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Random walks and market efficiency tests: evidence on US, Chinese and European capital markets within the context of the global Covid-19 pandemic

JEL Classification: *C58; G10; G11; G12; G14; G15; F3*

Keywords: *COVID-19; capital market; random walk hypothesis; efficient market hypothesis; arbitration; portfolio diversification*

Abstract

Research background: Covid-19 has affected the global economy and has had an inevitable impact on capital markets. In the week of February 24–28, 2020, stock markets crashed. The index FTSE 100 decreased 13%, while the indices DJIA and S&P 500 fell 11–12%, the biggest drop since the 2007–2008 financial and economic crisis. It is therefore of interest to test the random walk hypothesis in developed capital markets, European and also non-European, in order to understand the different predictabilities between them.
Purpose of the article: The aim is to analyze capital market efficiency, in its weak form, through the stock market indices of Belgium (index BEL 20), France (index CAC 40), Germany (index DAX 30), USA (index DOW JONES), Greece (index FTSE Athex 20), Spain (index IBEX 35), Ireland (index ISEQ), Portugal (index PSI 20) and China (index SSE) for the period from December 2019 to May 2020.
Methods: Panel unit root tests of Breitung (2000), Levin *et al.* (2002) and Hadri (2002) were used to assess the time series stationarity. The test of Clemente *et al.* (1998) is used to detect structural breaks. The tests for the random walk hypothesis follows the variance ratio methodology proposed by Lo and MacKinlay (1988).
Findings & Value added: In general, we found mixed confirmation about the EMH (efficient market hypothesis). Taking into account the conclusions of the rank variance test, the random walk hypothesis was rejected in the case of stock indices: Dow Jones, SSE and PSI 20, partially rejected in the case indices: BEL 20, CAC 40, FTSTE Athex 20 and DEX 30, but accepted for indices: IBEX 35 and ISEQ. The results also show that prices do not fully reflect the information available and that changes in prices are not independent and identically distributed. This situation has consequences for investors, since some returns can be expected, creating opportunities for arbitrage and for abnormal returns, contrary to the assumptions of random walk and information efficiency.

Introduction

The EMH (efficient market hypothesis) states that securities prices consider all available data and that investors cannot obtain extraordinary returns by trading based on such information. EMH is an important concept for financial institutions, individual or business investors and government regulators. An investor's investment long-term plan has impact largely by market efficiency (Vochozka *et al.*, 2020; Groda & Vrbka, 2017; Vrbka & Rowland, 2017). Market efficiency also provides the regulatory steps to be developed, in order to ensure the expansion and controlled management of a state's stock markets (Dsouza & Mallikarjunappa, 2015; Shirvani & Delcoure, 2016).

Different scientific contributions have analyzed the problematics of market efficiency, examining the forecast ability of returns through the decomposition of the mean-reversion of the prices in financial markets (Fama & French, 1988). When the hypotheses of random walk and also informational efficiency are rejected, they cause radical co-movements in stock prices. The occurrence of these phenomena may eventually decrease the implementation of efficient portfolio diversification strategies (Malafeyev *at al.*, 2019; Sadat & Hasan, 2019).

This study´s aim is to test the efficient market hypothesis, in its weak form, in 7 European and 2 non-European financial markets. Since Covid-19 appeared at the end of 2019 in the city of Wuhan, China and the World Health Organization (WHO) declared a global pandemic on March 12, 2020, we used a sample that covers the period from December 2019 to May 2020. The results show that daily returns do not have normal distributions and provide evidence of negative asymmetries, leptokurtic and conditional heteroscedasticity. In general, mixed evidence was found concerning the efficient market hypothesis (EMH). Based on the conclusions of the rank variance test the random walk hypothesis was rejected for the Dow Jones, SSE and PSI 20 indices. The results point out that prices do not fully consider the information available and that permutations in prices are not i.d.d. For the stock indices of BEL 20, CAC 40, DAX 30 and FTSE Athex 20 the random walk hypothesis was partially rejected between lags. As for the IBEX 35 and ISEQ markets, both were shown to be in balance.

This study adds two main contributions to literature. The first contribution deals with the research of mean reversion in developed European and also non-European markets, with the objective of understanding the different predictabilities between them. As far as it is known, authors like Tiwari and Kyophilavong (2014), Hamid *et al.* (2017) Singh and Kumar (2018), Rehman *et al.* (2018), Durusu-Ciftci *et al.* (2019), Sadat and Hasan (2019) or Malafeyev *et al.* (2019) analyzed the mean reversion in the prices of the financial markets, testing the random walk and efficient market hypotheses in their weak form. However, the approaches are essentially variant from the one used in this study. The second contribution deals with to the sample period, which comprises a period affected by the global Covid-19 pandemic crisis. The pandemic has had a very negative response on the global economy, as well as on the social and cultural life of populations (Moore & Kolencik, 2020; Popescu *et al.*, 2020; Segers, 2020; Thompson, 2020). Rating agencies such as Moody's and Standard & Poors have limited China's growth prediction for 2020. According the all these negative influences, it seems necessarily that financial markets have been equally affected (Liu *et al.*, 2020).

In terms of structure, this study is divided into 5 parts. The introduction is followed by Section 2, which deals with an analysis of the State of the Art through contributions on the random walk hypothesis in international financial markets, Section 3, which describes the data and methods used, Section 4, which includes the data and results, and Section 5, which presents the general conclusions.

Literature review

The EMH is one of the most interesting and important hypotheses in financial management. It argues that return rates have no memory — correlation, which means that traders cannot obtain extraordinary returns in financial markets through negotiation strategies adjusted to arbitration (Ferreira & Dionísio, 2016).

