Volatility transmission and changes in stock market interdependence in the European Community

By

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Abstract

A multivariate BEKK GARCH representation is employed to model stock market interdependence in groups of EC stock markets between 1987 and 2003. Using daily data, we estimate the effect that news or information spillovers from one market has on the next day returns in other markets. We quantify the sources of volatility transmission as price changes and noise. Our models allow interdependencies to vary over time allowing us to investigate whether interdependence changes following the introduction of the single currency. Generally, stock market integration increases after 1999 although there are differences in the levels of interdependence between (and within) northern and southern European markets. Information spillovers are tend to be transmitted more through noise than price changes though volatility transmission between Germany, Europe's leading economic power, and the UK, Europe's leading financial power, is through price changes after 1999. The results support the view that financial deregulation leads to financial market integration implying that further deregulatory acts can be expected to realise positive outcomes. The major European markets are increasingly integrated with the international (US) market. We observe the main transmission mechanism between Germany and the US is noise whereas it is price changes between the UK and US. Whereas US information influences UK returns more than UK information affects US returns, innovations in Germany are at least as important as US news is on next day German returns. Our conjecture is that the information content of European markets is not homogeneous to international markets.

Keywords: stock markets, integration, interdependence, volatility transmission, spillover, GARCH, BEKK representation, EC

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1. Introduction

This paper investigates information transfer between European stock markets. The finance literature reports that ' … unexpected developments in international stock markets seem to have become important "news" events that influence domestic stock markets' (Eun and Shim, 1989, p. 242). We estimate stock market interdependence by quantifying spillover effects resulting from an innovation or shock to returns, that is, we model volatility transmission between stock markets. Volatility or "news" is transmitted through two channels. The first channel is price changes (an increase in the volatility of the variance of returns) whereas the second channel is noise (an increase in the volatility of the variance of the forecast error). Using a GARCH methodology we can predict the effect that news in one stock market has on returns in other markets the next day and through which channel news is conveyed. A significant interaction is evidence of stock market interdependence or integration.

A priori stock market interdependence should be increasing over time. Global trading and the establishment of internal markets are likely to have increased the correlation between stock market returns in different countries. The convergence of economic fundamentals such as inflation and interest rates should realise larger stock market correlations, particularly if national business cycles become more synchronised and if market risks exhibit a similar profile (Bailey and Choi, 2003). Financial liberalisation or the removal of capital account and foreign exchange restrictions is known to stimulate the pace of financial integration (Gultekin *et al.*, 1989). Integration, however, implies that volatility shocks are transmitted with greater ease and speed. The greater likelihood of contagion is another adverse consequence of closer integration (Pretorius, 2002). Contagion may be exacerbated by herding behaviour and it can explain the increased correlation of stock market returns during episodes of financial crisis.[1]

Stock market integration has potential benefits that could facilitate an investment boom and economic growth (Sabri, 2002b).[2] For instance, the EC financial deregulation process aimed to foster stock market integration by removing impediments to market efficiency and designing policies that promote economic convergence and harmonisation.[3] It is claimed that the introduction of the euro and European Monetary Union positively affected the level of market integration (see Fratzscher, 2001; Hardouvelis *et al.*, 2002; Baele and Vennet, 2001; Baele, 2002). Specifically, the single currency removed currency risk for participating countries and reduced the costs associated with hedging foreign exchange risk thereby dissipating one of the barriers to

[1] For a detailed discussion of the roots of stock market volatility and crises see Sabri (2002a).
[2] The benefits of stock market integration include lowering the cost of equity, increasing liquidity, reducing risk, increasing diversification and increasing the investor base (Sabri, 2002b).
[3] The White Paper of 1986 established a time table for the elimination of capital controls, interest rate restrictions, and other impediments to market efficiency and the creation of the internal market by 1993. Similarly, the Maastricht Treaty of 1991 set the stage for eventual European Monetary Union, the establishment of the European Central Bank, and the introduction of the single currency.

