Modelling Spillover Effects between the UK and the US Stock Markets over the Period 1935 - 2020

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ABSTRACT

This study investigates the spillovers of shocks and volatilities between the UK and the US stock markets over the period 1935-2020. The empirical analysis is carried out for the full sample and four subsample periods by applying the asymmetric GARCH-BEKK model. Based on the empirical results, the evidence indicates that financial market linkages between the two markets have become stronger since the commencement of the European Monetary Union (EMU), which suggests that stronger financial market interactions and interdependence could increase the vulnerabilities of domestic markets to any global shocks and reduce the potential benefits of portfolio diversification.

1. INTRODUCTION

Which international monetary system most induced shock and volatility spillovers between the UK and the US – the pre-Bretton Wood (BW), the BW system of fixed exchange rates, the pre-European Economic and Monetary Union (EMU), or the EMU period? Do shocks and volatilities spill over between the UK and the US, uni-directionally, bi-directionally or non-directionally?

This study seeks to answer these fundamental questions. To answer these questions, we use a bivariate asymmetric GARCH-BEKK model to investigate the nature of shock and volatility spillovers between the UK and the US equity markets under different international monetary systems since 1st July 1935 when the FT30 index was introduced until 31st January 2020 when the UK officially exited the EU. The sample period features monumental economic and political episodes including World War II, the international monetary system crisis, the global oil crises, 1987 stock market crash, the European monetary crisis, the Asian currency crisis, the tech-market crisis, the global financial crisis, the EU debt crisis and most recently, the Brexit crisis.

To understand the nature of shock and volatility spillovers between the UK and US stock markets over a period of 85 years, we split the full sample into four subsamples based on changing international monetary systems: the pre-BW system (1st July 1935–2nd September 1945), the BW fixed exchange rate regime (3rd September 1945–15th August 1971), the pre-EMU (16th August 1971–31st December 1998), and the EMU (1st January 1999–31st January 2020). To the best of our knowledge, this is the first study to investigate shock and volatility spillovers between the UK and US stock markets within the frame of the above subsamples as aspects of the existing literature have hitherto been given limited attention.

Particularly, the focus will be on the transmission mechanisms between the two oldest stock market indices namely, the FT30 and Dow30, because the cities of London and New York have remained the global financial centres over many decades for international portfolio investments. In order to

take into account the different time zones of these international stock markets, we use the 'common trading window' approach to tackle the problem of nonsynchronous trading.[1]

Since the Great Depression, unexpected events and shocks have introduced significant volatility and uncertainty into the financial markets. Particularly, asset price shocks are usually accompanied by high volatility. The transmission effects of domestic and global news have been connected to shock and volatility spillovers across international financial markets. Hence, increasing financial market linkages have been connected with the level of transmission of shocks and volatilities from one financial centre to the rest of the world with close immediate reactions.

Moreover, the series of shocks and unexpected changes in price movement now generate higher persistent volatility in the international financial markets. For instance, shocks originating in one financial market may potentially spill over to other markets more quickly, particularly when the markets are highly integrated. That is why the use of multivariate asymmetric GARCH-BEKK model is suitable in modelling shock and volatility spillovers between the two markets, assuming that spillovers are realisations of international news influencing the global stock markets.

Over the past three decades, a number of studies on financial integration have focused on spillover effects (see Martins & Poon, 2001; Kim, Moshirian & Wu, 2005; Caporale, Pittis, & Spagnalo, 2006; Panapoulou & Pantelidis, 2009; Singh, Kumar, & Pandey, 2010; Diebold & Yilmaz, 2012; Li & Giles, 2015; Jain & Sehgal 2018). None of these studies has used a long dataset of the world's two oldest indices to carry out subsample analysis based on different international monetary systems.

The changing international monetary system serves as a catalyst towards further investigating the nature of spillover effects between the two most advanced financial markets. The level of interdependence between the UK and US stock markets under different international monetary

arrangements could provide evidence of increasing integration in international markets with important implications for portfolio diversification and evidence-based policy-making.

Overall, this study has several salient implications that will be relevant to investors and policymakers. For instance, investors will be able to make informed decisions about the potential benefits of portfolio diversification in increasingly interdependent markets. This suggests that the understanding of shock and volatility transmissions has important implications for international investors in a number of different areas such as asset pricing modelling, volatility forecasting and portfolio allocation. With regard to evidence-based policy making, policymakers will effectively design and implement well-calibrated responses to mitigating the risk of financial contagion and financial instability.

The remainder of this study is organised as follows. Section 2 reviews the historical changes of the international monetary systems over eight decades in light of the hypotheses pertinent to each of them. Section 3 reviews the theoretical and empirical arguments of shock and volatility transmissions. Section 4 sets out the methodologies used in estimating spillover effects. Section 5 describes the dataset. Section 6 discusses the empirical results and their implications while Section 7 provides a conclusion.

2. THE INTERNATIONAL MONETARY SYSTEM

The UK and US financial markets have continued to maintain leading roles in financial liberalisation and development over the last eight decades. However, the relationships between their stock markets are presumably not stable over time given the changing international monetary system. The key interesting question we are putting forward is whether the years before and during the BW system as well as the EMU led to more or less shock and volatility spillovers between the UK and the US. In general, the deeper understanding of the direction of shock and volatility spillovers under different international monetary systems could provide valuable information to international portfolio managers, institutional investors, and policymakers in managing economic and financial risks.

2.1 Pre-Bretton Woods System (1935 – 1945)

Briefly, the pre-BW period was the aftermath of the 'Great Depression' characterised by monumental global political instability caused by Interwar/WWII, banking crises, economic recessions and financial market instability. We hypothesize that the prevalence of political, economic and financial instability may strengthen bidirectional shock or volatility spillovers between the UK and the US financial markets during this period.

2.2 The Bretton Woods System (1945 – 1971)

The end of the war in 1945 culminated in the establishment of the BW with the objective of facilitating international trade and improving capital flows through an effective international monetary system. One of the key rules of the agreement is for each country to undertake a monetary policy that pegs its currency to the US dollar, while the US fixed the price of the dollar in terms of gold, hence creating a system of fixed exchange rates among countries. However, this period was overburdened with many exchange rate constraints arising from divergent macroeconomic policies of the member states (Bayoumi & Eichengreen, 2000). Consequently, the US singlehandedly

aborted the BW fixed exchange rate regime on August 15, 1971, which is commonly referred to as the 'Nixon Shock', therefore, making the US dollar a fiat currency and at the same time a reserve currency for many countries. Since the goal of the BW system of fixed exchange rate regime was to facilitate international trade and accelerate economic growth through macroeconomic stability, then we hypothesise the possible absence of bidirectional shock or volatility spillovers between the two markets.