Nisar and Hanif (2012), Mehla and Goyal (2013), El Khamlichi *et al.* (2014) tested the random walk hypothesis in different markets. Nisar and Hanif (2012) examined the main stock exchanges in South Asia (India, Bangladesh, Pakistan and Sri Lanka), for the period 1997–2011. The random walk hypothesis was rejected for South Asian stock markets, thereby suggesting market inefficiency, in its weak form. Authors Mehla and Goyal (2013) examined the Indian stock market, revealing that this market did not follow the random walk assumptions and, as such, was not efficient, in its weak form. El Khamlichi *et al.* (2014) tested Islamic indices and compared them with benchmarks such as the Dow Jones and S&P 500. El Khamlichi *et al.* (2014) show that Islamic indices have the same degree of efficiency or inefficiency as the benchmarks, but the MSCI and FTSE indices are less inefficient.

Sensoy and Tabak (2015), Rounaghi and Nassir Zadeh (2016), Shirvani and Delcoure (2016) tested efficiency in developed markets. Sensoy and Tabak (2015) showed that the 2008 global financial and economic crisis had a negative effect on almost all European stock markets. During the European sovereign debt crisis, there was an important impact on the markets of France, Spain and Greece. Rounaghi and Nassir Zadeh (2016) investigated the presence of long memory in the return rates of the S&P 500 and the London Stock Exchange (LSE). A comparison between the S&P 500 and the London Stock Exchange showed that both markets were efficient and were financially healthy during high and low times. Shirvani and Delcoure (2016) analyzed 16 OECD markets, showing that the markets were efficient because the hypothesis of mean reversion was not rejected.

Hamid *et al.* (2017), Ngene *et al.* (2017), Assaf and Charif (2017), Mohti *et al.* (2018) tested the efficiency hypothesis in developed and emerging markets. Hamid *et al.* (2017) dealt with the financial markets mainly of Asian countries (China, South Korea, Japan, Pakistan, Indonesia, India, Malaysia, Sri Lanka, Hong Kong, Philippines, Thailand, Singapore, Taiwan and Australia) for the period between January 2004 and December 2009. The researchers suggested that prices did not follow the random walk assumptions in countries in the Asia-Pacific region. Ngene *et al.* (2017) examined 18 emerging markets that presented several structural breaks, whereby the conclusions and results were consistent with the hypothesis of random walk for most of the analyzed markets. Assaf and Charif (2017) analyzed MENA's stock markets and tested the random walk hypothesis. The authors argued that the analyzed markets could be approaching efficiency, in its weak form, thereby highlighting the good future prospects for these markets. Mohti *et al.* (2018) analyzed the border markets, testing their efficiency. The authors showed that Slovenia was the only market to demonstrate market efficiency. The comparatively least inefficient markets were located primarily in America and Europe, while the most inefficient markets were located in the Middle East.

More recently, Malafeyev *et al.* (2019) analyzed the stock markets of two countries — China and India, revealing that these stock markets did not exhibit market efficiency, in its weak form. Caporale *et al.* (2020) analyzed five European stock indices: DAX30 (Germany), CAC40 (France), FTSE100 (United Kingdom), FTSE MIB40 (Italy) and IBEX35 (Spain), showing the presence of long memories, which could undermine market efficiency, in its weak form. Milos *et al.* (2020) examined seven stock markets in Central and Eastern Europe. The authors revealed that return rates showed long-term correlations, thereby supporting the idea that the stock markets in question were not efficient, nor had they reached the mature stage of market progression.

Research methodology

Data refer to the quotations of stock exchange indexes of Belgium (BEL 20), France (CAC 40), Germany (DAX 30), USA (DOW JONES), Greece (FTSE Athex 20), Spain (IBEX 35), Ireland (ISEQ), Portugal (PSI 20) and China (SSE), at the close of trading sessions and was obtained from the Thomson Reuters Datastream platform. The daily stock prices cover the period from December 1, 2019 to May 14, 2020, which includes the initial period of the current global pandemic (COVID-19). Prices are in local currency to mitigate exchange rate distortions.

The analysis of the random walk hypothesis is limited to the countries and indices listed in Table 1. The preference for these European financial markets is explained by the fact that they have stable economies and are, therefore, linked by a cultural heritage and some similar economic conditions. The financial markets of USA and China were selected, due to their importance in global economy and by being the center of global pandemic (COVID-19). It also helps to understand the different predictabilities between those main markets and the European markets in analysis.

To analyse the evolution of financial markets, Tsay (2005) proposes the use of logarithmic rates of return than prices, because investors are mainly interested in knowing the profitability of an asset or a portfolio of assets. In complementarity, series of logarithmic rates of returns show statistical characteristics that simplify the analytical treatment, in particular the characteristic of stationarity, which usually is not observed in price series. For these reasons, the series of price indices were modified transformed through the following expression:

$$r_t = ln\left(\frac{P_t}{P_{t-1}}\right) \tag{1}$$

Where r_t is the logarithmic rate of return, at day t, and P_t and P_{t-1} are the closing prices of the series, at moments t and $t-1$ respectively.

The methodology to develop this research follow several stages. First, the sample is characterized through descriptive statistics, the Jarque and Bera (1980) adherence test and quantile graphs. Next, the panel unit root tests of Breitung (2000), Levin *et al.* (2002) and Hadri (2002) are used to check the stationarity of the time series of rates of return, instead of the ADF (Dickey & Fuller, 1981), PP (Perron & Phillips, 1988) or KPSS (Kwiatkowski *et al.*, 1992) tests, since they increased the robustness of estimation. Breitung (2000) and Levin *et al.* (2002) identify the same null hypotheses (H0 = unit roots), while the panel unit root test of Hadri (2000) postulates the opposite hypotheses (H0 = stationarity). In addition to the stationarity tests, we will use the test by Clemente *et al.* (1998) to identify structural breaks resulting from the global pandemic.