cross-border investment.[4] Within the EC, closer integration should increase the supply of and reduce the cost of finance for less financially developed regions (Giannetti *et al.*, 2002). Nevertheless, there are remaining barriers to further financial market integration which have been identified and discussed elsewhere (see EC, 2002).[5]

In this paper, we use multivariate BEKK GARCH models to estimate stock market interdependence and the sources of volatility transmission across European stock markets between 1st January 1987 and 30th June 2003. We collect daily stock market indexes for EC stock markets and calculate returns in the standard manner. The period from January 1987 to end-June 2003 covers the extensive EU financial deregulation programme. We break down this period into two sub-periods in order to determine whether stock market interdependence changes following the introduction of the euro. The first period is from January 1987 to December 1998 whilst the second runs from January 1999 to June 2003.[6] Thus, the paper contributes to the literature on stock market interdependence. Pretorius (2002) classifies this literature into three categories. The first category of studies examines how interdependent a group of stock markets are. The second group investigates changes in interdependence typically by estimating before and after sub-periods. Finally, the third group seeks to explain why stock markets are interdependent by decomposing or modelling stock market correlations. Therefore, our study falls into Pretorius' first and second categories.

The study has interesting policy implications. Significant stock market interactions are evidence of stock market integration. For policy makers this would justify their approach of financial reform by legislative change. Furthermore, we can ascertain if stock market interdependencies have strengthened or weakened over time. For institutional investors, integration suggests the correlation of returns is increasing which should be used to inform asset allocation strategies. On the contrary, insignificant interactions suggest that efforts to cajole financial markets through legislation do not produce the desired effect. For institutional investors, however, less than perfect

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[4] The single currency also means that [liability] matching requirements for insurance companies, pension funds and other financial institutions cannot restrict cross-border investment. Recent stock exchange alliances are expected to reduce several types of risk by raising liquidity. The monetary policy of the European Central Bank of price stability is reducing the need for financial intermediaries to hedge against inflation risks (within the Eurozone) and this could reduce the level of home bias in portfolios. Finally, the convergence of Eurozone business cycles should allow reduce pricing differentials for equities as real cash flow expectations converge (see Baele and Vennet, 2001; Baele, 2002).

[5] The EC authorities have attempted to stimulate wider and more liquid financial markets that would increase the volume of finance that firms can obtain by issuing shares. However, and despite some progress made during the course of the 1990s, European markets in institutional investment and also in venture capital remain relatively underdeveloped. Furthermore, the cost of finance for European firms could be reduced if firms sourced a greater share of funds from markets as opposed to banks. Other barriers to integration include the relatively high cost of international transactions and settlements (the clearing and settlement of securities) compared to domestic transactions; the limited penetration of EU markets by foreign banks and other financial intermediaries; the domestic nature of the bulk of EU mergers and acquisitions because cross-border M&A activity is limited by existing differences in capital markets, tax and regulatory regimes as well as by labour market rigidities and a plethora of other administrative rules (see EC, 2002). Other barriers to international stock market integration are cited in the literature. For instance, the adverse effects of corporate governance problems and asymmetric information (see Pretorius, 2002); and differences in disclosure requirements, accounting standards, legal positions and taxation (see Solnik and McLeavey, 2003).

[6] We estimate the model for the period 1987 to 2003 and then re-estimate specifying a dummy variable that allows us to model interdependence in the two sub-periods. The results of a likelihood ratio test tell us which specification best fits the data.

integration implies there is a difference in the pricing of equities of similar risk profile across markets implying there is a risk premium determined by purely domestic factors.

The remainder of the paper is organised as follows. Section 2 provides a review of the academic studies of stock market integration in European markets. In section 3 we describe the BEKK representation of the GARCH methodology that will be used to estimate stock market interdependencies. A data analysis is reported in section 4 whilst the results from six different BEKK GARCH models of stock market interdependence are discussed in section 5. Finally, some conclusions are offered in section 6.