2.3   The pre-European Economic and Monetary Union (1971 – 1998)

The demise of the BW system of fixed exchange rate regime in 1971 led to European Economic Community (EEC) countries agreeing in 1972 to maintain stable exchange rate and subsequently created the European Monetary System (EMS) to keep the managed floating rate exchange rate arrangement institutionalised. The US became a fiat currency and at the same a reserve currency for the EEC and other countries. Although the UK had been an EEC member since 1973, it did not join the exchange rate mechanism (ERM) in 1979, owing to concerns that it would benefit the German economy more. When UK finally joined the ERM in 1990, the pound sterling came under major pressure from currency speculators, hence leading the UK to exit on 16th September 1992, subsequently dubbed 'Black Wednesday'. However, the EMS forged ahead in laying the foundation that would lead to the creation of the EMU. Given the eclectic exchange rate arrangement that ensued during this period, we hypothesise the absence of bidirectional shock or volatility spillovers between the two markets.

2.4   The European Economic and Monetary Union (1999 – 2020)

The discussion for the establishment of the EMU that began in 1990 culminated in the birth of the Euro currency on 1st January 1999, although the UK opted out of the single currency. The Eurozone countries remain the largest trading partner with the US and UK economies. Largely, the formation of the EMU has removed exchange rate risk, reduced transaction costs, expanded

international trade, increased integration of capital markets, stimulated investment and economic growth. Forty-three years after the UK joined the EEC, the referendum results in favour of leaving the EU was finally formalised on 31st January 2020 after over three years of Brexit uncertainty. Our final hypothesis is the possibility of bidirectional shock or volatility transmission under the EMU period, characterised by stronger economic ties, integration of capital markets, deepening financial liberalisation and heightened market turbulence.

Based on these chronological international monetary events, the subsample analysis will be instrumental to understanding the nature of spillover effects between the two most developed financial markets in the globe.

3. SHOCK AND VOLATILITY TRANSMISSION: THEORY AND EVIDENCE

The spillover effects occur when the arrival of news from one market has a persistent positive or negative effect on another market. In addition, the mechanisms of shock and volatility spillovers are underpinned by the transmission effects of domestic and international news affecting the global stock markets. A number of scholars have used spillover mechanisms to gauge the level of integration and interdependence of international financial markets.

Using daily and intraday stock prices over 1985 – 1988, Hamao, Masulis, and Ng (1990) found that when the post-October 1987 period is excluded from the sample, volatility spillovers become less pervasive across markets in Tokyo, London and New York, suggesting that volatility spill-overs are more pronounced during the market crisis. In contrast, Susmel and Engle (1994) investigated the interrelationship between the stock markets of the US and UK using hourly observations over the period 1987 - 1989 and found less evidence of either mean or volatility spillovers.

Kim, Moshirian, and Wu (2005) used the bivariate EGARCH framework to investigate the impact of the EMU on stock market integration over the period of 1989 to 2003. They found bidirectional

spillover effects between the US and major European markets. Baele (2005) used the regime-switching model to investigate volatility spillover effects in 13 European equity markets covering the period 1980 - 2001, and found that increased trade integration, equity market development and low inflation gave rise to the increase in EU shock spillover intensity. He also found evidence of contagion from the US to a number of European stock markets during the period of high world market volatility.

Caporale, Pittis, and Spagnalo (2006) examined the international transmission of the 1997 South East Asia financial crisis for US, European, Japanese and South East Asian stock market returns using the bivariate GARCH-BEKK model over the period 1986 - 2000. They found volatility spillover in all cases but the dynamics of conditional volatilities differ. Savva, Osborn, and Gill (2009) applied the dynamic conditional correlation (DCC) version of the VAR-multivariate EGARCH model to investigate interactions across the stock markets of New York, London, Frankfurt and Paris over the period 1990 - 2004. They found the existence of spillover effects from foreign markets for both returns and volatilities, with asymmetries in volatilities and conditional correlations such that negative shocks have a far greater impact than positive shocks. Furthermore, Panopoulou and Pantelidis (2009) investigated the international information transmission between the US and the rest of the G-7 countries using the GARCH-BEKK model from 1985 to 2004. They found increased interdependence in the volatility of the markets under examination.

To address the presence of nonsynchronous trading effects, Olbrys (2013) use open-to-close logarithmic returns to investigate the interdependence of price volatility across the US stock market and two emerging markets (Poland and Hungary) over the period 2004 - 2011. Using the multivariate EGARCH model, they found no pronounced volatility spillover among the three analysed markets; however, there is evidence that the US prices spill over to other markets. Beirne et al. (2013) applied the GARCH-BEKK model to volatility spillovers and contagion from mature

to emerging stock markets over the period 1990 - 2008. They found that mature market volatility affects conditional variances in many emerging markets.

Similarly, Li and Giles (2015) examined the linkages of stock markets across the USA, Japan and six Asian developing countries over the period 1993 – 2013 using the GARCH-BEKK model, and found significant unidirectional shock and volatility spillovers from the US market to both the Japanese and the Asian emerging markets.

Gamba-Santamaria et al. (2017) extended the framework of Diebold and Yilmaz, (2009, 2012) and constructed volatility spillover using a DCC-GARCH framework to model the multivariate relationships of the US and four Latin American countries over the period 2003 - 2016. They found that Brazil is a net volatility transmitter while Chile, Colombia and Mexico are net receivers. They similarly found that shock transmission from the US to Latin American countries substantially increased around the Lehman Brother's episode.

Jain and Sehgal (2018) examined volatility spillover among equity markets of eight mature market economies from 2003 to 2014 using the GARCH-BEKK model, and found no long-term volatility spillover for France and Germany with Italy, UK and US in the post-crisis period. Their findings confirmed the reduced economic influence of the US on other mature markets.

In summary, the existing empirical studies have mixed findings on shocks and volatility spillovers between international financial markets. However, empirical evidence is still scant on examining the shock and volatility transmissions between the two major global stock markets (US and UK) using a long dataset and carrying out subsample analysis based on different international monetary systems. In this study, the asymmetric GARCH-BEKK model is used on a long dataset to investigate the interdependence and interactions between the UK and the US stock markets from 1935 to 2020.

4. METHODOLOGY

Many financial time series exhibit stochastic trends or non-stationary behaviour but appears to be first-difference stationary. To measure the long run common stochastic trend among variables, cointegration tests are widely used by applied financial researchers (Engle & Granger, 1987; Johansen, 1988; Gregory & Hansen, 1996). According to Floros (2005), stock markets are interdependent if the stock indices of two or more countries are cointegrated (that is, they exhibit long-run relationship). If there is no cointegrating relationship between the two markets under consideration, then the vector autoregression (VAR) model is used to establish their short-run relationships, otherwise, we use the vector error correction model (VECM).

On the assumption that the mean equation follow a *VAR(p)* stochastic process, we specify each equation as follows:

$$R_{UK,t} = \alpha_{UK} + \sum_{i=1}^{p_{UK}} \beta_{UK,i} R_{UK,t-i} + \sum_{i=1}^{p_{US}} \beta_{US,i} R_{US,t-i} + \varepsilon_{UK,t} \tag{1}$$

$$R_{US,t} = \alpha_{US} + \sum_{i=1}^{p_{US}} \beta_{US,i} R_{US,t-i} + \sum_{i=1}^{p_{UK}} \beta_{UK,i} R_{UK,t-i} + \varepsilon_{US,t} \tag{2}$$

The VAR model indicates that the lagged changes of the natural log of UK and US stock indices depend on a constant, on their own lags and cross-lags and on the disturbances terms that capture the unexpected shocks on the endogenous variables.

