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COVID-19 and financial market efficiency: Evidence from an entropy-based analysis

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ABSTRACT

This study assesses the market efficiency of S&P 500 Index, gold, Bitcoin and US Dollar Index during the extreme event of COVID-19 pandemic. Market efficiency is estimated by a multiscale entropy-based method for the scales of hourly and 1 to 30 business days. At all scales, four markets’ efficiency decreases sharply and persistently during February-March 2020. Market efficiency decreases the most in S&P 500 Index and the least in Bitcoin market. Bitcoin market efficiency is more resilient than others during the extreme event, which is an attractive feature to serve as a safe haven asset.

1. Introduction

Market efficiency during extreme events and crisis has been a key focus of financial research. An efficient market fully and instantaneously incorporates all available information to asset price (Fama 1991). In this case the allocation of scarce capital resource is efficient and asset price cannot be predicted using past price information. Lim et al. (2008) find the 1997 financial crisis adversely affected the market efficiency in most Asian stock markets. Ortiz-Cruz et al. (2012) find the crude oil market efficiency declined during the economic recessions in early 1990s and 2008-2011. Moreover, Risso (2008) examines a set of stock indices and finds the probability of market crash increases as efficiency decreases.

The outbreak of COVID-19 pandemic has tremendously affected the financial markets. A series of research has investigated multiple aspects of its impacts (Goodell 2020). Baker et al. (2020) examine the response of US equity indices to COVID-19 development. Goodell and Goutte (2020) examine the co-movement of Bitcoin price with COVID-19. Conlon and McGee (2020) and Conlon et al. (2020) examine the performance of cryptocurrency markets as safe haven for equity markets in the pandemic. Corbet et al. (2020), Okorie and Lin (2020) and Yarovaya et al. (2020a) examine respectively the volatility spillover and contagion effect across different markets.

However, the market efficiency during COVID-19 has not been studied. In this paper, we fill the literature gap by examining the time-varying informational efficiency of four related markets, which are the S&P 500 Index, gold, Bitcoin and US Dollar Index. S&P500 is a benchmark equity index. Gold has traditionally been a safe haven asset for equity markets (Baur and Lucey 2010; Bredin et al. 2015). Bitcoin was developed as a cryptocurrency with its value related to exchange rate such as Dollar Index (Selgin 2015). But recently its property as a safe haven asset has triggered wide interests (Klein et al. 2018; Corbet et al., 2019; Shahzad et al. 2019; Urquhart and Zhang 2019; Conlon et al. 2020), though much of the research are performed in relatively normal periods. The COVID-19

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provides a unique setting to examine Bitcoin’s safe haven property in extreme events. For these reasons we select these four markets in this analysis. Al-Yahyae et al. (2018) similarly examine the time-varying efficiency of Bitcoin, equity index, US Dollar index and gold markets from 2010-2017, but not in the period of extreme economic shocks. Using the generalized Hurst exponent to compare with random walk process, they find Bitcoin is the least efficient market among the four studied markets and exhibits the highest efficiency variation.

We evaluate the time-varying informational efficiency through the refined composite multiscale fuzzy entropy (RCMFE) method. Market efficiency has been mostly assessed under the weak-form efficient market hypothesis, or EMH (Fama 1998). However, the EMH approach only offers an all-or-nothing response regarding the efficiency of market. The entropy-based approach offers more insights by quantifying the degree of efficiency through time and has been used in multiple markets (Alvarez-Ramirez et al. 2012; Ortiz-Cruz et al. 2012; Liu et al. 2020). We use the RCMFE algorithm developed by Azami et al. (2017) because it improves upon previous entropy estimation methods to attain higher accuracy and stability in short observations. In addition, RCMFE extracts more information by allowing for overlapping windows in estimation.

To our knowledge, this is the first assessment of financial markets’ efficiency during the extreme event of COVID-19 pandemic. We find the market efficiency decreases in all four markets, though the daily level efficiency of Bitcoin market is more resilient than the others. For all four markets, the decrease in efficiency is persistent up to the monthly scale. The resiliency of Bitcoin market efficiency is an attractive feature for it to serve as a safe haven asset. Our findings contribute to two schools of literature, one is the market efficiency during extreme events and the other is the use of cryptocurrencies as safe haven assets.

2. Methods

We take a two-step procedure to measure the informational efficiency. First, we estimate the entropy value using the RCMFE method developed by Azami et al. (2017). Second, we construct the market informational efficiency index following Ortiz-Cruz et al. (2012). We describe each step as below.