2. Integration in European Asset Markets

Early academic studies of stock market interdependence tended to focus on volatility transmission between international stock markets. Using a VAR model that traces out the responses of markets to innovations in a particular market, Eun and Shim (1989) find that innovations in the US are rapidly transmitted to the other markets (including several European markets) mostly with a one day lag.[7] Innovations run from the US but not from other countries to the US confirming the dominance of the US market. Eun and Shim note that the US, UK and Switzerland, and the other European markets have a strong bearing on the Japanese market. Innovations and Europe and the US account for around 9% and 11%, respectively of the variance in Japanese returns. The interdependence of the Swiss market with international markets is confirmed by Jochum (1989) who employs a GARCH-M model to estimate the price of risk. Jochum suggests that small markets like Switzerland are highly influenced by the behaviour of foreign markets since Switzerland prices covariance risk more often than its own market risk.

Kanas (1998) investigates volatility spillover between the three largest European markets, namely, London, Frankfurt and Paris over the period 1st January 1984 to 7th December 1993. Employing an EGARCH model, Kanas finds that spillovers are bi-directional between London and Paris and between Paris and Frankfurt. There is a uni-directional spillover effect from London to Frankfurt. Kanas considers the effects of the October 1987 stock market crash on the spillovers between the three European markets. The numbers of spillovers are found to increase after the 1987 crash and they are more intense than the spillover effects before the crash. Specifically, Paris and Frankfurt became more interdependent following the crash, which Kanas notes might be attributable to financial liberalisation in these markets that began in the late 1980s and the introduction of new automated trading systems in the three markets. However, the dominance of London in the post-crash period is emphasised.

Several authors have investigated stock market integration in Europe and the effects of EMU (European Monetary Union). Using a CAPM framework, Oh (2003) finds evidence of capital market integration in four European countries, namely France, Germany, Italy and the UK, between 1988 and 1995. However, the presence of strong country effects implies that integration is far from complete. Fratzscher (2001) examines the integration of European equity markets between January 1986 and June

[7] The countries are Australia, Canada, France, Germany, Hong Kong, Japan, Switzerland, the UK and the US (see Eun and Shim, 1989).

2000 using a GARCH methodology.[8] The results suggest European financial liberalisation increases the degree of stock market integration but most notably for EMU participating countries. The factors specific to EMU that are driving stock market integration are the reduction of exchange rate uncertainty and monetary convergence.

The implications of EMU and the introduction of the Euro are considered by Hardouvelis *et al.* (2002). The authors estimate a conditional asset pricing model and we discuss the implications that their results have for asset allocation strategies. First, reducing barriers to investment lessens home bias in equity portfolios and leads to an increase in the amount of cross-border equity holdings in Europe. Stock market integration (*vis-à-vis* the German market) is expected to be higher for countries participating in EMU. Since 1997-1998 (when forward interest rate differentials with Germany shrink) it appears that stock markets converge towards full integration. After this date, expected returns are determined more by European factors (risks) than domestic factors. Hardouvelis *et al.* (2002) confirm the view that the reduction of currency risk following the introduction of the euro is extremely important in enhancing stock market integration principally through a reduction in the volatility of European equity premia.

Baele and Vennet (2002) also estimate the effects of EMU on stock market integration using a conditional asset pricing model. The authors' objective is to deduce whether stock market integration has occurred in ten EMU and five non-EMU (European Monetary Union) countries[9]. The analysis uses weekly deutschmark-denominated prices for the period January 1990 to December 2000. The estimates of time-varying integration suggest that local factors are important in determining the price of risk implying imperfect integration for a restricted sample of European countries (France, Italy, Spain and the UK). In accordance with Fratzscher (2001) and Hardouvelis *et al.* (2002), Baele and Vennet (2002) find that the most important driver of stock market integration is the reduction of currency volatility. Monetary integration (convergence of inflation rates) is important for those countries that had relatively high interest rates at the beginning of the period. On the contrary, business cycle convergence has not as yet exerted any influence on stock market integration.

