces several criticism and challenges. To name a few, it appears to be designed by engineers, sidelining the considerations of legal and regulatory experts (Böhme et al., 2015). This means that due to its technical decentralized setup in which payments go from peer-to-peer without the passing an intermediary financial institution, no central bank or financial supervisory board can intervene in Bitcoin´s creation and trading. Consequently, commercial disputes cannot be remedied by the authorities (Mehta et al., 2019). Further, as erroneous or unwanted transactions cannot be reversed, transactional mistakes can be costly. Next, security breaches on online platforms are not uncommon, for example the hacking incident of the online trading site Mt. Gox in 2014 that resulted in a loss of more than 800,000 BTC, approximately 460 million USD (McMillan, 2014) with no bulletproof solution so far. Thus, even if the blockchain technology has not been breached until now, the supporting exchange platforms and gadgets (such as firmware) have been subject to cyberattacks. The authors Böhme et al., (2015) categorize these aforementioned risks the following way: "We review market risk, the shallow market problem, counterparty risk, transaction risk, operational risk, privacy-related risk, and legal and regulatory risks. In addition, any user holding bitcoins faces market risk via fluctuation in the exchange rate between bitcoin and other currencies" (Böhme et al., 2015, p.226).

Another criticism of BTC is related to its fundamental value, which, according to some scholars is zero (e.g., Cheah & Fry, 2015); in other words, it has no intrinsic value, unlike gold, silver, or stocks, for example. As an observation, common FIAT money[3], such as the US dollar or the Euro bills, also lack intrinsic value. In addition, as BTC must be "mined" on very powerful computers that require a lot of energy, the sustainability of its functioning has been seriously questioned as it is too energy intensive. Finally, the high volatility of Bitcoin prices makes it unpractical and useless for signaling prices, usually a basic money function, to be able to use it as a unit of account. Figure 1 shows the historic price changes of Bitcoin since January 2017. As it is observable from Figure 1, the price changes of Bitcoin indicate huge volatility, going from about 800 USD in early 2017 to above 19,000 USD by the end of the same year, and a drop to 6,300 USD by February 2018. The latest trend in the second half of 2020 shows another explosive price increase from about 5,000 USD in March to above 40,000 USD by February 6, 2021 followed by an all-time high of 49,375.94 USD on February 14, 2021 (Coindesk, 2021).

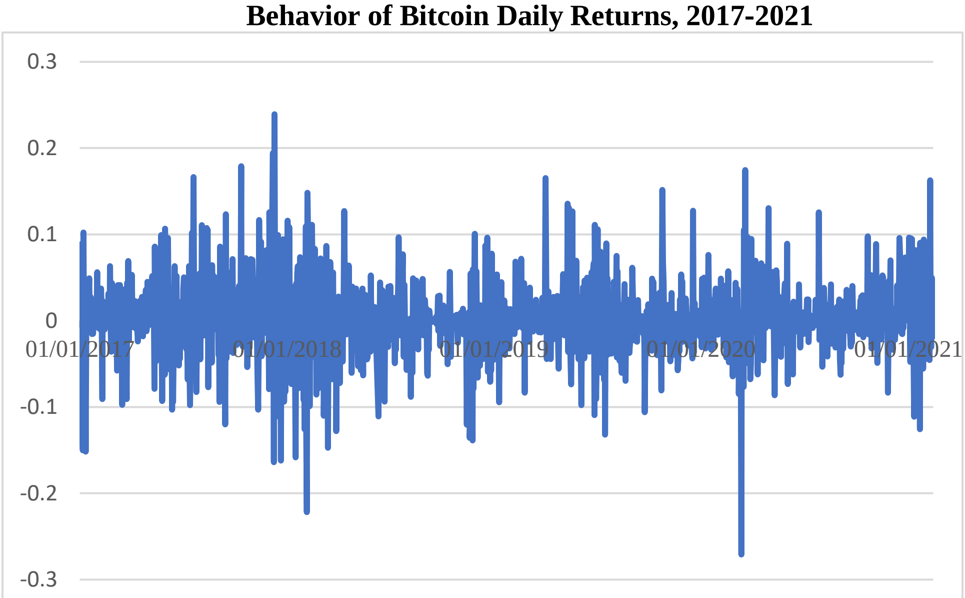
As empirical studies of the price history of financial assets usually use returns instead of market prices, Figure 2 shows also, the behavior of Bitcoin daily simple returns from 2017 to 2021. Once again one can observe the high volatility features of the cryptocurrency. Seemingly periods of high volatility alternate with periods of lower volatility. It appears that Bitcoin currently (beginning of 2021) undergoes a phase of relatively high volatility. Historically speaking the maximum (minimum) daily return occurred on December 10, 2017 (March 12, 2020) with 23.9% (-27.1%) (Coindesk, 2021).