2.1. RCMFE

Entropy measures the degree of disorder and uncertainty in a dynamic system. In the information theory, entropy estimates the richness of patterns to quantify the amount of information in a time series. A higher entropy value of time series corresponds to more efficient information transmission and lower predictability (Gulko 1999).

We estimate the entropy values following the RCMFE algorithm developed by Azami et al. (2017). For time series \( y = \{y_1, y_2, \ldots, y_N\} \), where \( N \) is the number of observations, a demeaned vector is constructed for each time \( t \) of \( y \) as \( U^m_{m} = \{y_t, y_{t+1}, \ldots, y_{t+m-1}\} - y_0 \). Here \( y_0 = \sum_{j=0}^{m-1} \frac{Y_j}{m} \) for \( t = 1, 2, \ldots, N - (m - 1) \). \( m \) is the number of embedding dimensions that define the number of samples contained in each vector. The distance between any two vectors is defined as:

\[
d_{t_1, t_2} = d(U^m_{t_1}, U^m_{t_2}) = \max \left\{ U^m_{t_1+k} - U^m_{t_2+k} : k \in [0, m-1] \text{ and } t_1 \neq t_2 \right\}.
\]

If the distance is smaller than a predefined tolerance level \( r \), then a match happens between the two vectors. The degree of similarity between two vectors is measured by the fuzzy membership function \( D_{t_1,t_2} = \exp\left(-\frac{(d_{t_1,t_2})^2}{r}ight) \) for a given \( r \) and fuzzy entropy power \( n \). The fuzzy entropy of \( y \) is defined as:

\[
FE(y, m, n, r) = -\ln \left( \frac{\varphi^{m+1}}{\varphi^m} \right).
\]

where the function \( \varphi^m \) is defined as:

\[
\varphi^m(y, m, n, r) = \frac{1}{N-m} \sum_{i=1}^{N-m-1} \sum_{j=1, j \neq i}^{N-m} D_{t_1,t_2}.
\]

In addition, the RCMFE estimates the entropy values at different time scales which we use to obtain the multiscale market efficiency. Market may incorporate information with different efficiency at daily, weekly or monthly level. To investigate the multiscale efficiency changes, a coarse-graining procedure is applied to filter the time series to extract variations at each scale.

For each time scale factor \( \tau \), we construct \( \tau \) different coarse-grained time series \( z^{(u)}_u = \{y_1, \ldots, y_\tau\} \), for which the mean is \( \mu_{z^{(u)}} = \frac{1}{\tau} \sum_{u=0}^{\tau-1} z^{(u)}_u \). Compared to the multiscale entropy (MSE) method (Costa et al. 2005) that divides the time series into non-overlapping windows of length \( \tau \), the advantage of RCMFE is that it extracts more information from the original data by allowing for overlapping windows at each \( \tau \). Next a fuzzy entropy for each time scale is calculated and averaged across \( u = 1, \ldots, \tau \) to obtain the average \( \varphi^{m}_{\tau,u} \) and \( \varphi^{m+1}_{\tau,u} \). Finally, the RCMFE is computed as:

\[
RCMFE(y, \tau, m, n, r) = -\ln \left( \frac{\varphi^{m+1}_{\tau,u}}{\varphi^m_{\tau,u}} \right).
\]
2.2. Relative informational efficiency index

As stated in the EMH, in a weakly efficient market, asset prices should be random walk and the price returns should be a Gaussian white noise. For this reason, the entropy of Gaussian white noise serves as the theoretical benchmark of the entropy of asset prices in an efficient market. Following Ortiz-Cruz et al. (2012), the relative market efficiency index is defined for each time scale \( \tau \) as:

\[
I_{\text{IME}}(\tau) = \frac{\text{RCMFE}(y, \tau, m, n, r)}{\beta(\tau)} \times 100% ,
\]

where \( \beta(\tau) \) is the Gaussian white noise entropy upper bound of 5,000 Monte Carlo simulation samples. If the asset market entropy is below that of Gaussian white noise, or \( I_{\text{IME}}(\tau) < 100\% \), then the market is only fractionally efficient.

3. Data and parameter selection

We collect the daily closing values of S&P 500 Index, Bitcoin, US Dollar Index and the nearby futures price of gold at CME for each business day from January 2\(^{nd}\) 2018 to May 29\(^{th}\) 2020, for a total of 606 observations. In addition, we collect the hourly closing values of these markets from December 2\(^{nd}\) 2019 to May 29\(^{th}\) 2020 to shed more light on the intra-day efficiency, because market reactions to COVID-19 events can be fast moving. We calculate the log price return series \( y_t = \ln(p_t) - \ln(p_{t-1}) \) for each market to estimate the RCMFE\((y, \tau, m, n, r)\).