In an extension to the above work, Baele (2002) develops a regime switching volatility spillover framework to validate the origins of time variation in correlations between 13 European equity markets and the US.[10] In this model, domestic unexpected returns are decomposed into three components; a country specific shock, a regional European shock and a global shock. Specifically, Baele investigates whether the intensity of spillovers resulting from innovations in the EU and US markets changes over time. For the majority of European countries, the shock spillover intensity from both the European region and the US has noticeably increased during the 1980s and 1990s. Interestingly, the increase in the intensity of spillovers from the regional European

[8] The countries include EMU participants Austria, Belgium, Finland, France, Germany, Italy, the Netherlands and Spain. Also included are EC members Denmark, Sweden and the UK and five non-European countries, namely, Australia, Canada, Japan, Norway and Switzerland (see Fratzscher, 2001).

[9] The countries are Austria, Belgium, Finland, France, Germany, Ireland, Italy, the Netherlands, Portugal and Spain. The non-EU countries are Denmark, Norway. Sweden, Switzerland and the UK (see Baele and Vennet, 2001).

[10] The EMU participating countries are Austria, Belgium, France, Germany, Ireland, Italy, the Netherlands and Spain plus Denmark, Sweden and the UK, plus Norway and Sweden. A regional [aggregate] European market and the US market are also included (see Baele, 2002).

market is greater than that from the US for European countries. However, the US is still the dominating influence as shocks from the US account for 20% of local variance compared to 15% for shocks from the European region. Baele (2002) examines factors that might explain the increase in the shock spillover intensity from the European regional market. Baele (2002, p. 33) reports 'that countries with an open economy, low inflation, and well developed financial markets share more information with the regional European market'. In contrast to the earlier work of Baele and Vennet, Baele notes that there is some evidence suggesting that the business cycle is affecting the intensity of shock spillover.

Bekaert *et al*. (2003) find that more than 30% of the conditional mean variance in European returns is attributed to shocks from the US. However, in seven out of ten European markets, local information is found to be important for explaining pricing errors.[11] Small European markets have larger betas and are more highly correlated with the European market than with the US market. Allowing the estimated betas and correlations to change shows the trends in the patterns of regional and global integration. For Europe, the betas with respect to the US increase more than the regional betas. A cautious interpretation is that European markets are becoming more integrated both regionally and internationally. In terms of contagion effects, there is intra-European contagion [of residual correlations] but no evidence of excess correlation between Europe and the US.

3. The BEKK GARCH representation of volatility transmission

The ability to forecast financial time series such as stock market returns, inflation and exchange rates varies from one period to another. For instance, forecast errors may be relatively small in one period but large in another and then small in the next period. This suggests the variance of forecast errors varies over time and that autocorrelation is present in the variance of forecast errors. In order to capture autocorrelation in the variance of the forecast error term, Engle (1982) has developed the autoregressive conditional heteroskedasticity (ARCH) model. In ARCH models the variance of the disturbance term at time t depends on the squared disturbance term in the previous period. Thus, the variance is conditioned on information available in period $t - 1$, which allows the conditional variance to change over time as a function of past errors leaving the unconditional variance constant. Engle's ARCH process simultaneously models the mean and variance of a time series. Since stock markets have been found to be linked through their second moment it been suggested that models should take account of the second moment in modelling time series that are characterised by uncertainty (see Engle and Kozicki, 1993).

Bollerslev (1986) introduced a generalisation to the ARCH model (GARCH) to take account of the fact that ARCH models tended to require a long lag length. In the ARCH framework, the conditional variance is specified as a linear function of past sample variances whereas the GARCH approach allows lagged conditional variances to enter as well (Bollerslev, 1986). The GARCH (p,q) framework specifies p squared error terms and q past variances. The literature suggests that a GARCH (1,1) process is appropriate

[11] The European markets included are Austria, Belgium, Denmark, Finland, Greece, Norway, Portugal, Spain, Sweden and Turkey.

for modelling and forecasting the volatility of stock market returns (see Engle and Kroner, 1995; Solnik and McLeavey, 2003).