[3] The term "FIAT money" refers to an intrinsically useless object that is used as a medium of exchange, such as paper bills and banknotes (Wallace, 2017).

Figure 1
Behavior of Bitcoin Market Price, 2017-2021

Source: Coindesk (2021).

Figure 2
Behavior of Bitcoin Daily Returns, 2017-2021



Source: Coindesk (2021).

As the authors Böhme et al., (2015) reviewed the use of Bitcoin since it became a viable electronic payment system, there have been a few major transformations. Early adopters used BTC to test it and as a means of payment for many illicit items trading on the Silk Road site (drugs, weapons, pills, etc.).

Later, users bought BTC for payments and increasingly as a buy-and-hold asset, diversifying their financial portfolios. The most recent demand of BTC and trading is due to two circumstances: 1) people use it as a mainstream store of value, similar to that of other hard currencies, including gold; 2) due to the near zero interest rates in developed countries when quantitative easing is taking place from the US, the European and Japanese markets, investors expect inflationary pressure and look for better investment opportunities, hence they turn to the cryptomarkets, in addition to the traditional stock and asset markets. All these markets have experienced an increase due to more available cash in the financial markets. Moreover, as the authors Schilling & Uhlig (2019) outline, Bitcoin is financed with a US dollar tax, as dollars are supplied by the U.S. central bank and they are used for buying Bitcoins. This partially explains the rising demand for Bitcoin in 2020.

Additional explanations include cash savings in some segments of the society as people are not spending on many consumer goods, travel or eating out during the COVID-19 pandemic (Fitzgerald, 2020). New Bitcoin adopters, such as Paypal, Mastercard or investors including Elon Musk who embraced openly Bitcoin also contribute to its recent price rise (Bradshaw & Murphy, 2020; Szalay, 2021). Jim Rieder, CIO of the US investment firm BlackRock, stated that Bitcoin may soon replace gold (Coindesk, 2020). Highly respected financial publications, such as the Financial Times, also describe a bullish tendency on the cryptomarkets indicating high earnings amid very high volatility and a possible steep fall (Szalay, 2020; Samson, 2020, Smith, 2021). Although the long-term trend probably holds for more price jumps and collapses, analysists expect an overall upward trend, due the scarcity of Bitcoin and the promise of the stock-to-flow model (PlanB, 2020).

II. METHODOLOGY

To answer the initial research question, whether scholars consider the Bitcoin market to be efficient or inefficient in terms of the EMH, we conducted a non-quantitative documentary research from primary sources. To this end 25 articles were selected from indexed academic journals that are related to Bitcoin´s market analysis and efficiency. In order to find a convincing, but simple criterion to answer our research question we group the analyzed studies within two groups: articles that accept (or at least do not reject) the EMH for the Bitcoin market and articles which reject the EMH. Most of the articles were published in specialized financial and economic journals between 2014 and 2020 (for example, International Journal of Economic Sciences, Economics Letters, Finance Research Letters, Journal of Applied Finance & Banking, Risks). However, some articles were published in journals from different disciplines, such as physics and statistics (e.g. Physica A: Statistical Mechanics and its Applications). There are many more studies as BTC and cryptocurrencies is a highly dynamic research field, however, we selected articles with high-impact citations that focused on the market efficiency of Bitcoin specifically. For this reason, we are confident that our selection of 25 high-rated papers represents a comprehensive state of the art picture of efficiency studies of the Bitcoin market.

III. RESULTS AND DISCUSSION

Presentation of Results

The results of the present study can be seen summarized in Appendix A which is organized in two sections: Section A includes the group of articles that do not reject and potentially accept the EMH, while Section B presents the group of articles that do reject the EMH. Within both sections, the articles are first organized in chronological order according by the year of publication and within each year, the articles are listed in alphabetical order by author. The organization we use helps to have a better overview of the evolution of the interpretation within the literature.

In addition to basic information of each article – such as the authors and the year of publication, the title of article, the journal where it was published – Appendix A presents two additional columns that provide qualitative summary analysis of every article. In the column called *Key Focus*, in addition to the most relevant objective of the article, the time period of the data analysis is indicated, along with the most important models used by the authors and the cryptocurrencies or other assets that were the subject of the analysis. It is important to note that where it was possible, we mentioned both the month and the year the data was collected, and if more than 3 models were used. Often more than 8 models or tests were applied, and more than 5 currencies studied, but not all are included in this table, due to space limitations. We indicated in the table those cases where we encountered an excess of models and currencies, such as one study that included more than 450 currencies (Wei, 2018). The abbreviations of the listed cryptocurrencies can be found in Appendix B and the statistical models and tests in Appendix C.

The column *Conclusion* presents the most relevant conclusions which are critical for the evaluation of the EMH in each study, resuming whether the article accepts or rejects the EMH.