The efficient market hypothesis, in its weak form, states that it is not possible to forecast future prices based on historical prices. Rosenthal (1983) argues that if a capital market is efficient, in its weak form, then there should be no linear dependence between the lagged returns, both in the statistical sense (absence of autocorrelation) and in the economic sense (no positive returns after considering the transaction costs).

To test the random walk hypothesis, we will use the variance-ratio methodology applied by Lo and Mackinlay (1988) to assess the autocorrelation between the series of returns. Such a methodology can be classified as a parametric test.

Defining P_t as the price of an asset in *t* and X_t as the natural logarithm of P_t, the random walk hypothesis is given by:

$$X_t = \mu + X_{t-1} + \epsilon_t \tag{2}$$

where μ is an arbitrary motion parameter and ϵ_t is the random error term.

It is the shared opinion of the authors that a significant characteristic of the random walk process is that the variance of the increments grows linearly according to the observation interval. That means, the variance of $X_t - X_{t-2}$ is twice the variance of $X_t - X_{t-1}$. The validity of a random walk model can therefore be tested by comparing profitability variance estimators at different frequencies. For example, the variance of the weekly profitability series should be five times greater than the variance of the daily profitability. The model tests whether the variance ratio for diverse intervals weighted by their duration is equal to one.

The variance of a q -differentiated series $(X_t - X_{t-q})$ will be q times the variance of the series of the first differentiation $(X_t - X_{t-1})$.

The variance ratio test is performed according to the estimator consistent with heteroscedasticity, as defined by Lo and Mackinlay (1988). In a sample with $nq + 1$ observations, where q is an integer greater than 1, the following estimators are defined:

$$\hat{\mu} \equiv \frac{1}{nq} \sum_{k=1}^{nq} (X_k - X_{k-1}) = \frac{1}{nq} \left(X_{nq} - X_0 \right) \tag{3}$$

$$\bar{\sigma}_a^2 \equiv \frac{1}{nq} \sum_{k=1}^{nq} (X_k - X_{k-1} - \hat{\mu})^2 \tag{4}$$

$$\bar{\sigma}_c^2(q) \equiv \frac{1}{m} \sum_{k=1}^{n} \left(X_{qk} - X_{qk-q} - q\hat{\mu} \right)^2 \tag{5}$$

where:

$$m = q(nq - q + 1) \left(1 - \frac{q}{nq} \right) \tag{6}$$

The variance ratio is given by:

$$\widehat{VR}(q) = \frac{\bar{\sigma}_c^2(q)}{\bar{\sigma}_a^2} \tag{7}$$

The robust test statistic of heteroscedasticity, a characteristic inherent to the series of returns on financial assets, is presented by:

$$z^*(q) = \frac{\sqrt{nq}(\widehat{VR}(q) - 1)}{\sqrt{\hat{\phi}(q)}} \tag{8}$$

where:

$$\hat{\phi}(q) = \sum_{j=1}^{q-1} \left[\frac{2(q-j)}{q} \right]^2 \hat{\delta}(j) \tag{9}$$

$$\hat{\delta}(j) = \frac{\sum_{t=j+1}^{nq}(X_k - X_{k-1} - \hat{\mu})^2 \left(X_{k-j} - X_{k-j-1} - \hat{\mu}\right)^2}{\sum_{t=j+1}^{nq}(X_k - X_{k-1} - \hat{\mu})^2} \quad (10)$$

Results and discussion

Figure 1 shows the course over time of the stock market indices in prices (levels) of Belgium (index BEL 20), France (index CAC 40), Germany (index DAX 30), USA (index DOW JONES), Greece (index FTSE Athex 20), Spain (index IBEX 35), Ireland (index ISEQ), Portugal (index PSI 20), and China (index SSE), in the period from 2 December 2019 to 12 May 2020. We can observe a significant decline in most of the stock markets during February and March of 2020, which could be related to the uncertainty and pessimism in international financial markets as an effect of the global pandemic (Covid-19). The stock market of China shows an earlier instability in the series of prices.

Table 2 shows the main descriptive statistics for logarithmic rates of return of indices under analysis and Table 3 Jarque-Bera adherence test. The analysis of descriptive statistics allows us to identify that most of the obtained rates of return have negative daily averages, with exception to the Chinese capital market. The capital market with the most significant standard deviation (risk) is Greece. The asymmetry characteristics are negative, with the Chinese capital market having the most significant levels of asymmetry. Additionally, all series of return rates, evidence signs of deviation from the normality hypothesis because the Jarque-Bera test allows the rejection of the null hypothesis of normality (H0) in benefit of the alternative (H1), non-normality hypothesis, at a level of significance of 1%.

The stationarity results of first differences in indices prices, estimated through Breitung (2000), Levin *et al.* (2002) and Hadri (2000) tests show that indices prices series are nonstationary and , which is a fundamental assumption for using the Lo and Mackinlay (1988) model to estimate market efficiency in its weak form. The test results are presented in Tables 4, 5 and 6.

In order to corroborate the unit root tests, it is estimated the CUSUMQ test by Inclán and Tiao (1994) based on the logarithmic rates of returns. The determination of disturbances in the residues variance is relevant, because it has an effect, potentially, similar to the unit root tests. Through graphical analysis it is possible to check if there are disturbances in the variance (see Figure 2). Therefore, when examining the cumulative sum graphs (CUSUMQ) with the 95% probability limits, it could be identified that the probability limits have been violated and that the series shows unstable behavior.