For the choice of input parameters \( \tau, m, n \) and \( r \), we set their values as following. For time scale \( \tau \), we set it up to 30 business days,
which is equivalent to 6 weeks and nests the daily (1 day), weekly (5 days) and monthly (22 days) efficiency indices. For intraday analysis we focus on the hourly scale. For embedding dimensions $m$, we set it at 2 because the sample size $N$ should be within the range of $10^m \sim 30^m$ (Liu et al. 2020). To obtain more stringent match of patterns in each return series, we set the fuzzy power $n$ at 2 following Richman and Moorman (2000) and set the tolerance range $r = 0.15\sigma$ following Ahmed and Mandic (2011), where $\sigma$ is the standard deviation of return series.

4. Results and discussions

We present the results in two steps. First, we estimate the RCMFE and informational efficiency of each market for the full sample period. Next, we examine the impact of COVID-19 on the time-varying informational efficiency through a rolling window approach.

4.1. Informational efficiency for full sample

Fig. 1 shows the RCMFE and informational efficiency estimates across the 1 to 30 days scales. The upper panel shows the estimated entropy values. In all markets the entropy declines as time scale increases, suggesting a reduction of pattern richness after filtering the original return series with coarse-graining procedure. The lower entropy values at longer time scales also imply the price returns are more predictable with less information content. The declining entropy with time scales are consistent with previous studies on financial and commodity markets using entropy methods (Alvarez-Ramirez et al. 2012; Ortiz-Cruz et al. 2012; Liu et al. 2020).

The lower panel shows the informational efficiency across time scales. At the daily scale, the Dollar Index exhibits the highest efficiency at 85%, followed by gold market (71%), Bitcoin (60%) and S&P 500 Index which is the lowest at 43%. As time scale increases, the efficiency level shows a generally declining pattern. This is consistent with the findings of Alvarez-Ramirez et al. (2012) that the Dow Jones Index is more efficient in shorter scales. However, the finding on daily efficiency contrasts with Al-Yahyae et al. (2018) who study a similar combination of markets but report Bitcoin is the least efficient one during 2010-2017. We shed light on this difference by investigating the time-varying efficiency in the following section.

4.2. Time-varying informational efficiency

We employ a rolling window approach to analyze the changes in market informational efficiency through time for both the daily and hourly observations. For daily analysis, we set window length at 252 business days, which is equivalent to one year and the RCMFE estimates have stabilized at this length (see the Appendix for more details). The start of estimation window is January 2$^{nd}$, 2018 to January 2$^{nd}$, 2019. For each window we estimate its $I_{ME}(t)$, which represents the informational efficiency in the one-year period.

Fig. 2 shows the daily informational efficiency. Several observations can be obtained from the figure. First, all four markets’ efficiency falls steeply during March 2020 when COVID-19 broke out massively in the US. From March 2$^{nd}$ to March 31$^{st}$, the informational efficiency declines the most in S&P 500 Index by 37%, followed by a 24% decrease in Dollar Index and a 16% decrease in...
gold. Bitcoin market efficiency falls the least by only 5%. The huge efficiency decline in S&P 500 Index is due to the market crash during March. The continued falling trend of equity index reduces the uncertainty of price returns and leads to lower entropy values. The efficiency decline in the other three markets are less severe because of less persistent price trend. Bitcoin only suffers small efficiency loss during March because the scare in equity market fails to create a one-sided trend in Bitcoin prices. This can be partially explained by Yarovaya et al. (2020), which finds the herding behavior does not get stronger in Bitcoin market during COVID-19. Our finding is similar to Lim et al. (2008) and Ortiz-Cruz et al. (2012) that extreme events can reduce market efficiency, though our finding suggests the degree of impact is different depending on the nature of asset.

Second, we find that Bitcoin market efficiency is more resilient during the pandemic compared to the other three markets, which...
supports its safe haven asset attributes. Bitcoin market remains around the 60% average efficiency level after the drop, while other markets all fall to their lowest levels in the sample. This is an important finding because it contributes to the ongoing discussion of whether cryptocurrencies can serve as safe haven assets for equity markets during extreme events. Corbet et al. (2020) and Conlon and McGee (2020) find Bitcoin do not perform as a safe haven but rather amplifies the contagion. On the contrary, Goodell and Goutte (2020) suggest Bitcoin can act as a safe haven in the pandemic because of its co-movement with COVID-19 cases. Our finding adds from the perspective that Bitcoin market is relatively more efficient and resilient during COVID-19. Thus, it creates an advantage over other markets in risk management as a safe haven asset in extreme events.