Discussion of Results

After reviewing the summary table in Appendix A, it is apparent that there are far more research articles that reject the EMH than the ones that accept it: 20 articles (80%) rejected the EMH, while 5 (20%) accepted it, with only document no. 2, potentially accepting the hypothesis, which indicates that most researchers consider the Bitcoin market as inefficient, and that it is prone to develop speculative bubbles from time to time. It is noteworthy that three articles that considered the Bitcoin market as efficient used data prior to the late 2017 price surge; in other words, their data did not include the multiple episodes of boom and bust that were not seen previously. Only two studies included data from the 2nd half of 2017 (Caporale & Plastun, 2019; Vidal-Tomás & Ibañez, 2018), which indicates that despite a dramatic increase in Bitcoin prices in 2017, these authors did not find evidence that the Bitcoin market would be inefficient. The scholars Vidal-Tomás & Ibañez (2018) found evidence for the semi-strong form of market efficiency, observing that investors overreact to events and public announcements related to the Bitcoin market, but not to other monetary policy announcements. Similarly, the authors Caporale & Plastun (2019), considered the 2017 price spike as an overreaction from investors in the cryptocurrency markets, which may be exploited to generate profits with the right strategy. However, the scholars could not reject the EMH based on their empirical test results.

The other 20 studies that reject the EMH often used data ranging from 2010 until 2018, most commonly over 4-7 years. However, there are a few studies that used only one- or two-year data periods, for example Fry & Cheah, 2016), and yet, they found enough evidence to reject the EMH. The sources of the data seem to be very consistent among all 25 studies, as they tend to use the most common cryptocurrency information providers, such as Coindesk or Coinmarketcap.

Considering the multiple and diverse tests that these 25 studies applied, there are also several reoccurring models and tests, which help to compare the results among the diverse currencies and time periods selected. Among the most used methods are the Ljung-Box test for autocorrelation, Bartel´s test used for independence of returns, vector autoregression (VAR) tests and its variations such as FCVAR for random walk analysis, Brock, Dechert and Scheinkman (or BDS) test for independence test, detrended fluctuation analysis (DFA), Hurst exponent test, OLS model, Augmented Dickey-Fuller (ADF) test, GARCH-type models, the PWY model (Phillips, Wu and Yu, 2011a and 2011b), PSY model (Phillips, Shi and Yu, 2015). These latter two models, especially the PSY (2015) model, are often applied by other authors (e.g. Cheung et al., 2015; Geuder et al., 2019), making it one of the most ubiquitous among these papers, as these authors note that it offers the best predictive capacity.

Several recent articles favor the log-periodic power law (LPPL) model. This is more common in studies that include data for the 2017 price increase which required the analysis of exponential growth, for example, the study of Geuder, Kinateder & Wagner, 2019; Wheatley et al., 2018; Xiong et al., 2020. Testing for and confirming the presence of martingale for highly explosive speculative bubble tendencies on the Bitcoin market is also present in the article of Schilling & Uhlig (2019). As mentioned previously, most studies use multiple models, often up to 6-8 models and tests.

With respect to the cryptocurrencies included in the 25 articles, there is also great diversity although Bitcoin is the common denominator and often the only digital currency analyzed. Other major cryptocurrencies that were present include Ethereum, Ripple, Litecoin, and DASH. The authors Hu, Valera, & Oxley (2019) analyzed a significantly higher number of cryptocurrencies testing 31 digital currencies, while Wei (2018) analyzed 456 cryptocurrencies. In addition to cryptocurrencies, several studies compared and tested the Bitcoin market behavior to that of other currencies, such as USD, GBP, AUD, etc. (e.g., Cheah et al., 2018) or to other types of assets, such as gold or U.S. stocks (Bartos, 2015; da Fonseca & da Fonseca, 2019). When comparing Bitcoin to currencies or other types of assets the authors found more extreme behavior in the cryptomarkets and conclude that cryptocurrencies are more likely to present extreme speculative bubble cycles than other asset classes.

Further, it is noticeable that some scholars, for example Stosic et al., 2019, examined Bitcoin and seven other cryptocurrencies' behavior from the point of view of chaos theory, analyzing its complexity and entropy, along with the seemingly chaotic behavior observed by its trading patterns. As the Brazilian authors noted, "cryptocurrencies range from being partially deterministic (predictable from the past) to being completely unpredictable (high entropy and zero complexity); Bitcoin and other major cryptocurrencies fall somewhere in between" (Stosic et al., 2019, p.555).

One curious prediction of the authors Xiong et al., published in early 2020, using the LPPL model is that the "next large bubble is expected by the second half of 2020" (p.10) and seems to be on point. By early 2021, one Bitcoin was selling at the most recent all-time high levels of above 40,000 USD. Given Xiong et al.'s remarkably successful prediction, their proposed testing and predictive models will probably be re-tested by other researchers.