Table 7 shows the results of the test by Clemente *et al.* (1998) who identified the most severe structural break in each indices. Most markets showed significant structural breaks in March 2020, with the exception of the Spanish and Chinese markets. Thus, most European indices had their most severe structural break few days before the declaration of global by WHO. In general, these results are in accordance with the evidence obtained by Liu *et al.* (2020) and Zeren and Hizarci (2020), which showed significant structural breaks resulting from the COVID-19 outbreak.

The results of Lo and Mackinlay (1988) tests, which includes the rank variance ratio test, are shown in Tables 8 to 16. The statistics were estimated for lags of 2 to 16 days. Taking into account the results of the rank variance test the random walk hypothesis is rejected in the USA (index DOW JONES), China (index SSE) and Portugal (index PSI 20) stock market indices. In the capital markets of Greece, Belgium, France and Germany we have mixed results. In the case of stock index FTSE Athex 20, the rejection of the random walk hypothesis occurs between days 2 to 12, which did not occur between the period of 13 to 16 days. Meanwhile, in the case of index BEL 20 we have a market imbalance on days 2 to 6, but on days 7 to 16 there is no rejection of the random walk hypothesis. In the French capital market (index CAC 40) there is a rejection of the random walk hypothesis on days 2 to 10, and on days 11 to 16 we find that the market tends towards equilibrium. In Germany (index DAX 30), we find that the market shows some imbalance on days 4 to 16, and on days 2 to 3 random walk hypothesis is confirmed. In the capital markets of Spain (index IBEX 35), and Ireland (index ISEQ) the variance ratio tests show that the random walk hypothesis is not rejected.

Under these conditions, most markets tend to overreact to information and eventually correct it in the following days, whether it is good news or bad news. The high sensitivity of prices to the arrival of new information could likely be due to the climate of pessimism and uncertainty experienced by investors during the global pandemic of 2020. In addition, this situation is of great importance to investors, since it means that the rates of returns could be partially forecasted, creating possibilities for arbitrage operations and the potential occurrence of extraordinary returns, contrary to the assumptions of the random walk and information efficiency. However, to confirm the inefficiency of these markets (in their weak form) identified in our results, it would be necessary to demonstrate the existence of abnormal returns.

In general the obtained results are hybrid, since we have total and partial rejections of the random walk hypothesis and the information efficiency hypothesis. These results are in accordance with evidence obtained by other researchers, namely with the studies of Richards (1997), Worthington and Higgs (2013), Dsouza and Mallikarjunappa (2015), Hamid *et al.* (2017), Aggarwal (2018), Sadat and Hasan (2019) and, partially, with those of Ngene *et al.* (2017), Abakah *et al.* (2018) and Malafeyev *et al.* (2019).

Conclusions

In this article, we test the efficient capital market hypothesis, in its weak form, through the stock indices of Belgium (index BEL 20), France (index CAC 40), Germany (index DAX 30), USA (index DOW JONES), Greece (index FTSE Athex 20), Spain (index IBEX 35), Ireland (index ISEQ), Portugal (index PSI 20) and China (index SSE). Data from December 2019 to May 2020 were used, as a result of which the analysis covers the first period of Covid-19.

We used the test by Clemente *et al.* (1998) to assess the structure breaks in the analyzed markets, which revealed significant breaks in March 2020, with exception to the Spanish and Chinese markets. To test market efficiency, in its weak form, we used the Lo and Mackinlay (1988) test, which includes the rank variance ratio test, whereby the statistics were calculated for lags of 2 to 16 days. Results show the rejection of the random walk hypothesis in its weak form in the case of stock indices: Dow Jones, SSE and PSI 20. Thus, the results show that, for a relevant part of analyzed data, prices do not consider all information available and therefore changes in prices are not i.i.d. This creates opportunities for arbitrage and abnormal returns, out of assumptions of random walk and information efficiency.

For the stock indices: BEL 20, CAC 40, DAX 30 and FTSE Athex 20, the random walk hypothesis was partially rejected. Within these assumptions, capital markets tend to overreact to data and information in the short-term, whereby the reactions could have been the result of the uncertainty knew by investors during the global outbreak.

As general conclusion, the results of the tests carried out with econometric models, demonstrate that the current COVID-19 global pandemic has important impact on the memory properties of the main indices of the analyzed financial markets. Globally, we found mixed confirmation about the efficient market hypothesis (EMH). Through the rank-variance ratio test, evidence regarding the random walk hypothesis shows the markets to be efficient, less efficient and/or balanced. Although, a robustness confirmation of inefficiency in these markets, in their weak form, would necessary involve, proving the existence of abnormal returns.

This research is yet limited to the first period of the global pandemic. Thus future research could be undertaken to estimate stock markets efficiency in a longer period that includes the effects of COVID-19 second wave. In addition, this research used general indices, of daily frequency, to analyze efficiency in its weak form. With further research, it would also be of interest to use higher frequency data, intraday based, quotes per minute, in order to perform a finer analysis of data and to provide results more robust.