In classical econometric models, the mean and variance of the disturbance term are assumed to be constant (homoskedastic). However, data for returns on financial assets typically exhibit volatility clustering, that is, periods of relatively low volatility followed by periods of high volatility (Fama, 1965). When this is the case, the assumption of constant variance is unrealistic, hence the need to consider modelling time-varying second-order moments.

Assuming that the disturbance vector $\varepsilon_t = (\varepsilon_{\text{UK},t}, \varepsilon_{\text{US},t})$ is normally distributed $\varepsilon_t | I_{t-1}(0, H_t)$, the conditional covariance matrix H_t is modelled by means of an asymmetric GARCH BEKK model (Kroner and Ng, 1998) specified as follows:

$$H_t = CC' + A'\varepsilon_{t-1}\varepsilon_{t-1}'A + B'H_{t-1}B + D'\eta_{t-1}\eta_{t-1}'D \tag{3}$$

where, the parameter matrices for this model are restricted to be upper triangular for matrix *C*, and unrestricted matrices for *A, B* and *D*. The model guarantees positive semi-definiteness in the construction of the covariance matrices by working with quadratic forms which thereby give it an advantage over the VECH models.

The generality of the asymmetric GARCH BEKK (*1, 1*) specification for a two-asset case is expanded as follows;

$$H_t = \begin{pmatrix} h_{11,t} & h_{12,t} \\ h_{21,t} & h_{22,t} \end{pmatrix} = CC' + \begin{pmatrix} \alpha_{11} & \alpha_{12} \\ \alpha_{21} & \alpha_{22} \end{pmatrix}' \begin{pmatrix} \varepsilon_{11,t-1}^2 & \varepsilon_{1,t-1}\varepsilon_{2,t-1} \\ \varepsilon_{2,t-1}\varepsilon_{1,t-1} & \varepsilon_{22,t-1}^2 \end{pmatrix} \begin{pmatrix} \alpha_{11} & \alpha_{12} \\ \alpha_{21} & \alpha_{22} \end{pmatrix} + \tag{4}$$

$$\begin{pmatrix} \beta_{11} & \beta_{12} \\ \beta_{21} & \beta_{22} \end{pmatrix}' \begin{pmatrix} h_{11,t-1} & h_{12,t-1} \\ h_{21,t-1} & h_{22,t-1} \end{pmatrix} \begin{pmatrix} \beta_{11} & \beta_{12} \\ \beta_{21} & \beta_{22} \end{pmatrix} + \begin{pmatrix} \delta_{11} & \delta_{12} \\ \delta_{21} & \delta_{22} \end{pmatrix}' \begin{pmatrix} \eta_{11,t-1}^2 & \eta_{1,t-1}\eta_{2,t-1} \\ \eta_{2,t-1}\eta_{1,t-1} & \eta_{22,t-1}^2 \end{pmatrix} \begin{pmatrix} \delta_{11} & \delta_{12} \\ \delta_{21} & \delta_{22} \end{pmatrix}$$

where $h_{11,t}$ and $h_{22,t}$ denote the conditional variance at time *t* for the UK and US, respectively. The diagonal parameters in matrices A $(\alpha_{11}, \alpha_{22})$ and B (β_{11}, β_{22}) measure the effects of own past shocks and past volatilities of each market on its own country's volatility, while the diagonal parameters in matrix D $(\delta_{11}, \delta_{22})$ measure the response of each market to its own past negative shocks. The off-diagonal parameters in matrices A $(\alpha_{12}, \alpha_{21})$ and B (β_{12}, β_{21}) capture the cross-market shock and volatility effects, while the off-diagonal elements for D $(\delta_{12}, \delta_{21})$ measure the cross-market asymmetric effects.[2]

Engle and Kroner (1995) and Kroner and Ng (1998) noted that the above BEKK specification can be estimated efficiently and consistently using the full information maximum-likelihood method. It proceeds by letting L_t be the log likelihood function of observation *t*, *n* be the number of stock indices and *L* be the joint log likelihood function assuming normally distributed errors, which gives

$$L = \sum_{t=1}^{T} L_T \tag{5}$$

$$L_t = \frac{n}{2}\ln(2\pi) - \frac{1}{2}\varepsilon_t' H_t^{-1}\varepsilon_t \tag{6}$$

where T is the number of sample observations. To obtain the final estimates and their asymptotic standard errors, the simplex algorithm was employed. According to Susmel and Engle (1994), the assumption of a student-t distribution delivers better estimation for conditional errors than assuming a normal distribution when modelling high-frequency data. Therefore, the fat-tailed distributions are captured in these estimations based on the assumption of multivariate student-t distributions.

In summary, we evaluate the significance of the coefficients attached to own-market shocks, cross-market shocks, own-market variances, cross-market variances, own-asymmetric effects and cross-asymmetric effects governing equations (3) and (4). The essential feature of the GARCH BEKK specification is that it permits the conditional variances and covariances of the two series to influence each other, hence allowing to test the null hypothesis of no shock and volatility spill-over effects in a unidirectional or bidirectional way.

5. DATA ANALYSIS

The dataset consists of daily closing prices of the FT30 and Dow30 indices from 1st July 1935 to 31st January 2020. The stock prices are denominated in local currency with the view of understanding the direct linkages between the markets under scrutiny without considering the effect of exchange rate risk.

Error! Reference source not found. displays the closing prices of the UK and US stock indices for the full- and sub-periods. Over time they follow similar patterns. For instance, intense periods of crisis, such as World War II, the 1971 international monetary crisis, the 1973/1974 global oil shock, the October 1987 stock market crash, the 1997 Asian crisis, the 1998 Russian debt crisis, the 2000 dot-com bust and the 2008 stock market crash, all caused their stock prices to plunge from peaks to historic lows.

"Insert Figure 1 Here"

Error! Reference source not found. depicts the plots of the UK and US stock returns for the full and sub-periods. It seems the UK market shares similar phases of market dynamics with the US market. The pre-BW and EMU periods show that the US stock returns fluctuated more intensely between negative and positive values than the UK while the UK stock returns fluctuates more rapidly than the US in the BW and pre-EMU periods. This suggests that substantial variation in the stock returns of the UK and US in these periods may affect their levels of market interactions and interdependence. The significant spikes in the pre-EMU and EMU periods are attributed to the 1987 stock market crash and 2008 global financial crisis, respectively. The monumental shifts in the stock returns of these markets due to shocks are worthy of further empirical investigation. Overall, the plots show the clustering of larger returns around major historical episodes, indicating the presence of heteroscedasticity.

"Insert Figure 2 Here"

The descriptive statistics of the daily stock returns (logged first differences) are presented in **Error! Reference source not found.Error! Reference source not found.**. The average stock returns of the US market far exceed the UK in the full- and sub-periods, whilst both markets exhibit relatively similar volatility as measured by their standard deviation. This may suggests that the US market offer higher returns on equities than the UK given the same level of risk.