CONCLUSIONS

The research objective of the present paper was to investigate the efficiency of the cryptocurrency market based on a documentary research of Bitcoin in particular. Out of the sample of 25 analyzed studies, 20 present evidence against the EMH and just 5 accept (or at least do not reject) the EMH. Surprisingly, just one study (Urquhart, 2016; included in the group of accepting studies) presents mixed evidence and suggests that the behavior of the cryptocurrency market may settle in the future when the market is more established (Urquhart, 2016). Given the overwhelming support for rejecting the EMH based on the analysis of the 25 academic articles, we conclude that as of 2020 the Bitcoin and the cryptocurrency markets are inefficient, as the appearance of speculative bubbles as major examples of market inefficiencies is proven for the past and can be expected for the future.

Furthermore, it is worth mentioning that the authors Corbet et al., (2019) have conducted a systematic classification of 32 journal articles published between 2009-2018, and according to the topics they focus on, they established five main categories as research areas within the Bitcoin/cryptocurrencies literature: 1) bubble dynamics, 2) regulation, 3) cyber-criminality, 4) diversification and 5) efficiency. This article of Corbet et al., (2019) did not focus on the efficiency of cryptocurrency markets, but rather grouped the selected literature according to the five main topics.

Our article contributes to the research that assess Bitcoin´s market efficiency based on the criteria of the classic EMH. In addition to systematically organizing and analyzing 25 academic articles, we considered several other characteristics in our assessment, such as the time span of the data, the type of models used for analysis and the cryptocurrencies that were compared. Considering the evidence of the present study related to modern cryptocurrency markets, we contribute to the long list of contemporary and less recent research projects that question the practical relevance of the EMH. Further research can include more published academic research in this rapidly changing and growing area of financial literature. We highly recommend that the process of testing the EMH in Bitcoin and other cryptocurrency markets should continue to find even more evidence against (or in favor of) the efficiency of cryptomarkets. Moreover, new empirical studies could possibly refine existing statistical methods which may adapt even better to the innovative characteristics of those currencies.

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APPENDICES

Appendix A
25 selected articles analyzed according to accepting or rejecting the EMH

SECTION A: ARTICLES THAT DO NOT REJECT / ACCEPT THE EMH CONSIDERING THE BITCOIN MARKET					
Doc. No.	**Article (authors, year)**	**Title**	**Journal**	**Key focus (Time period, models and tests used; cryptocurrency studied)**	**Conclusion**
1	Bartos, J. (2015)	Does Bitcoin follow the hypothesis of efficient market?	International Journal of Economic Sciences	Studies whether or not the price of Bitcoin follows hypothesis of efficient markets. The main features of Bitcoin and its price behavior are analyzed in this paper. Period: Mar **2013**-Jul **2014** Model used: Augmented Dickey-Fuller (ADF) test, Breusch-Godfrey LM test, OLS model, error correction model (ECM). Cryptos: BTC, LTC vs. other stocks and assets.	Finds that **Bitcoin prices follow the semi-strong form of EMH** as they immediately react to the publication of new information. Furthermore, it states that Bitcoin can be seen as a standard economic good that is priced by interaction of supply and demand on the market. Rejects that exogenous macroeconomic effects drive the price change in Bitcoin.
2	Urquhart, A. (2016)	The inefficiency of Bitcoin.	Economics Letters	Analyzes the market efficiency of Bitcoin through several robust tests. Periods: Aug **2010–** Jul **2016 (segmented: 2010-2013, 2013-2016** Model used: automatic VAR test, Ljung-Box test, Bartel´s test, AVR test, BDS test, Hurst exponent (R/S Hurst) test for long memory of stock returns. Crypto: BTC.	Provides evidence that returns of Bitcoin are significantly inefficient over the full sample, but when sample is split into two subsample periods, it finds **that some tests indicate that Bitcoin is efficient between 2013-2016**. Concludes that **Bitcoin market may be in the process of moving towards an efficient market.**
3	Nadarajah, S., & Chu, J. (2017)	On the inefficiency of Bitcoin.	Economics Letters	Re-examines Urquhart´s (2016) research on the market efficiency of Bitcoin by means of five different tests on Bitcoin returns. (The original study concluded that the Bitcoin returns do not satisfy the EMH.) Periods: Aug **2010–** Jul **2016 (segmented: 2010-2013, 2013-2016)** Model used: Ljung-Box test, Bartel´s test for independence of returns, variance ratio tests, and BDS. Crypto: BTC.	Proves that a simple power transformation of the **Bitcoin returns does satisfy the weak form of EMH hypothesis** with the use of eight different tests (including martingale difference test). Only the tests for independence are rejected, other tests accept the null hypothesis, indicating **weakly efficient markets**.