Third, prior to the decline of market efficiency due to COVID-19 pandemic, Bitcoin is the least efficient one among the four markets. Before March 2020, Bitcoin market efficiency has ranged between 50% - 64%, consistently below the other three markets. This is consistent with the findings of Al-Yahyaee et al. (2018) during normal periods. The huge decline since March drags the full sample efficiency estimates lower for the S&P 500 Index, gold and Dollar Index and explains why S&P 500 Index exhibits the lowest efficiency (as discussed in Section 4.1).

In Fig. 3 we further illustrate the multiscale market efficiency from the rolling window estimates. We find market efficiency not only decreases at the daily scale, but also at longer time scales. In Bitcoin and gold markets, market efficiency decreases across 1 to 30 days scales. In the S&P 500 Index and Dollar Index, the decline persists from 1 day up to 20 days (monthly) scales. The results indicate the COVID-19 impact on market efficiency is not limited to the daily level, but profoundly up to monthly scales.

To complement the daily level analysis, we further evaluate the evolution of hourly market efficiency. The rolling window length is set as one month. The window starts with December 1st – 31st, 2019. Because trading hours are different in four markets, the number of observations in each window range from 168 (S&P 500), 485 (gold), 523 (Dollar Index) to 731 (Bitcoin). Fig. 4 shows the results. Compared to the daily efficiency, hourly efficiency exhibits higher variability because of its shorter window length. Similar to the daily level results, market efficiency sharply dropped in all markets after COVID-19 became a pandemic. Among the four markets, there is a timing difference in the efficiency decline. The S&P 500, Dollar Index and gold market efficiency concurrently declined in mid-February and started to recover after a month. On the other hand, Bitcoin market remained around 70% efficient until mid-March when the decline started, which is about a month later than other markets. When Bitcoin market efficiency declined, other markets have regained their efficiency. The disjointed efficiency changes corroborate the daily analysis findings that Bitcoin suffers less contagion from the other three markets during pandemic, which is attractive as a safe haven asset.

5. Conclusion

We assess the financial market efficiency during the extreme event of COVID-19 outbreak. Market efficiency is estimated by a multiscale entropy-based informational efficiency index using the RCMFE method. We compare the time-varying information efficiency in the four markets of S&P 500 Index, gold, Bitcoin and Dollar Index. Our finding contributes to two areas of research. First, on the performance of financial markets in extreme events, we find the COVID-19 leads to efficiency decreases in all four markets, which is consistent with Lim et al. (2008) and Ortiz-Cruz et al. (2012). The contagion effect not only exists in asset pricing and volatility, but also spread into market efficiency, which opens a new perspective for further research. The decrease is particularly large in the S&P 500 Index because the continued equity market crash created a declining trend, which reduces entropy and efficiency. Market efficiency gradually recovered after a month based on intraday analysis.

Second, the resiliency of Bitcoin market efficiency and its disjointed change with other markets contribute to the ongoing discussion of cryptocurrency as safe haven asset (Corbet et al. 2020; Conlon and McGee 2020; Goodell and Goutte 2020). Prior to the pandemic, Bitcoin is the least efficient market, which is consistent with Al-Yahyaee et al. (2018). But during the pandemic we find
Bitcoin market efficiency is relatively more resilient and exhibits less contagion from other markets, which can be partially explained by the findings of (Yarovaya et al., 2020b) that COVID-19 does not amplify herding behavior in cryptocurrency markets. The robustness of Bitcoin market efficiency is an attractive feature for it to serve as a safe haven asset.

CRediT authorship contribution statement

Jingjing Wang: Conceptualization, Data curation, Investigation, Software, Visualization, Writing - original draft. Xiaoyang Wang: Conceptualization, Methodology, Formal analysis, Supervision, Validation, Writing - review & editing.

Appendix. Average RCMFE across rolling window sizes

To examine the changes in RCMFE with respect to the size of rolling window, we start from the window size \( N_w = 100 \) and increase it up to \( N_w = 500 \) days. At each window size, we estimate the RCMFE by rolling window method and calculate the average RCMFE. The daily scale RCMFE \((\tau = 1)\) is shown in Fig. A.1. In general, the average RCMFE value stabilizes for window sizes above the 180 days. For this reason, we set the window size at 252 days to study the time-varying market efficiency.

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