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Annex

Table 1. Countries and indices of capital markets

Country name	Index
Belgium	BEL 20
France	CAC 40
Germany	DAX 30
Greece	FTSE Athex 20
Ireland	ISEQ
Portugal	PSI 20
Spain	IBEX 35
USA	DOW JONES
China	SSE

Table 2. Descriptive statistics for indices (logarithmic rates of returns)

	BEL 20	CAC 40	DAX 30	DOW JONES	FTSE ATHEX	IBEX 35	ISEQ	PSI 20	SSE
Mean	-0.0022	-0.0022	-0.0020	-0.0016	-0.0037	-0.0028	-0.0023	-0.0016	0.0001
Std. Dev.	0.0268	0.0260	0.0260	0.0319	0.0346	0.0264	0.0254	0.0211	0.0142
Skewness	-1.9575	-1.3660	-0.9314	-0.5062	-1.2158	-1.8674	-1.0269	-1.4681	-1.9774
Kurtosis	12.118	9.114	10.246	7.750	7.236	12.691	6.335	10.736	11.929
Observ.	108	108	108	108	108	108	108	108	108

Table 3. Jarque-Bera test results

	BEL 20	CAC 40	DAX 30	DOW JONES	FTSE ATHEX	IBEX 35	ISEQ	PSI 20	SSE
Jarque-Bera	443.086	201.805	251.899	106.146	107.340	485.364	69.030	308.096	429.153
P value	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Observ.	108	108	108	108	108	108	108	108	108

Table 4. Panel unit root test of Breitung results

Method			**Statistic**	**P value**
Breitung t-stat			-26.384	~0.00
Series	S.E. of **Regression**	**Lag**	**Max Lag**	**Obs**
D(BEL 20)	112.658	0	12	109
D(CAC 40)	163.207	0	12	109
D(DAX 30)	372.468	0	12	109
D(DOW JONES)	1184.79	0	12	109
D(FTSE ATHEX 20)	31.4570	0	12	107
D(IBEX 35)	210.067	1	12	108
D(ISEQ)	184.978	0	12	109
D(PSI 20)	122.629	0	12	109
D(SSE)	57.8893	0	12	109
	Coefficient	t-Stat	SE Reg	Obs
Pooled	-0.89657	-26.385	0.034	969

Note:D()means the first differences.

Table 5. Panel unit root test of Levin results

Method				**Statistic**		**P value**	
Levin, Lin & Chu t				-34.4351		~ 0.00	
Series	2nd Stage Coefficient	Variance of Reg	HAC of Dep.	Lag	Max Lag	Band-width	Obs
D(BEL 20)	-0.941	6653.0	352.60	0	12	37.0	109
D(CAC 40)	-0.967	13619.	549.92	0	12	51.0	109
D(DAX 30)	-0.965	71085.	1336.0	0	12	108.0	109
D(DOW JONES)	-1.354	448894	55289.	0	12	21.0	109
D(FTSE ATHEX 20)	-1.013	483.65	42.611	0	12	22.0	107
D(IBEX 35)	-0.762	33549.	2018.8	1	12	34.0	108
D(ISEQ)	-0.918	18323.	354.34	0	12	108.0	109
D(PSI 20)	-0.943	7874.0	578.47	0	12	32.0	109
D(SSE)	-1.010	1642.1	140.65	0	12	25.0	109
	Coefficient	t-Stat	SE Reg	mu*	sig*		Obs
Pooled	-1.0049	-30.555	1.010	-0.518	0.774		978

Note:D()means the first differences.

Table 6. Panel unit root test of Hadri results

Method	Statistic	P value
Hadri Z-stat	-0.704	0.760
Heteroscedastic Consistent Z-stat	-0.646	0.741

Series	LM	Variance HAC	Bandwidth	Obs
D(BEL 20)	0.132	9666.006	5.0	110
D(CAC 40)	0.135	19767.74	6.0	110
D(DAX 30)	0.118	105351.8	6.0	110
D(DOW JONES)	0.128	372429.0	2.0	110
D(FTSE ATHEX 20)	0.166	623.0325	5.0	108
D(IBEX 35)	0.168	53761.90	6.0	110
D(ISEQ)	0.143	28027.62	6.0	110
D(PSI 20)	0.136	12221.64	6.0	110
D(SSE)	0.080	1661.430	4.0	110

Table 7. Unit root tests for structural breaks

Index	t-stat	Break Date (m/d/y)	P value
BEL 20	-12.26(0)	03/09/2020	0.000
CAC 40	-12.20(0)	03/09/2020	0.000
DAX 30	-12.10(0)	03/10/2020	0.000
DOW JONES	-16.31(0)	03/23/2020	0.000
FTSE Athex 20	-12.42(0)	03/05/2020	0.000
IBEX 35	-11.66(0)	12/16/2019	0.000
ISEQ	-10.92(0)	03/09/2020	0.000
PSI 20	-11.69(0)	03/09/2020	0.000
SSE	-13.75(0)	01/23/2020	0.000

Table 8. Rank variance tests for the stock index BEL 20

Joint Tests		Value	df	P value
Max |z| (at period 2)*		2.816321	33	0.070
Wald (Chi-Square)		69.63021	15	0.000
Individual Tests				
Period	Var. Ratio	Std. Error	z-Statistic	P value
2	0.509741	0.174078	-2.816321	0.005
3	0.430198	0.259500	-2.195771	0.028
4	0.383630	0.325669	-1.892624	0.058
5	0.243208	0.381385	-1.984327	0.047
6	0.256775	0.430331	-1.727100	0.084

Table 9. Rank variance tests for the stock index CAC 40

Joint Tests		Value	df	P value
Max |z| (at period 2)*		2.682346	33	0.104
Individual Tests				
Period	Var. Ratio	Std. Error	z-Statistic	P value
2	0.417252	0.217253	-2.682346	0.007
3	0.291844	0.296008	-2.392354	0.017
4	0.290851	0.339718	-2.087463	0.037
5	0.252314	0.370694	-2.016992	0.044
6	0.196794	0.396906	-2.023667	0.043
7	0.181185	0.419893	-1.950055	0.051