Doc. No.	Article (authors, year)	Title	Journal	Key focus (Time period, models and tests used; cryptocurrency studied)	Conclusion
4	Vidal-Tomás, D., & Ibañez, A. (2018)	Semi-strong efficiency of Bitcoin.	Finance Research Letters	Studies the semi-strong efficiency of Bitcoin in the Bitstamp and Mt.Gox markets and shows how Bitcoin reacts to monetary policy and other events related to the cryptocurrency market. Period: Sep **2011–**Dec **2017** Model & tests used: event study, GARCH-type models (CGARCH, AR-CGARCH) Crypto: BTC.	Evidence confirms that **Bitcoin has become more efficient over time** in relation to its own market events. Therefore, the semi-strong form of the EMH is accepted. However, Bitcoin is not affected by monetary policy news, announced by the central bank as the digital currency is not connected to the regulated financial markets.
5	Caporale, G. M., & Plastun, A. (2019)	Price overreactions in the cryptocurrency market.	Journal of Economic Studies	Examines price overreactions and the day of the week effect in the case of the four major cryptocurrencies. A trading robot approach is then used to establish whether these statistical anomalies can be exploited to generate profits. Period: **2013 - 2017** Model used Average analysis, Student´s t-test, ANOVA test, Kruskal-Wallis test and regression analysis with dummy variables. Cryptos: BTC, LTC, XRP, DASH.	Several parametric and non-parametric tests confirm the presence of price patterns after overreactions: the next day price changes in both directions are bigger than after "normal" days. However, **the overreactions detected in the cryptocurrency market do not give rise to exploitable profit opportunities** (because of transaction costs according to the authors) and **cannot be seen as evidence against the EMH**. More tests and bigger cryptocurrency sample is recommended for future tests.
SECTION B: ARTICLES THAT REJECT THE EMH CONSIDERING THE BITCOIN MARKET					
Doc. No.	**Article (authors, year)**	**Title**	**Journal**	**Key focus (Time period, models and tests used; cryptocurrency studied)**	**Conclusion**
1	Garcia, D., et al., (2014)	The digital traces of bubbles: feedback cycles between socio-economic signals in the Bitcoin economy.	Journal of the Royal Society Interface	Studies the role of social interactions in the creation of price bubbles. Focusing on Bitcoin, the authors hypothesize that the price fluctuations are largely driven by the interplay between different social phenomena. Period: Jan **2009** – Oct **2013** Models & tests used: vector autoregression (VAR) test Cryptos: BTC.	The authors find two positive feedback loops in the Bitcoin market that lead to price bubbles in the absence of exogenous stimuli: one driven by word of mouth, and the other by new Bitcoin adopters. **Due to the existence of positive feedback loops and formation of asset bubbles, the EMH cannot be accepted.**
2	Cheung, A., Roca, E., & Su, J. J. (2015)	Crypto-currency bubbles: an application of the Phillips–Shi–Yu (2013) methodology on Mt. Gox bitcoin prices.	Applied Economics	Analyzes whether Bitcoin is characterized by bubbles and bursts (such as the case of the crash of the trading exchange, Mt. Gox), using the Phillips–Shi–Yu (PSY) (2013) methodology. Period: Jul **2010 –** Feb **2014** Models & tests used: PSY model, ADF t-test, GSADF (Generalized Supremum ADF) test. Cryptos: BTC.	Detects the existence of three major and other smaller bubbles between 2010-2014, including the collapse of Mt Gox exchange, using the PSY technique. It confirms the existence of bubbles that have been previously reported in the non-academic financial media. Therefore, **evidence is provided the Bitcoin cannot be considered as an efficient market**. Lastly, Bitcoin is considered as a speculative commodity by the authors which possesses no intrinsic value.