The skewness values suggest that negative shocks are more prevalent than positive shocks in the full- and sub-periods. The kurtosis values for the returns are greater than three implying leptokurtic distributions (that is, fat-tailed distributions), extreme observations and possibly volatility clustering. The higher kurtosis values in the return series suggest that large shocks are common features of high-frequency financial data. In addition, the Jarque-Bera test for normality indicates that we reject the null that the stock returns are normally distributed. The Ljung-Box test statistics indicates a significant presence of serial correlation in the returns of both markets. The serial correlation of the squared returns, which is a proxy for volatility, suggests strong evidence of the

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presence of high persistence, time-varying volatility and volatility clustering. The McLeod-Li test indicates strong ARCH effects or conditional heteroscedasticity in all returns. The ADF tests of the presence of unit root in the price returns indicate trend stationary processes for the full sample and subsample.

"Insert Table 1 Here"

Error! Reference source not found. reports the test for equality of means, medians, variances and distributions between the four sub-periods. The trends show a strong difference in volatility as well as distribution between the sub-periods, whereas no differences in mean occur. The difference in median fades away after the BW period for the UK, whilst the US shows little or no differences. Overall, the UK and US series behave differently over time as such the partitioning of the empirical analysis is a necessary modelling strategy.

In the light of the presence of conditional heteroscedasticity, serial correlation and non-normality multivariate volatility models will be employed to evaluate the nature of spillover effects in a multi-sample period setting.

"Insert Table 2 Here"

6. EMPIRICAL RESULTS

6.1 Return Spillovers

Error! Reference source not found. sets out the results for the cointegration analysis using the log prices of UK and US stock indices. Both the Engle-Granger and Johansen tests indicate no cointegrating relationships at conventional levels between the UK and US stock markets for the full- and sub-periods. After controlling for structural breaks in the cointegrating relationships by using the Gregory-Hansen test (GH), the evidence also shows no long-run equilibrium in the full and sub-periods except for the post-EMU period.

Based on the popularity of Engle-Granger and Johansen tests for cointegration in empirical literature, it can be concluded that the two markets do not co-move towards a stationary long-run equilibrium in the full- and sub-periods. The findings of absence of cointegrating relationship between the UK and US agree with existing evidence (see Ammer & Mei, 1996) and contrast with other findings (see Floros, 2005; Hatemi 2008).

"Insert Table 3 Here"

The short-run relationship between the UK and US stock returns is estimated using the VAR(2) model and the results are set out in Table 4. The evidence indicates that the US market leads the UK by at least a day in the full and sub-periods. The Granger-causality test also confirms mostly unidirectional causality from the US market to the UK. Overall, the US stock market has maintained a dominant influence over the UK stock market in terms of return spillovers, corroborating existing studies (e.g. Kim, Moshirian, & Wu, 2005).

These results may be attributed to few possible explanations. Firstly, the US economy is the largest in the world and being a leading global financial centre, market participants can eliminate arbitrage opportunities more rapidly in the US than the UK. Secondly, the strong degree of market efficiency in these markets suggests that based on the daily series analysis,

one day is sufficiently long enough for the stock index to reflect fundamental information (e.g. macroeconomic news). Finally, the US stock index has the potential to adjust more rapidly to reflect the fundamental value given the quick reaction of investors to information from the US financial markets (see Singh, Kumar, & Pandey, 2010).

The diagnostic statistics indicate the absence of serial correlation in the residuals for the full period and half of the subsamples. However, there is significant serial correlation in the squared residuals for all the periods suggesting the presence of conditional heteroscedasticity and volatility clustering.

<center>"Insert Table 4 Here"</center>

6.2 Shock and Volatility Spillovers

As the series are stationary, a VAR(2) specification for the mean equation is adopted for the full- and sub-periods.[3] The residuals obtained from the VAR(2) specification are used to carry out the empirical estimates of the asymmetric GARCH-BEKK model and the results are reported in **Error! Reference source not found.**. The model allows the conditional variances and covariances of the two returns from US and UK stock markets to affect each other thereby making it possible to test the null hypothesis of no shock/volatility spillover effects in a unidirectional or bidirectional way.

A considerable number of statistically significant transmission coefficients suggest substantial interactions between the conditional volatilities. The stationarity condition for the BEKK covariance matrix H_t is satisfied as the largest eigenvalue of the sum of the Kroneker products of ARCH and GARCH terms has eigenvalues less than unity in modulus.[4] This suggests a high level of persistent shocks in both markets. The likelihood ratio (LR) test soundly rejects the null of constant covariance matrix H_t for the full and sub-periods.[5]

The estimated diagonal parameters are statistically significant in the full and sub-periods indicating own domestic past shocks and volatilities affect the conditional variances of the UK and US stock markets. We first consider the own-shock effect in the full period, the result shows that the past shock of the UK market has the largest effect ($\alpha_{11} = 0.277$) on its own conditional variance, and the US stock market has the smallest own shock effect ($\alpha_{22} = 0.146$). This result is also similar for the sub-periods, thus, indicating that past shocks play a greater role in the volatility of the UK market than the US market. Perhaps, this is an indication that the US market is more mature than the UK market, since it is less affected by its own past shocks.

Second, the result of the own-market volatility effect which measures the effects of past volatility of a market on its conditional variance, indicates high degree of volatility persistence since the magnitudes of these estimates are close to one. For the full period, the volatility persistence is slightly lower for the UK stock market ($\beta_{11}= 0.956$) than for the US stock market ($\beta_{22}= 0.963$), indicating that the UK market derive relatively less of its volatility persistence from its own past volatility than does the US market. The higher degree of volatility persistence in the US market is evident in the periods of pre-BW, BW and pre-EMU.

We also consider own-market asymmetric effect which measures the asymmetric response of a market to its own past negative shocks or 'bad news'. The asymmetric responses are highly significant, but the average values of δ_{11} and δ_{22} indicate that the US market is more responsive to negative shocks than does the UK market. In the full period, the magnitude of the US stock market's reaction to its own negative shock is $\delta_{22} = 0.253$, and that for the UK market is only $\delta_{11} = 0.158$. Moreover, for the US market, the negative shocks have a greater effect ($\delta_{22} = 0.253$) than the effects from the overall shocks ($\alpha_{22} = 0.146$) on its own conditional variance, but for the UK market, the magnitude of the overall shock effect ($\alpha_{11} = 0.277$) is greater than the negative shock effect ($\delta_{11} = 0.158$). Except for the pre-BW period, all the sub-periods indicate more pronounced negative shock effects in the US market than the UK market.

A crucial aspect of this study is to investigate shock and volatility transmissions between the UK and US stock markets, which can be captured by the off-diagonal parameters of the matrices A, B and D. We first analyse the shock spillover effect for the full period, and the evidence indicates significant bidirectional shock spillovers between the UK and US stock markets. This suggests that the impact of past shock originating from the UK market increases the US current volatility ($\alpha_{21} = 0.036$), whereas a past shock originating from the US have a decreasing effect on the UK market's current volatility ($\alpha_{12} = -0.019$). Similar significant bidirectional shock spillovers exist in the pre-BW and EMU periods but past shocks originating from the US increase volatility more in the UK than the other way round. These periods suggest significant linkages between the two markets during the most politically and economically turbulent times. These periods also witnessed the highest number of crisis episodes such as the WWII, the 2000 Dot-Com bubble burst, the 2008 stock market crash, the Eurozone debt crisis and recently the Brexit crisis. The results also suggest that their past shocks play a pivotal role in explaining the time dynamics of their conditional volatilities, and should hence be taken into consideration when forecasting the volatility of their future stock returns. The result is consistent with the finding of significant volatility spillover after the commencement of the EMU (see Savva, Osborne & Gill, 2009; Panopoulou & Pantelidis, 2009).