Table 10. Rank variance tests for the stock index DAX 30

Joint Tests		Value	df	P value
Max |z| (at period 16)*		2.691442	110	0.102
Individual Tests				
Period	Var. Ratio	Std. Error	z-Statistic	P value
2	1.052967	0.081916	0.646607	0.518
3	1.171179	0.132158	1.295265	0.195
4	1.309851	0.186564	1.660825	0.097
5	1.450702	0.238000	1.893710	0.058
6	1.594826	0.281091	2.116135	0.034

Table 11. Rank variance tests for the stock index DOW JONES

Joint Tests		Value	df	P value
Max |z| (at period 2)		6.559175	109	0.000
Wald (Chi-Square)		133.7246	15	0.000
Individual Tests				
Period	Var. Ratio	Std. Error	z-Statistic	P value
2	0.371745	0.095783	-6.559175	0.000
3	0.307373	0.142784	-4.850859	0.000
4	0.264183	0.179193	-4.106284	0.000
5	0.179201	0.209849	-3.911374	0.000
6	0.207701	0.236781	-3.346126	0.000

Table 12. Rank variance tests for the stock index FTSE ATHEX 20

Joint Tests		**Value**	**df**	**P value**
Max |z| (at period 2)		5.063650	107	0.000
Wald (Chi-Square)		51.18971	15	0.001
Individual Tests				
Period	Var. Ratio	Std. Error	z-Statistic	P value
2	0.510479	0.096674	-5.063650	0.000
3	0.376631	0.144113	-4.325571	0.000
4	0.385131	0.180860	-3.399696	0.000
5	0.335972	0.211801	-3.135146	0.000
6	0.387489	0.238984	-2.562984	0.003
7	0.355678	0.263488	-2.445356	0.003
8	0.354005	0.285965	-2.259003	0.009
9	0.383712	0.306839	-2.008506	0.016
10	0.378967	0.326408	-1.902628	0.030
11	0.390941	0.344886	-1.765972	0.051

Table 13. Rank variance tests for the stock index IBEX 35

Joint Tests		**Value**	**Df**	**P value**
Max |z| (at period 16)*		1.447963	110	0.909
Individual Tests				
Period	Var. Ratio	Std. Error	z-Statistic	P value
2	0.897228	0.139823	-0.735016	0.462
3	1.068437	0.223268	0.306524	0.759
4	1.174804	0.299482	0.583687	0.559
5	1.278069	0.362603	0.766869	0.443
6	1.416547	0.413217	1.008058	0.313

Table 14. Rank variance tests for the stock index ISEQ

Joint Tests		**Value**	**df**	**P value**
Max |z| (at period 2)		0.919561	110	0.745
Wald (Chi-Square)		17.13772	15	0.364
Individual Tests				
Period	Var. Ratio	Std. Error	z-Statistic	P value
2	1.087677	0.095346	0.919561	0.352
3	0.999280	0.142134	-0.005064	0.997
4	0.969055	0.178377	-0.173480	0.887
5	0.963586	0.208893	-0.174319	0.875
6	0.996686	0.235702	-0.014058	0.990

Table 15. Rank variance tests for the stock index PSI 20

Joint Tests		**Value**	**df**	**P value**
Max |z| (at period 2)		4.660357	109	0.000
Wald (Chi-Square)		53.19133	15	0.000
Individual Tests				
Period	Var. Ratio	Std. Error	z-Statistic	P value
2	0.553619	0.095783	-4.660357	0.000
3	0.397288	0.142784	-4.221137	0.000
4	0.297901	0.179193	-3.918118	0.000
5	0.242215	0.209849	-3.611094	0.000
6	0.233082	0.236781	-3.238936	0.000

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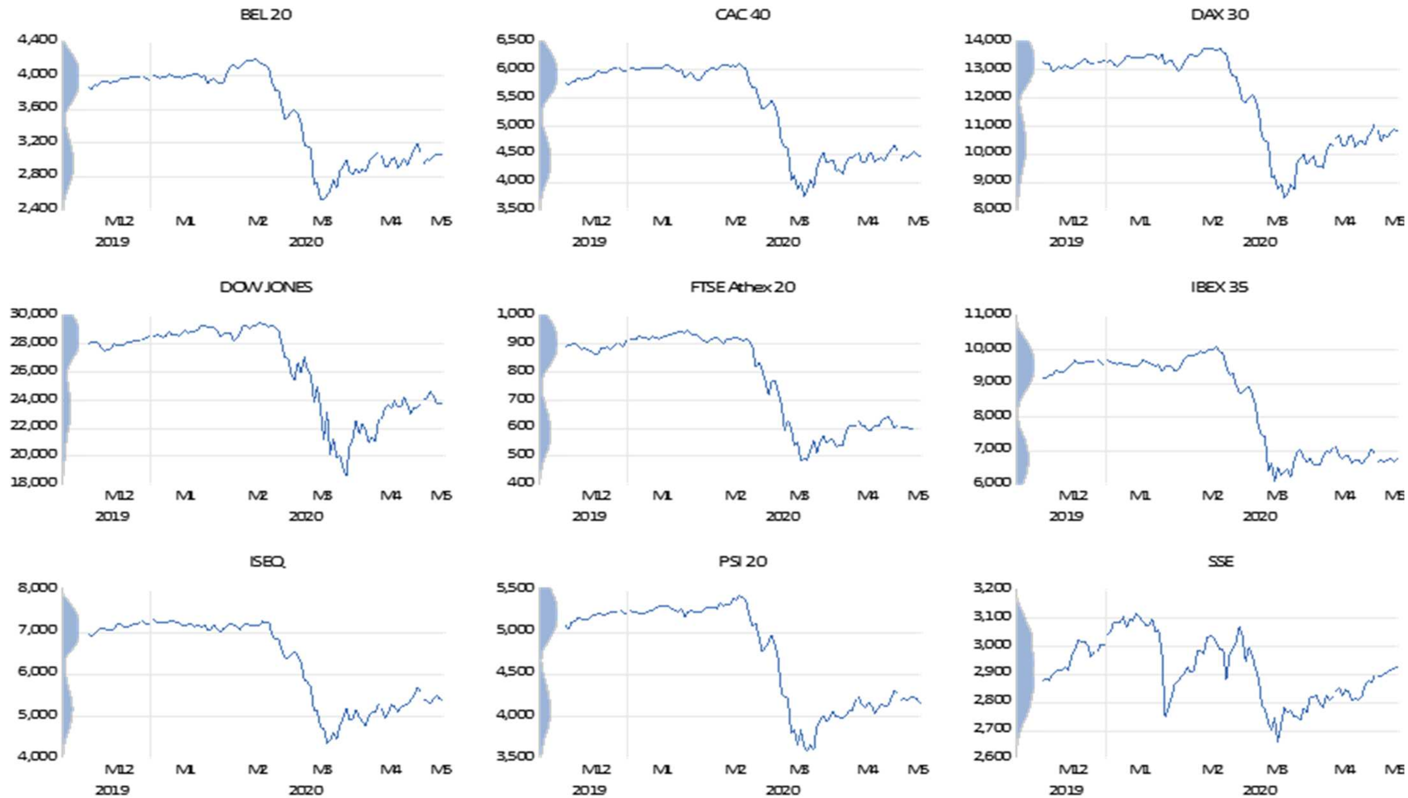
Table 16. Rank variance tests for the stock index SSE