A large literature has emerged which proposes several different GARCH frameworks including integrated or IGARCH, exponential or EGARCH, factor or FGARCH, and GARCH-M (in mean).[12] The multivariate GARCH model was introduced by Bollerslev *et al*., (1988). In multivariate models, the first conditional variance is a function of its own lag and a function of the conditional variance of the *n* series as well as the conditional covariance (all lagged). As the number of parameters to be estimated became excessively large some simplifying assumptions were imposed. Bollerslev *et al*., (1988) propose the diagonal *VEC* model in which variances depend only on own past squared errors and covariances on the own past cross-products of errors. However, the *VEC* model is restrictive in the sense that it requires the positive definiteness of the conditional covariance. The BEKK[13] representation of the GARCH model circumvents the problem of positive definiteness by developing a general quadratic form for the conditional covariance equation (see Engle and Kroner, 1995).

GARCH models with conditional correlation are employed in the finance literature to examine the patterns of transmission or spill over effects from one market to another. Multivariate GARCH models are commonly used in time-varying (second moment) studies of covariance. In this study, we adopt the BEKK GARCH (1,1) model since the BEKK representation offers several advantages over other model specifications whilst the literature notes that the (1,1) specification is appropriate for modelling and forecasting the volatility of stock market returns.

The BEKK GARCH model is shown below:

$$r_t = \alpha + \sum_{p=1}^{n} \Phi_p r_{t-n} + e_t, e_t|\Omega_{t-1} \sim N(0, H_t) \qquad [1]$$

Where
r_t is the stock market return series,
e_t is the error term of the return equation,
α is the constant term in the return equation,
Φ_p is the matrix of coefficients with the p lagged values of r_t,
Ω_{t-1} is the matrix of conditional past information that includes the p lagged values of r_t.

To avoid the problems of dealing with normal distributions[14], the first moment of errors e_t is represented by a Martingale process, as shown in equation [2]. It is assumed that e_t in equation [1] follows a process of $E(\varepsilon_t)$.

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[12] For excellent reviews of the ARCH and GARCH literature see Bollerslev *et al*., (1992), Gavala *et al*., (2003) and Bauwens *et al*., (2003).
[13] BEKK stands for Baba, Engle, Kraft and Kroner.
[14]This is important for smoothing the series for calculating the conditional volatility of returns according to the data. In this way, we transform the non-linear BEKK GARCH model into a stochastic model.

where,

$$E(\varepsilon_t) = E(r_t - \mu_t) \quad [2]$$

μ_t is the long-term drift component

and

$$H_{t+1} = CC' + B'H_t + A'\varepsilon_t * \varepsilon_t' A \quad [3]$$

In the variance equation [4] of the BEKK GARCH model, the squared innovation series are smoothed with a n-period moving average technique:

$$\tilde{\varepsilon}_t^2 = \frac{1}{n}\left(\varepsilon_t^2 + \varepsilon_{t-1}^2 + \ldots + \varepsilon_{t-n+1}^2\right) \quad [4]$$

These are the main features of the BEKK GARCH modelling approach that is used to investigate volatility spillover between EU stock markets.[15]

In this study, we extend the bi-variate analysis to a multivariate analysis. This means that we investigate information spillover effects between groups of four markets, or in other words, the current returns in market *i* that can be used to predict future returns (one day in advance) in market *j*. The multivariate model realises measurement of the effects of innovations in stock market returns in one series on its own lagged returns and those of the lagged returns in other markets.

The model includes dummy variables that are included in order for us to estimate stock market interactions in two sub-periods. In this way, we can identify changes in stock market interdependence, for instance, whether the introduction of the single currency in 1999 lead to changes in stock market interdependence as suggested by the established literature. We estimate the effect that information (innovations or shocks) in one market has on another market the next day, the source through which this information or news is conveyed and whether these features are constant over time.

4. Data

Daily stock market index data from 15 EU countries plus Norway, Switzerland and the US (New York) were sourced from DataStream International for the period January 1st 1987 and June 30th 2003 (see Table A1). Stock market returns are calculated in the standard way - see equation [5].

$$\mathrm{Return} = \ln\left(P_t / P_{t-1}\right) \quad [5]$$

[15] See Appendix 1 for an expansion of equation [3].

where

P_t is the share price index in period *t*,
and P_{t-1} is the share price index in the previous period *t*.