In the BW period, the evidence shows significant unidirectional shock spillover, such that past shocks from the UK increase the current volatility of the US. This implies that the UK market plays a dominant role in shock transmission during this period as it is relatively insulated from external shocks itself. However, the pre-EMU period indicates absence of shock spillovers between the two markets, suggesting there is little or no transmission of news during less volatile period.

If we consider volatility spillover, the full period shows significant unidirectional volatility spillover from the US to the UK market. This suggest that the impact of past volatility

originating from the US market increases the UK current volatility ($\beta_{12} = 0.004$). Corroborating the evidence of Baele (2005), the increasing volatility in the UK from the transmission of news from the US may be due to the state of the US business cycle having a dominant influence on the world market in general and the UK financial market in particular. In the pre-BW, the impact of past volatility originating from the US market decreases the UK current volatility ($\beta_{12} = -0.036$), while in the BW period, the impact of past volatility from the UK market has a decreasing effect on the US market's current volatility ($\beta_{21} = -0.008$). However, the pre-EMU and EMU periods indicate volatility transmissions are no longer significant.

If we further consider only negative shocks in the full period, there is bidirectional asymmetric effect between the UK and US, suggesting that bad news originating from the US ($\delta_{12} = -0.033$) tends to cause higher volatility in the UK, whilst bad news originating from the UK ($\delta_{21} = 0.050$) have a decreasing effect on the US market's current volatility. The average value of δ_{21} (-0.033) is far less than that of α_{21} (0.036). This suggests that the overall shock spillovers are much stronger than 'negative news' spillovers from the UK market to the US market. Surprisingly, the results for the pre-BW, BW and pre-EMU periods indicate that the US market's current volatility increases more in response to the negative shocks from the UK market, but not vice versa.

Accordingly, the evidence seems supportive of our hypotheses of significant bidirectional shock or volatility spillovers for pre-BW and EMU periods. This suggests strong financial linkages during a period characterised by currency floats, macroeconomic instability and, heightened financial volatility. However, we cannot exclude the possibility that the higher magnitude of the significant shock spillovers from the US market to the UK market is partly due to the presence of overlapping trading hours and cross-border listing between the two markets. In a similar vein, the evidence support our hypotheses of insignificant bidirectional

shocks or volatility spillover for the BW and pre-EMU periods. This suggests weak international financial linkages during a period characterised by fixed exchange rate regime and eclectic currency arrangement.

The diagnostic tests indicate that most of the serial correlations in the standardised residuals and squared residuals have been captured. In particular, Ljung-Box Q statistics indicates that there no series dependence in the squared standardised residuals, suggesting the appropriateness of the fitted variance-covariance equations by the two-variable asymmetric BEKK model. The sign bias tests show evidence of asymmetric volatility, indicating that previous positive and negative shocks have a different impact on heteroscedasticity. Therefore, the asymmetric GARCH-BEKK can fully account for the leverage effects in the returns of the two markets in the full period (see Kroner & Ng, 1998).

In summary, the evidence demonstrates that the UK and the US past shocks are more important in predicting future volatility than past volatility for the entire period. Particularly, the pre-BW and EMU periods indicate a more significant prediction of future volatility arising from both the UK and US past shocks. Unlike the BW and pre-EMU periods that exhibited limited market interactions, the commencement of the EMU has increased financial linkages between these two markets (see Aladesanmi, Casalin & Metcalf, 2019). Thus, the growing interdependence between the two global financial centres may intensify the vulnerabilities of domestic markets to any global shocks and limit portfolio international diversification benefits.

"Insert Table 5 Here"

7. CONCLUSIONS

This study investigates the shock and volatility spillover effects between the UK and US stock markets over the period 1935 - 2020. The evidence validates our hypotheses of significant bidirectional shock or volatility spillovers between the UK and US stock markets in the pre-BW and EMU periods; and insignificant transmission effects in the BW and pre-EMU periods. Especially, the EMU period characterised by currency floats, macroeconomic instability and heightened financial volatility, evinces the strongest financial market interactions and interdependence. The magnitude of the shocks from the US market confirms an established view that the US stock market is the principal shock transmitter and crisis epicentre (see Li, 2007; Li & Giles, 2015). This suggests that strong financial market linkages could increase the vulnerabilities of domestic markets to any global shocks and reduce the potential benefits of international diversification, whereas weak financial market linkages could insulate domestic markets from international shocks and increase potential diversification benefits.

For financial market operators, the high level of shock spillovers particularly in the EMU period indicates that international investors are in a position to potentially benefit less from international portfolio diversification as a result of increasing interdependence. For instance, shocks originating from the US market will lead to increased volatility in the UK market, hence the benefit of risk diversification is limited for an international investor holding a UK-US stock portfolio. However, investors may improve their potential diversification benefits by taking into account the US past shock and volatility dynamics when forecasting volatility of UK stock returns as well as other assets' returns. International investors may also diversify more broadly into developed, emerging and frontier markets in order to enhance their risk-return benefits. Reasonably, increasing market interdependence and integration will engender timely portfolio management through efficient and accessible information, hence leaving international diversification benefits to more skilled investors.

For policymakers, the stability of financial markets hinges more on building resistance to negative shock spillovers and financial contagion by effectively managing key macroeconomic fundamentals. Finally, the magnitude of a crisis and risk of financial contagion could be substantially mitigated through proactive effective well-calibrated policy responses capable of improving liquidity and confidence in the financial markets.