Doc. No.	Article (authors, year)	Title	Journal	Key focus (Time period, models and tests used; cryptocurrency studied)	Conclusion
3	Cheah, J. E.T. & Fry, J. (2015)	Speculative bubbles in Bitcoin markets? An empirical investigation into the fundamental value of Bitcoin.	Economics Letters	Applies economic and econometric modelling for Bitcoin prices. Period: Jul **2010 –** Jul **2014** Models & tests used: speculative bubble component perspective (key assumptions: intrinsic rate of return, intrinsic level of risk), BDS tests. Cryptos: BTC.	Concludes that **Bitcoin exhibits speculative bubbles**. Hence, the EMH is rejected. Also, the authors show empirical evidence that the fundamental price of Bitcoin is zero.
4	Fry, J., & Cheah, J. E. T. (2016)	Negative bubbles and shocks in cryptocurrency markets.	International Review of Financial Analysis	Studies the relationship between statistical physics and mathematical finance to develop statistical models to assess and test the existence financial bubbles and crashes. Period: for BTC analysis Jul **2010-Feb 2015**; reduced set for comparison: Feb **2013 –**Feb **2015** Models & tests: speculative bubble perspective (key assumptions: intrinsic rate of return, intrinsic level of risk), multivariate model. Cryptos: BTC and XRP.	Results **confirm the existence of a negative bubble in 2014 for both Bitcoin and Ripple**. Hence, these digital markets cannot be considered as efficient as described by the EMH. This study combines the approaches of econophysics and mainstream financial models to monitor and analyze financial markets.
5	Bariviera, A. F. (2017)	The inefficiency of Bitcoin revisited: A dynamic approach.	Economics Letters	Reviews the informational efficiency of the Bitcoin market, analyzing the time-varying behavior of memory of returns on Bitcoin and volatility. Period: **2011-2017** Models & tests: R/S method, DFA test (using the Hurst Exponent). Cryptos: BTC.	Confirms that **price volatility exhibits long memory during all the period**. This reflects a different underlying dynamic process generating the prices and volatility. Identifies clear difference in returns of pre- and after 2014 data; recommends using the DFA model.
6	Kurihara, Y. & Fukushima, A. (2017)	The market efficiency of Bitcoin: A weekly anomaly perspective.	Journal of Applied Finance & Banking	Examines empirically whether weekly price anomalies exist in the Bitcoin market, by testing the market efficiency of Bitcoin. Period: Jul **2010** – Dec **2016** Models & tests used: ADF test, OLS and RLS (ordinary and robust least squares) regression models. Cryptos: BTC .	The **empirical results show that the Bitcoin market is not efficient, considering weekly data**. However, the test results show that Bitcoin transactions are becoming and can become more efficient.

Doc. No.	Article (authors, year)	Title	Journal	Key focus (Time period, models and tests used; cryptocurrency studied)	Conclusion
7	Alvarez-Ramirez et al., (2018)	Long-range correlations and asymmetry in the Bitcoin market.	Physica A: Statistical Mechanics and its Applications	Analyzes long-range correlations and informational efficiency of the Bitcoin market. Period: **2013-2017** Models & tests used: Detrended fluctuation analysis (DFA) test Cryptos: BTC.	Based on the reported results the authors conclude that the **Bitcoin market is not uniformly efficient, as** anti-persistence of the price returns appeared cyclically with a period of ~0.75 years. Possible explanations offered: a) exogenous macroeconomic effects; b) endogenous effects of intrinsic market dynamics of an emerging cryptocurrency market.
8	Cheah, J.E.T., et al., (2018)	Long memory interdependency and inefficiency in Bitcoin markets.	Economics Letters	Models cross-market Bitcoin prices as long-term processes and analyzes dynamic interdependence among different exchange platforms, from 5 developed markets. Period: Nov **2011 –** Mar **2017** Models & tests used: GARCH (1,1) model, VAR and FCVAR tests, two-step Exact Local Whittle (ELW) estimator model, test for fractional cointegration. Crypto: BTC (vs. EUR, USD, AUD, CAN, GBP).	Summarizes that **Bitcoin markets are "moderate to highly inefficient", therefore rejects the EMH**. Due to this feature, investors may exploit the estimated long memory in prices for speculative profits. Confirms that uncertainty has an overall negative influence on Bitcoin markets. Suggests that observed inefficiency could possibly be regulated.
9	Corbet, S., Lucey, B., & Yarovaya, L. (2018)	Datestamping the Bitcoin and Ethereum bubbles.	Finance Research Letters	Examines the existence and dates of pricing bubbles in Bitcoin and Ethereum, applying the (Phillips et al., 2011) methodology Period: Jan **2009 –** Nov **2017** Models & tests used: PSY model, SADF, GSADF and BSADF tests. Cryptos: BTC, ETH.	Concludes that there are periods of clear bubble behavior, **with Bitcoin almost certainly in a bubble phase in 2017-2018.** However, the authors find no clear evidence that persistent bubbles exist in either the Bitcoin or Ethereum market. Based on the findings, the EMH cannot be accepted.
10	Kristoufek, L. (2018)	On Bitcoin markets (in) efficiency and its evolution.	Physica A: Statistical Mechanics and its Applications	Studies efficiency of two Bitcoin markets (with respect to the US dollar and Chinese yuan) and its performance over time. Period: **2010** – **2017** Models & tests used: long range dependence and its estimators, Hurst exponent, Efficiency Index (EI). Cryptos: BTC.	Finds **convincing evidence that both Bitcoin markets are inefficient between 2010 and 2017**, except several periods of price drops that follow significant bubble-like price increases. Thus, the EMH is not accepted.