A set of descriptive statistics for each of the standardised series of returns by stock exchange is provided in Table 1. For each series the sample mean is significantly different from zero at the 1% level of significance. The highest mean return is Norway (68.27%) which might be explained by the unusual structure of the Norwegian economy with the strong influence of the oil sector. New York (34.05%) and Switzerland (24.85%) have higher mean returns than EU stock markets where the most attractive markets are Germany (23.32%), Ireland (22.69%) and the UK (21.21%). Negative returns are found in Greece (-9.84%) and Sweden (-0.85%). Each series is negatively and significantly skewed at the 1% level (except Sweden). A large kurtosis indicates a platykurtic distribution (for example, Norway) whereas a smaller statistic is evidence that the returns distribution is leptokurtic. All of the series are significant at the 1% level with the majority of the series exhibiting evidence of leptokurtic distributions.

Table 1 here

In order to validate the appropriateness of the BEKK GARCH specification we carry out certain statistical tests of the data. An OLS regression is estimated in which stock market returns are a function of their lagged values (for up to five lagged periods – see Table A1 for the optimal number of lags for each series). Using the BIC (Bayesian Information Criterion) or Schwartz criterion we identify the optimal number of lags for each returns series. Second, from the OLS model we calculate Ljung-Box Q statistics for the returns, squared returns, residuals and squared residuals. This provides a test for autocorrelation at 8, 16, 24 and 32 lags, respectively (given that the maximum number of lags in the optimal lag estimation procedure was five). The Ljung-Box Q statistics are shown in Table 2a and b. The data strongly support the presence of autocorrelation and suggest that the application of the BEKK GARCH model is appropriate for the data.

Table 2a and b here

5. Estimates of Stock Market Interdependence

We estimate GARCH (1,1) models for six groups of four EU stock markets. Our procedure is to estimate each model for the full period (from 1987 to 2003) and then to re-estimate the model specifying two sub-periods that allow us to identify whether stock market interdependence is either constant or changing over time. A likelihood ratio test is used to select the most appropriate model specification. The results are conclusive and support the specification of two sub-periods; from 1987 to 1998, and 1999 to 2003. In addition and for each model, we test the null hypothesis that the joint significance of the transmission coefficients, which are evidence of stock market interdependence, is equal to zero. The null hypothesis is strongly rejected for each model by the data.

The estimated coefficients show the effect that "news" has on stock market returns the next day within a domestic market and across domestic markets. Although our intention is to estimate cross-border volatility transmission, our results show next day returns are mostly influenced by domestic information. In order to identify the most important volatility transmission mechanism we examine the magnitude of the coefficients as well as their significance. A larger coefficient in the transmission of returns relative to the transmission of noise indicates that increased volatility of returns or price changes are the major source of news transmission and vice-versa.

5.1: Model 1 - Germany, France, the UK and the US

Model 1 estimates stock market interdependencies between the largest European stock markets and the international stock market (represented by the New York Stock Exchange). In section 2 we noted the general finding in the established literature that information in the US stock market spills over into European markets. Thus, the estimates from model 1 may be considered to be a robustness test of the literature.

In general, our estimates imply stock market integration increases between European markets and the US after introduction of the euro in 1999. We observe bi-directional interactions between Germany and the US, and the UK and the US between 1999 and 2003. "News" is transmitted across these markets via price changes and noise (the variability of forecast error). The magnitude of the transmission coefficients implies price changes are the main source of volatility transmission between the UK and the US whereas noise is the more important source of information spillover between Germany and the US. Information concerning price changes in the US affects next day UK and German returns differently. News concerning US price changes raises next day UK returns but lowers German returns but noise from the US leads to higher next day German returns. Whilst US news influences UK returns more than UK news influences US returns, German and US noise exert effects of a similar magnitude whereas news regarding German price changes influences US returns more than US news influences returns in Germany. Whilst there are significant interactions between the US and the UK, and the US and Germany after 1999, our estimates imply weaker stock market interdependence between the US and France. Between 1987 and 1998, news about price changes was bi-directionally transmitted between the US and France. Subsequently, we observe only a uni-directional spillover effect from the US to France that lowers next day French returns and is transmitted via price changes.