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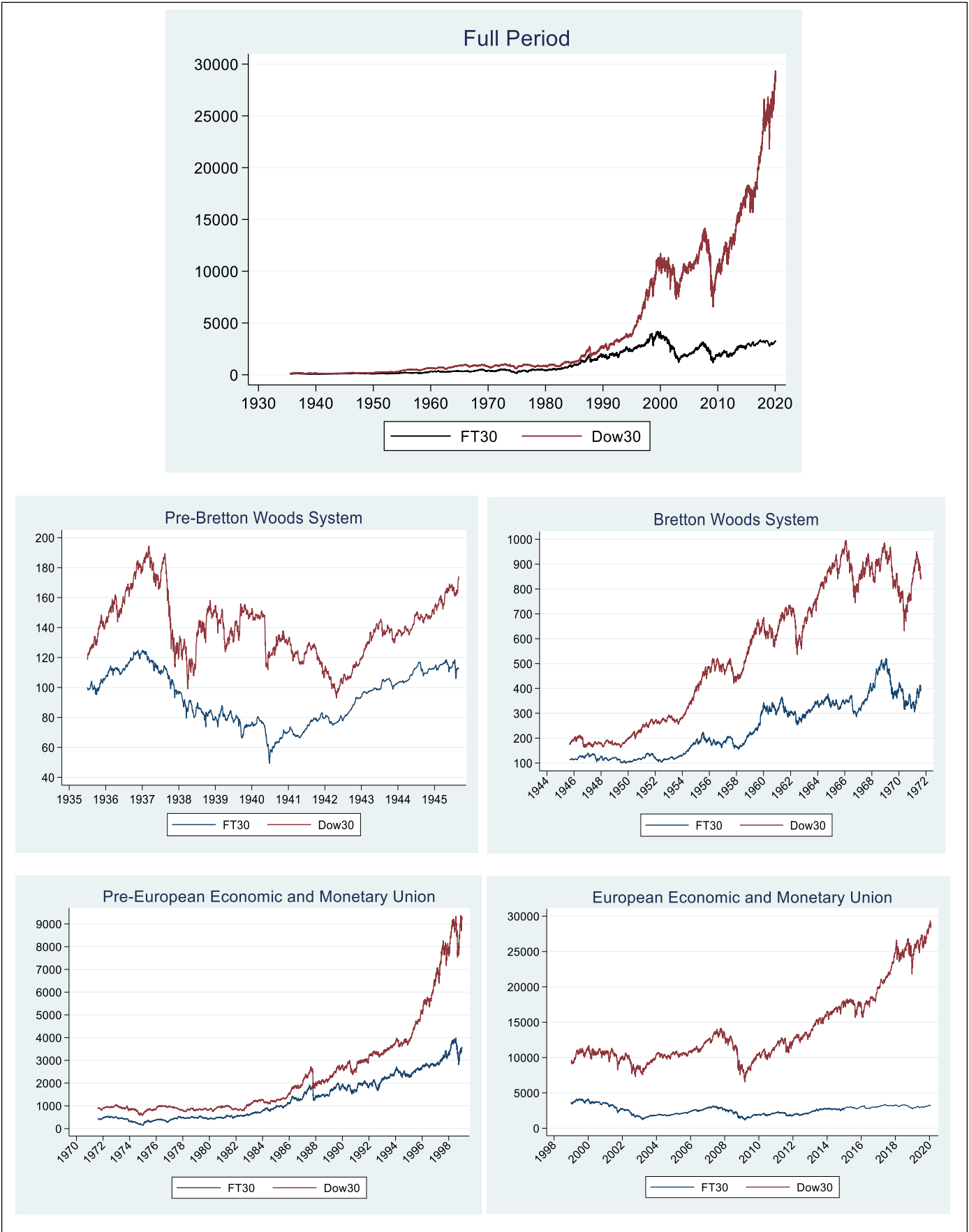
Figure 1: Closing Prices of FT30 and Dow30 for the full period and four sub-periods
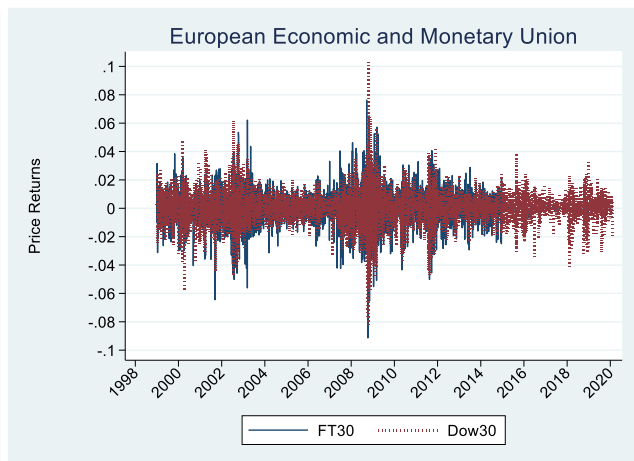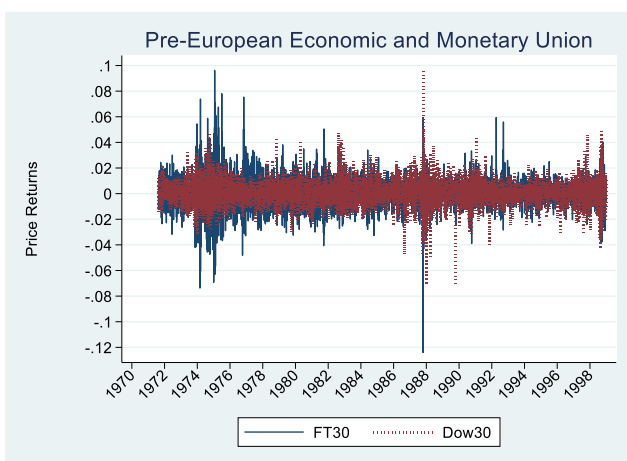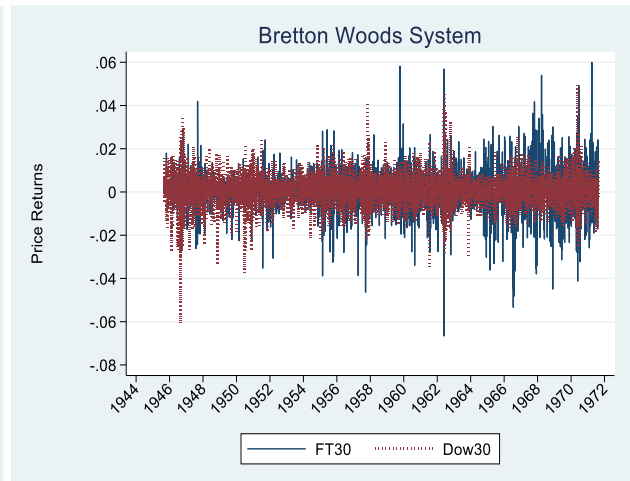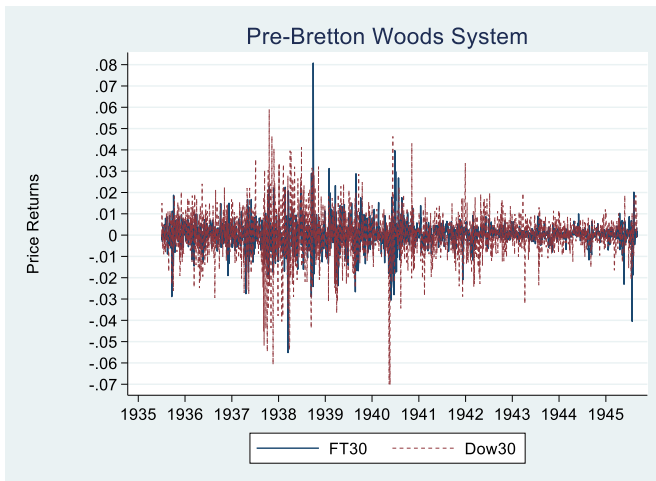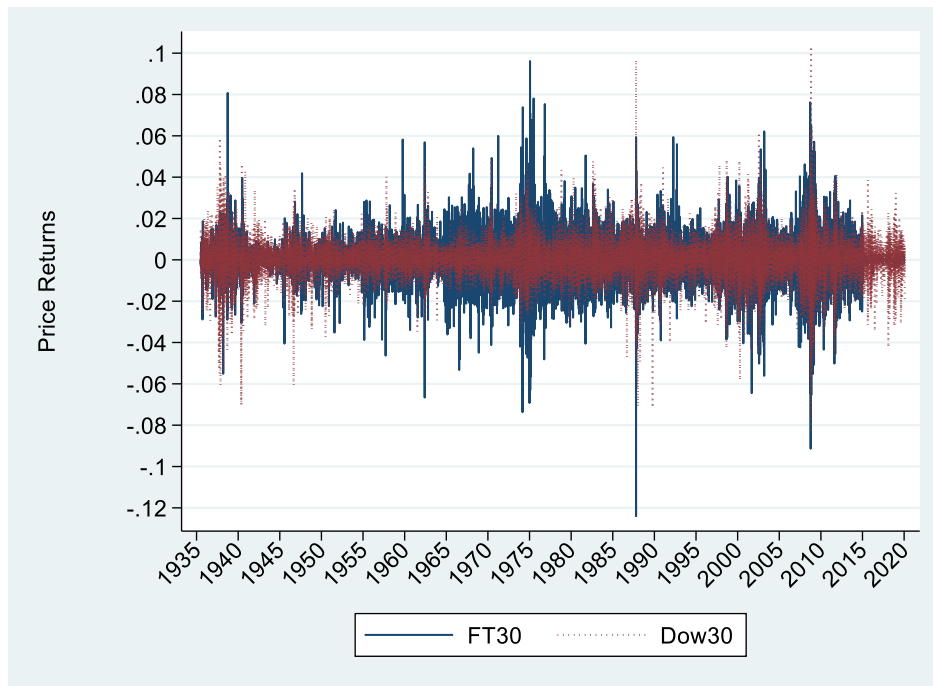
Figure 2: Price Returns of FT30 and Dow30 for the full period and four sub-periods