Doc. No.	Article (authors, year)	Title	Journal	Key focus (Time period, models and tests used; cryptocurrency studied)	Conclusion
11	Wei, W. C. (2018)	Liquidity and market efficiency in cryptocurrencies.	Economics Letters	Examines the liquidity of 456 different cryptocurrencies and tests whether return predictability reduces in cryptocurrencies with high market liquidity. Period: **Jan-Dec 2017** Models & tests used: Ljung-Box test, Bartel´s test, VAR test, BDS test on serial independence. Crypto: BTC and 455 other currencies (grouped in 5 categories).	**The empirical results show that the Bitcoin market is not efficient**. Confirms that although Bitcoin may indicate efficiency, numerous cryptocurrencies still show signs of autocorrelation and non-independence. However, the results show that Bitcoin transactions and other digital currencies are becoming and can become more efficient transactions as liquidity increases.
12	Wheatley, S., et al., (2018)	Are Bitcoin bubbles predictable? Combining a generalized Metcalfe's Law and the LPPLS model. and the LPPLS Model.	Swiss Finance Institute Research Paper	Presents a convincing diagnostic for bubbles and crashes in Bitcoin, by studying the coincidence of fundamental value and technical indicators. Period: **2011–2018** Models & tests used: generalized Metcalfe's Law and the LPPLS models. Crypto: BTC.	Using a generalized Metcalfe's Law based on network properties, a fundamental value is quantified, and the authors show that the price exceeded the fundamental value. This was the case on at least four occasions, when bubbles developed and later burst in the Bitcoin market. **Due to the existence of bubbles, the EMH is not considered as acceptable.**
13	Bundi, N., & Wildi, M. (2019)	Bitcoin and market-(in) efficiency: a systematic time series approach.	Digital Finance	Analyzes Bitcoin and verifies the pertinence of the efficient market hypothesis. While there may have been inefficiency in their early days, BTC transitioned into efficient markets recently. The authors challenge this claim by proposing simple trading strategies. Period: Apr**2014-** Jan **2019** Models & tests used: GARCH-model, log returns, ARMA forecast models, non-linear neutral tests. Cryptos: BTC.	Confirms that statistical evidence was found to violate the EMH, as the authors find positive serial correlation of returns. **The authors strongly reject the EMH for the Bitcoin market** during the sample period and in recent times in particular. Notes that departures from linearity seems to be marginal and may be limited only after the 2018 Bitcoin price crash.
14	da Fonseca, V. M., & da Fonseca, M. A. (2019)	A Simple Approach to Assess if a Financial "Bubble" is Present: The Case of Bitcoin.	Applied Economics and Finance	Evaluates if the recent price behavior of Bitcoin can be characterized as a financial market "bubble". To test this, it uses a statistical definition of a **"**bubble" derived from the EMH and proposes a simple method to test this proposition, based on the time-series model known as random walk. Period: original sample **2009 –2018, reduced sample: 2013-2018** Models & tests used: simple regression analysis. Crypto: BTC (vs. other U.S. stocks).	Finds consistent evidence for the period of 2013-2018 - with close to 100% confidence - that **Bitcoin does not follow the dynamics pattern of a random walk; hence, the EMH is rejected.** According to the authors Bitcoin follows a financial "bubble", much more so than other stock indexes that were used as benchmark (Nasdaq, Russell 2000 index).

Doc. No.	Article (authors, year)	Title	Journal	Key focus (Time period, models and tests used; cryptocurrency studied)	Conclusion
15	Geuder, J., Kinateder, H., & Wagner, N. F. (2019)	Cryptocurrencies as financial bubbles: The case of Bitcoin.	Finance Research Letters	Studies bubble behavior in Bitcoin prices based on two distinct testing methodologies. The PSY model is used to identify multiple bubble periods. Period: May **2016** –Sep **2018** Models & tests used: PSY model (2015), log-periodic power law (LPPL) of Filimonov and Sornette (2013) Cryptos: BTC.	Underlines that bubble behavior is clearly a common and reoccurring characteristic of Bitcoin prices. The log-periodic power law (LPPL) model identifies bubble growth and potential bubble termination times. As **the authors confirm the existence of bubbles, the EMH cannot be accepted.**
16	Hu, Y., Valera, H. G. A., & Oxley, L. (2019)	Market efficiency of the top market-cap cryptocurrencies: Further evidence from a panel framework.	Finance Research Letters	Analyzes 31 cryptocurrencies using various panel tests whether their behavior is consistent with the efficient market hypothesis or not. Period: Aug **2017** –Jan **2019** Models & tests used: panel unit root/stationary tests, CADF regression model. Cryptos: BTC and other 31 cryptocurrencies.	**Based on empirical evidence** presented, it **concludes that the price fluctuations of 31 cryptocurrencies are inconsistent with the EMH**, signaling market inefficiency in the most common cryptocurrency market. The authors also confirm cross- section dependence among the most popular cryptocurrencies, indicating bubble spillovers.
17	Stosic et al., (2019)	Exploring disorder and complexity in the cryptocurrency space.	Physica A: Statistical Mechanics and Its Applications	Treats the cryptocurrency market as a complex system and analyzes it with methods from statistical physics. The complexity–entropy causality plane (or CH plane) is employed in order to explore disorder and complexity in the space of cryptocurrencies. Periods: May **2013–** Jan **2018** Models & tests used: complexity-entropy causality plane (CH plane) Cryptos: BTC, ETH, XRP, BTH, LTC, NEO, NEM, XLM, DASH.	Cryptocurrencies are found to exist on distinct planar locations in the representation space. Further, these currencies at different position along the CH plane behave very different over time. **Cryptocurrencies range from being totally predictable from the past (deterministic) to being completely unpredictable**. According to the authors Bitcoin and other major cryptocurrencies lie between the extremes. **Hence, these markets are not considered as efficient.**
18	Agosto, A., & Cafferata, A. (2020)	Financial Bubbles: A Study of Co-Explosivity in the Cryptocurrency Market.	Risks	Investigates co-explosivity in crypto assets, i.e., whether explosivity in one cryptocurrency leads to explosivity in other cryptocurrencies. Period studied: **2017-2018** Models used: PWY, PSY models Cryptos: 5 largest (BTC, ETH, XRP, LTC, XLM).	Finds significant relationships between explosive behaviors of cryptocurrencies and finds that the price dynamics of cryptocurrencies are highly interdependent among cryptocurrencies. Documented several explosive episodes within the Bitcoin market prices as well as in other cryptocurrency markets.