Joint Tests		**Value**	**df**	**P value**
Max |z| (at period 2)*		3.128012	109	0.026
Individual Tests				
Period	Var. Ratio	Std. Error	z-Statistic	P value
2	0.487755	0.163760	-3.128012	0.002
3	0.307130	0.228915	-3.026752	0.003
4	0.303356	0.269715	-2.582891	0.010
5	0.208000	0.299945	-2.640480	0.008
6	0.178436	0.324679	-2.530389	0.011
7	0.159091	0.346230	-2.428755	0.015
8	0.136371	0.365837	-2.360693	0.018
9	0.131082	0.383864	-2.263607	0.024
10	0.126616	0.400685	-2.179726	0.029
11	0.096434	0.416798	-2.167875	0.030
12	0.108024	0.432393	-2.062883	0.039
13	0.095684	0.447530	-2.020681	0.043
14	0.088798	0.462198	-1.971453	0.049
15	0.099068	0.476308	-1.891490	0.059

Figure 1. Course of stock indices prices in the 9 capital markets



Note: M12 – December 2019, M1 to M5 – January 2020 to May 2020.

Figure 2. CUSUMQ test to disturbances in the variance of residues

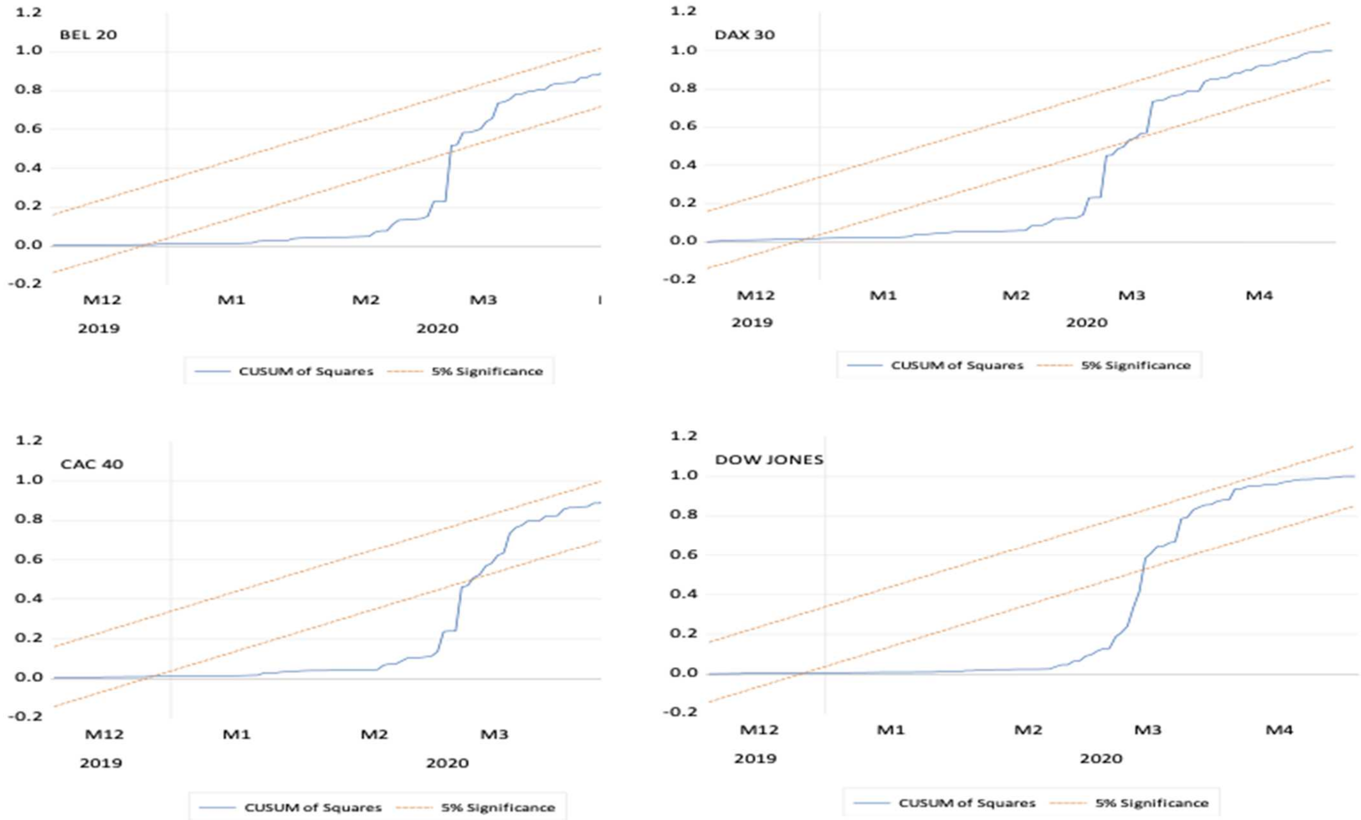


Figure 2. Continued

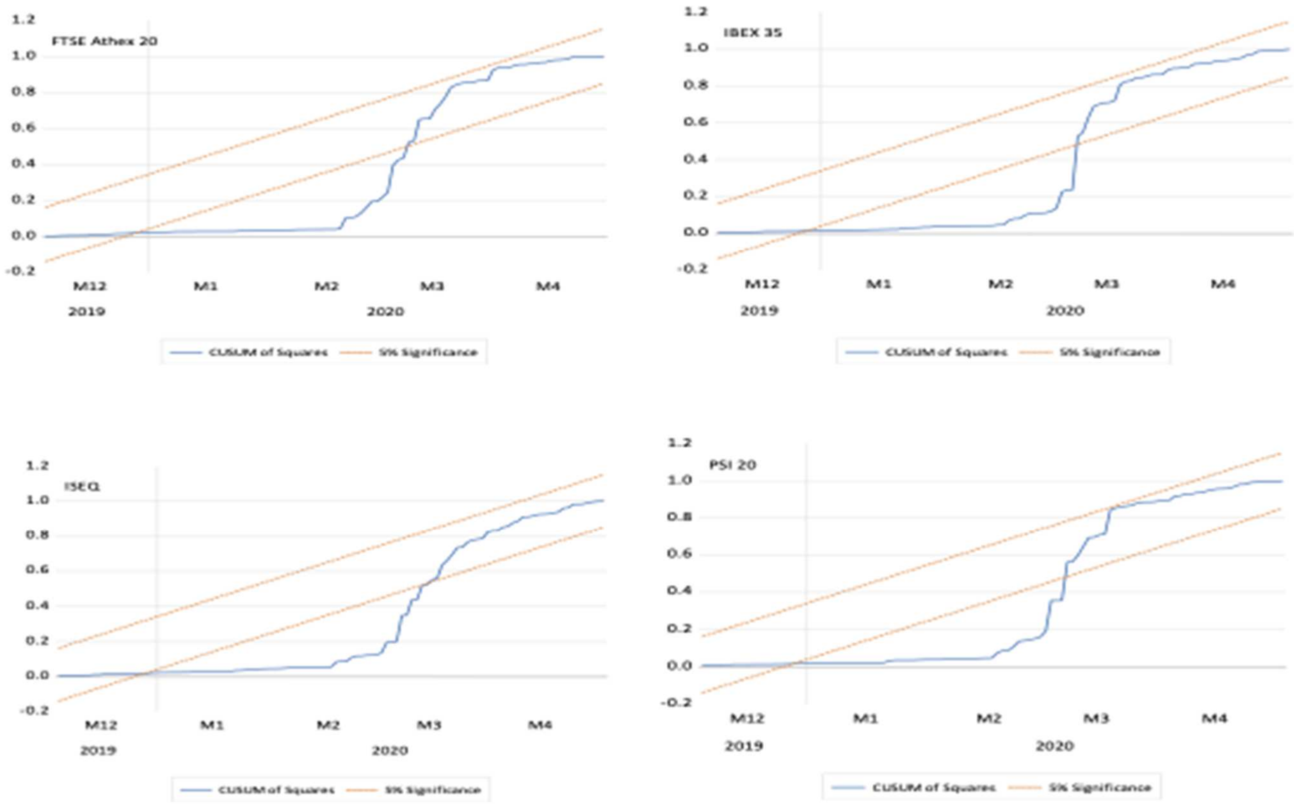
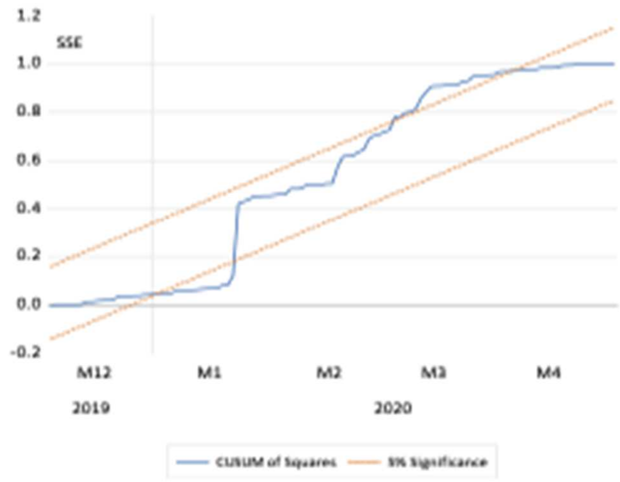


Figure 2. Continued



Note: Blue line represents the logarithimic rates of returns and disturbance in variance occurs when it violates the 95% limit (red lines). Statistics for a level of significance of 5%.