Table 1: Descriptive Statistics of UK and US Stock Market Returns

	Mean (x10^{-3})	Standard Deviation	Skewness	Kurtosis	Jarque Bera test	Q (12)	Q^2 (12)	ARCH (4)	Unit Root Test (ADF)
Full Period (1935-2020)									
UK	0.157	0.010	-0.205***	11.82***	3701***	257.3***	14568***	3702***	-65.66***
US	0.240	0.010	-1.094***	34.19***	9274***	59.69***	2375***	980.8***	
Pre-BW(1935-1945)									
UK	0.047	0.007	-0.322***	21.49***	680.7***	305.1***	897.6***	469.7***	-64.85***
US	0.145	0.011	-0.493***	10.37***	487.4***	36.17***	725.9***	184.9***	
BW (1945-1971)									
UK	0.192	0.008	-0.135***	10.77***	1034***	314.7***	581.4***	207.7***	-64.70***
US	0.236	0.007	-0.523***	9.093***	1135***	135.0***	1106***	461.8***	
Pre-EMU (1971-1999)									
UK	0.301	0.012	-0.125***	9.617***	986.6***	99.20***	4599***	1386***	-65.58***
US	0.332	0.010	-2.482***	70.72***	5249***	55.85***	355.1***	208.6***	
EMU (1999-2020)									
UK	-0.021	0.011	-0.316***	10.03***	857.9***	66.95***	4601***	992.3***	-66.77***
US	0.207	0.011	-0.122***	11.35***	874.1***	54.56***	4757***	904.3***	

Notes: Daily stock returns are calculated as $r_t = ln(p_t) - ln(p_{t-1})$. *, ** and *** denote significance at the 10%, 5% and 1% levels. The Ljung-Box (Q) is applied to raw and squared returns to test for serial correlation and heteroscedasticity using *12* lags. The Jarque-Bera test is used to test for normality in distribution. McLeod and Li test is used to test for ARCH effects. The critical values at 1%, 5%, and 10% levels of the ADF test for unit root based on four optimal lags are -3.960, -3.410 and -3.120, respectively.

Table 2: Test for equality of means, medians, variances and distributions of stock market returns across the sub-periods 1935 – 1945 (Pre-BWS), 1945 – 1971 (BW), 1971 – 1999 (pre-EMU), 1999 – 2020 (EMU)

	Equality of means (×10^{-3})	Equality of medians	Equality of variances	Equality of distributions
UK: BW = pre-BW	0.148	7.708***	0.007***	0.069***
US: BW = pre-BW	0.231	0.172	0.008 ***	0.065***
UK: Pre-EMU = BW	0.010	40.66***	0.010 ***	0.137***
US: Pre-EMU = BW	0.081	1.847	0.009 ***	0.069***
UK: EMU = Pre-EMU	-0.308	2.199	0.012 ***	0.095***
US: EMU = Pre-EMU	-0.040	3.072*	0.010***	0.026**

Notes: *, ** and *** denote significance at the 10%, 5% and 1% levels. The two-sample *t* and Levene tests assess the null of equality of means and equality of variances. The test statistic for the two-sample and Levene tests are reported in parenthesis. For these tests the figure reported are the differences between means, and between variances. *k*-sample and Kolmogorov-Smirnov test assess the null of equality of medians, and equality of distributions.

Table 3: Cointegration Relationships between the UK and US Stock Prices for the full sample and the sub-periods

Cointegration tests	Full Period 1935-2020	Pre-BW 1939-1945	BW 1945 – 1971	Pre-EMU 1971 – 1999	EMU 1999 – 2020
Engle-Granger Test	-1.801	-1.397	-1.789	-1.740	-1.990
Johansen test $\lambda_{TR}/\lambda_{MAX}$	5.124/4.987	9.125/7.687	12.81/10.92	5.978/5.626	5.377/5.349
Gregory-Hansen Test	-48.46	-32.81	-36.69	-45.58	-69.16**

Notes: *, ** and *** denote significance at 10%, 5% and 1% levels respectively. We specify the type of cointegration relationship that incorporates a constant trend with two lags based on AIC. The critical values for the maximum statistics (λ_{max}) for 1% and 5% are 15.41 and 20.04 and Trace statistics (λ_{trace}) are 14.07 and 18.63 based on zero cointegrating relationship. For one cointegrating relationship, their critical values are 3.76 and 6.65. The Engle-Granger residuals-based test for the null of no co-integration with critical values at 1%, 5% and 10% is equal to -3.96, -3.41 and -3.12, respectively. The critical values for Gregory-Hansen (GH) are -69.37 for 1%, -58.58% for 5% and -53.31 or 10%.