Table 3 here

The estimates point to a change in the relative importance of national stock markets as producers of news. Stock market interdependence between the US and the UK and the US and Germany increases over time. We believe European (UK and German) news is not homogenous and is acted upon in different ways by stock market participants. Whereas London is a major international financial centre and the largest in Europe, German news is expected to contain information pertinent to the Eurozone and the euro (which the UK has not adopted). German news appears to become more important for the international (US) market after 1999 especially in relation to France (another large, continental European market). As reported above, news about German and UK price changes and market noise affect US returns differently. German news leads to lower next day US returns whilst UK news has the opposite effect. Similarly, US news affects the two European markets differently with the UK market relatively more responsive to US news.

Given these statements, we consider stock market interactions between the three European markets. Consistent with our line of reasoning and discussion of news homogeneity, we observe an increase in interdependence between Germany and the UK after 1999. There are bi-directional spillover effects transmitted through price changes and noise with news in the two countries leading to an increase in next day returns in both stock markets. Specifically, price change is the main transmission channel with German news influencing UK returns to a larger degree than UK news affects German returns. These interactions are not observed between 1987 and 1998. During that period information spillover effects were relatively large between the UK and France with transmission occurring through price changes and noise. This relationship is no longer significant after 1999 except for a uni-directional (and relatively large) transmission of noise from the UK to France, which increases French returns. Similarly, news concerning German price changes positively affected next day French returns; after 1999, news is transmitted from Germany to France through price changes and noise with the latter effect dominant (and leading to an increase in French returns). After 1999, French news does not affect next day returns in either Germany or the UK.

5.2: Model 2 - Belgium, Luxembourg, France and the Netherlands

The second model estimates stock market interdependence between four northern European markets. There are strong cultural relationships between the four countries. The inclusion of Luxembourg is interesting because of her role as an offshore financial centre particularly for Belgian, French and German residents. We observe that Luxembourg is highly integrated with the other markets over both time periods. However, news from other markets has a greater effect on next day returns in Luxembourg than innovations in Luxembourg have on returns in other markets. Generally, the four markets are highly integrated although there are some differences in volatility transmission over time. The magnitude of the stock market interactions tend to be lower after 1999 with next day returns more influenced by noise spillovers than information about price changes.

News about price changes appears to have less effect on next day returns following the introduction of the euro. Across 1987 and 1998, there are bi-directional interactions between France and Belgium, France and Luxembourg, France and the Netherlands, and the Netherlands and Luxembourg. These interactions become uni-directional except for the latter pairing between 1999 and 2003: Belgian news lowers French returns, French news raises Luxembourg returns, Dutch news raises French returns but lowers Luxembourg returns. On the contrary, the Belgian and Luxembourg markets are increasingly integrated with Belgian news raising Luxembourg returns but Luxembourg news having the opposite effect on Belgian returns. In terms of the magnitude of the coefficients on the transmission of returns, the greatest interactions are from Belgium to Luxembourg and Belgium to the Netherlands. Next day returns in Luxembourg are determined more by information about Belgian prices than Belgian noise whereas the opposite is found for the volatility transmission between Belgium and the Netherlands.

Table 4 here

The magnitude of the coefficients on the transmission of noise is smaller after 1999 compared to before although the interactions are significant over time. The degree of interdependence between the four markets is emphasised by the fact that each pairing has either a uni-directional or bi-directional interaction. Interdependence between France and Belgium and the Netherlands and Belgium increases after the introduction of the euro with noise from France and the Netherlands lowering next day Belgian returns. The interaction between France and the Netherlands reduces to a uni-directional relationship over time with noise from France causing lower returns in the Netherlands.