Doc. No.	Article (authors, year)	Title	Journal	Key focus (Time period, models and tests used; cryptocurrency studied)	Conclusion
19	Pagnotta, E. (2020)	Bitcoin as Decentralized Money: Prices, Mining, and Network Security.	The Review of Financial Studies	Focuses on how the prices of Bitcoin are determined in a decentralized monetary economy. Analyzes users' forecast on the transactional and resale value of Bitcoin holdings and price the risk of malicious system attacks. Periods: Jul **2010–** Jan **2020** Models & tests used: security model analyzed; decentralized monetary equilibria (DME) is modeled. Crypto: BTC, ETH, XRP.	Confirms that price-security feedback effects can increase the volatility impact of fundamental shocks, and lead to boom-bust cycles and welfare losses. Consequently, these movements are not compatible with the EMH as they indicate market inefficiency. The authors present evidence that the viability of Bitcoin compared to fiat currencies depends of its acceptability and inflationary pressures.
20	Xiong, J., Liu, Q. & Zhao, L. (2020)	A new method to verify Bitcoin bubbles: Based on the production cost.	The North American Journal of Economics and Finance	Focuses on Bitcoin price cycles to test bubble theory during a two -year period. Builds on existing bubble theory. Period: Jan **2017 –** Dec **2018** M Models & tests used: LPPL model, VAR test, Granger causality test. Crypto: BTC.	Based on previous asset bubble theory, it verifies that the Bitcoin bubble is based on the production cost with the application of VAR and LPPL models, and that this method achieved good predictive power. The authors describe the bubble size, the scale of collapse, the production cost and its change with the LPPL model. Forecasts the next Bitcoin bubble, after 2018, by late 2020.

Source: the authors´ compilation.

Appendix B
List of abbreviation of cryptocurrencies mentioned in Appendix A

BTC – Bitcoin
BTH – Bithereum
ETH – Ethereum
XRP – Ripple
LTC – Litecoin
XLM – Stellar
DASH – Dash
NEO – NEO (smart contract platform)
NEM (XEM) –New Economy Movement (NEM)
Source: Coinmarketcap (2021).

Appendix C
List of abbreviation of statistical models and tests mentioned in Appendix A

ADF test – Augmented Dickey-Fuller test
ANOVA test – one-way analysis of variance test
ARMA model – Autoregressive-moving average model for forecasting
Bartel´s test – used for independence of returns
BDS test – Brock, Dechert and Scheinkman (or BDS) test for independence
BSADF – Backward Supremum ADF (Augmented Dickey-Fuller) test
CADF test – cross-sectionally augmented Dickey–Fuller (ADF) regressions
DFA test – detrended fluctuation analysis
DME – decentralized monetary equilibria
ELW – Error correction model
ELW – Exact Local Whittle component
FCVAR – fractionally cointegrated vector autoregressive (FCVAR) test
GARCH model – generalized autoregressive conditional heteroskedasticity
GSADF test – Generalized Supremum ADF test
Hurst test, using the Hurst exponent
Ljung-Box test – used for autocorrelation
LPPL model – log-periodic power law
LPPLS model – log-periodic power law singularity model
OLS model – Ordinary Least Square model
PSY model – Phillips, Shi and Yu (2015)
PWY model – Phillips, Wu and Yu (2011a and 2011b)
RLS model – Robust Least Squares model
SADF – Supremum ADF test
VAR test– vector autoregression (VAR) test

Source: Newbold, Carlson & Thorne (2013), Phillips, Shi and Yu (2015).