Table 4: VAR Results – Return spillovers between the UK and US stock market in the full- and sub-periods

	Full Period 1935-2020		Pre-BW 1939-1945		BW 1945 – 1971		Pre-EMU 1971 – 1999		EMU 1999 – 2020	
	$UK(i=1)$	$US(i=2)$	$UK(i=1)$	$US(i=2)$	$UK(i=1)$	$US(i=2)$	$UK(i=1)$	$US(i=2)$	$UK(i=1)$	$US(i=2)$
$R_{1i}(1)$	0.036*** (.016)	.222*** (.007)	.240*** (.019)	.109*** (.011)	.034*** (.012)	.258*** (.014)	.034*** (.012)	.258*** (.014)	-.147*** (.016)	.345*** (.015)
$R_{1i}(2)$	0.016** (.019)	-.048*** (.007)	.110*** (.011)	-.046*** (.012)	.005 (.012)	-.098*** (.015)	.005 (.011)	-.098*** (.015)	-.039*** (.015)	.061*** (.016)
$R_{i2}(1)$	-.002 (.006)	.056* (.034)	-.035 (.034)	.066*** (.019)	.006 (.010)	.066*** (.012)	.006 (.010)	.066*** (.012)	.023 (.016)	-.082 *** (.016)
$R_{i2}(2)$	0.012* (.007)	.240 (.032)	.133*** (.033)	-.012 (.020)	.015 (.010)	-.042*** (.012)	.015 (.010)	-.042*** (.012)	-.006 (.015)	.047*** (.016)
GC	1006***	3.324	105.1***	94.93***	165.2***	0.346	363.7***	2.680	503.1***	2.399
Q(6)	33.32***	13.21***	11.17*	9.747	24.02***	30.62**	14.81**	13.90**	9.837	24.29***
$Q^2(6)$	7360***	1693***	588.6***	416.1***	470.6***	724.5***	3188***	341.0***	2406***	2435***
Return Spillovers										
Unidirectional (US)		Bidirectional		Unidirectional (US)		Unidirectional (US)		Unidirectional (US)		

Notes: *, ** and *** denotes significance at 10%, 5% and 1% levels. The Ljung-Box test for serial correlation in the raw residuals (Q) and squared residuals (Q^2) up to 6 lags. GC represents Granger-Causality test.

Table 5: Estimation of Bivariate Asymmetric GARCH BEKK (*1,1*)

	Full period 1935 - 2020		Pre-BW 1935 - 1945		BW 1945 - 1971		Pre-EMU 1971 - 1999		EMU 1999 - 2020	
Variables	UK (i=1)	US (i=2)	UK (i=1)	US (i=2)	UK (i=1)	US (i=2)	UK (i=1)	US (i=2)	UK (i=1)	US (i=1)
					SHOCK					
$A(i,1)$	0.277***	0.036***	0.468***	0.042**	0.274***	0.029***	0.227***	0.016	0.206***	0.093***
	(0.008)	(0.005)	(0.039)	(0.019)	(0.023)	(0.011)	(0.015)	(0.012)	(0.017)	(0.009)
$A(i,2)$	-0.019***	0.146***	0.160***	0.180***	-0.017	-0.093***	0.012	0.157***	0.140***	-0.081***
	(0.006)	(0.008)	(0.035)	(0.033)	(0.012)	(0.028)	(0.008)	(0.012)	(0.020)	(0.024)
					VOLATILITY					
$B(i,1)$	0.956***	-0.001	0.862***	0.005	0.934***	-0.008**	0.963***	0.001	0.952***	0.000
	(0.002)	(0.001)	(0.013)	(0.005)	(0.008)	(0.004)	(0.004)	(0.003)	(0.004)	(0.003)
$B(i,2)$	0.004**	0.963***	-0.036**	0.973***	-0.002	0.948***	-0.001	0.972***	0.003	0.951***
	(0.002)	(0.002)	(0.016)	(0.005)	(0.005)	(0.007)	(0.002)	(0.003)	(0.005)	(0.004)
					ASYMMETRY					
$D(i,1)$	0.158***	-0.033***	0.204**	0.083**	0.247***	0.031**	-0.173***	0.076***	0.248***	0.006
	(0.015)	(0.007)	(0.090)	(0.034)	(0.026)	(0.012)	(0.028)	(0.019)	(0.021)	(0.015)
$D(i,2)$	0.050***	0.253***	0.007	-0.142**	0.013	0.354***	0.020	0.165***	-0.020	0.373***
	(0.008)	(0.010)	(0.062)	(0.062)	(0.016)	(0.023)	(0.014)	(0.018)	(0.022)	(0.018)
					CONSTANT					
$C(i,1)$	-0.000***	0.000	0.001***	-0.000**	0.001***	0.000**	0.001***	0.000**	0.000***	-0.001***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
$C(i,2)$		0.0001***		0.001*		0.001***		0.001***		-0.000
		(0.000)		(0.000)		(0.000)		(0.000)		(0.003)
					DIAGNOSTICS					
LR ratio	2081300***		129421***		102814***		482816***		397989***	
Q(6)	206.5***	67.34***	13.27**	11.09*	45.51***	27.82***	5.018	20.88**	70.59***	19.54
$Q^2(6)$	68.49***	8.891	0.313	19.04***	113.8***	2.837	11.13*	6.768	9.731	5.080
Sign Bias	0.000*	0.000***	0.000**	0.000***	0.000	0.000***	0.000	0.000	0.000	0.000***
	Full period		**Pre-BW**		**BW**		**Pre-EMU**		**EMU**	
Shock spillover	Bidirectional		Bidirectional		Unidirectional (UK)		Non-directional		Bidirectional	
Volatility spillover	Unidirectional (US)		Unidirectional (US)		Unidirectional (UK)		Non-directional		Non-directional	
Asymmetry spillover	Bidirectional		Unidirectional (UK)		Unidirectional (UK)		Unidirectional (UK)		Non-directional	

Notes: *, ** and *** denote significance at 10%, 5% and 1% levels, respectively. Standard errors are in parentheses. The likelihood ratio (LR) tests for the null hypothesis that conditional variances of the two return series are independent. The Ljung-Box tests the autocorrelation in the standardised residuals (Q) and McLeod-Li tests for squared residuals (Q^2) up to 6 lags. Engle and Ng (1993) Sign Bias test for significance of $I(\varepsilon_t^i < 0)$ for *i = 1 and 2*. The summary of the shock and volatility spill-overs indicate blank if there are no cross-markets effects; unidirectional if there are unilateral transmission effects and bidirectional if there are feedback transmission effects.

NOTES

[1] Using 'common trading window' approach to solve nonsynchronous trading effect – data are collected for the same dates across the stock markets, when any series has a missing value due to no trading then the previous data are brought forward (see Aladesanmi, Casalin & Hugh, 2019).

[2] The diagonal elements in matrix *A* capture the own ARCH effect, the diagonal elements in matrix *B* capture the own GARCH effect and the diagonal elements in matrix *D* capture the own asymmetric effect. The parameters of matrix *D* capture the magnitude of asymmetry of volatility effect such that the term η_{t-1} takes the value *1* for negative shocks and *0* otherwise (that is, $\eta_{t-1} = 1$ when $\varepsilon_{t-1} < 0$ and $\eta_{t-1} = 0$ when $\varepsilon_{t-1} \geq 0$).

[3] Following Li and Giles (2015), a VAR(2) model is adequate for the mean equation for the sample periods based on the optimal lag selection criteria

[4] The persistence of the whole system is captured by the eigenvalues of the system. The closer the eigenvalues to unity, the higher would be the persistence of shocks.

[5] The LR statistic tests for the null (*H₀*: $\alpha_{11} = \alpha_{12} = \alpha_{21} = \alpha_{22} = \beta_{11} = \beta_{12} = \beta_{21} = \beta_{22} = 0$).