5.3: Model 3 - Denmark, Finland, Sweden and Norway

The Scandinavian markets form another regional group of countries characterised by close economic and political ties. The group is particularly interesting because Denmark has retained its domestic currency; Sweden decided not to adopt the euro; and Norway is not a member of the EC. Another relevant point is that a number of large Scandinavian companies have sought listings on international stock exchanges, notably London and more recently in the US, in addition to their listing on more than one regional (Scandinavian) exchange.

Between 1987 and 1998, information spillovers across Scandinavia are limited to uni-directional interactions that are transmitted via price changes and noise. There are several relatively large coefficients that indicate the strength of market interdependence; for instance, from Finland to Norway and Sweden to Norway (through price changes), and Denmark, Finland and Sweden to Norway (through noise). Comparing the magnitude of the transmission coefficients, we note that innovations that are transmitted via noise tend to be more important than innovations transmitted through price changes. There are notable exceptions. For instance, information concerning price changes in both Finland and Sweden exerts a very large (negative) effect on next day returns in Norway.

Table 5 here

Stock market interdependence in Scandinavia increases over time. Several uni-directional interdependencies in 1987-1998 become bi-directional in 1999-2003: for example, between Norway and Denmark, and Norway and Finland (through price changes and noise with the latter being the more important source of volatility transmission), and Sweden and Finland (through noise). Furthermore, there are uni-directional interdependencies that are not seen in 1987-1998. These interactions are from Finland to Denmark and Sweden (through price changes) and Denmark to Sweden (through noise). Stock market interdependence between Finland and Denmark visibly increases after 1999 because of the above mentioned uni-directional interaction transmitted through price changes and a bi-directional interaction transmitted via noise. We note again in the magnitude of several of the coefficients on the transmission of returns and noise, which are an indication of the strength of stock market interdependence in this region. We have noted the negative effect that information spillover concerning price changes in Scandinavian markets has on next day Norwegian returns in 1987-1998 and this feature remains after 1999. However, there is a change because noise in other Scandinavian markets becomes more important than price changes in influencing Norwegian returns.

5.4: Model 4 - Germany, Greece, Spain and Portugal

In this model we investigate stock market interdependence between three southern European markets and Germany. This is a valid exercise because economic fundamentals in Greece, Portugal and Spain have converged towards the European mean during the 1990s. Generally speaking, the level of stock market interdependence between the four markets is limited to a small number of uni-directional interactions between 1987 and 1998. Volatility is mainly transmitted through price changes during this period: from Germany and Greece to Spain, and from Greece to Portugal (though the magnitude of this coefficient is very small).

Table 6 here

After the introduction of the euro in 1999, we observe greater stock market interdependence with volatility transmitted through price changes and noise. As might be expected, there is evidence of information spillover effects from Germany to Greece (transmitted via price changes and noise) and to Spain (via noise only). The magnitude of the coefficients implies that noise from Germany has a much stronger (positive) effect on Greek returns than news concerning German price changes. The coefficients show price changes and noise in Portugal and Spain affect next day returns in Greece but Greek news does not impact on either Portugal or Spain. As with spillovers from Germany, the main transmission mechanism from Portugal and Spain to Greece is noise, which leads to an increase in next day Greek returns. In 1999-2003, stock market interaction between Portugal and Spain is stronger with news about Spanish price changes affecting (lowering) next day returns in Portugal whereas noise in the markets is transmitted in a bi-directional (and positive) manner.

5.5: Model 5 - Germany, Switzerland, Italy and Austria

The four countries in the southern Alpine region of Europe have historically close economic and political ties. There are strong linguistic ties with German being a common legal language in all countries except Italy, and Italian being a legal language of Switzerland. The inclusion of Switzerland adds another dimension to the model because of her position as an international financial centre and a non-member of the EC. There estimates imply volatility spillovers increase across the four markets after 1999. Table 7 shows greater interdependence between Switzerland and Italy, and Switzerland and Austria with the interaction between Austria and Germany becoming stronger over time. However, there appears to be no interdependence between Germany and Italy.

In 1987-1998, news about prices changes in Germany leads to higher next day returns in Switzerland and lower next day returns in Austria. News is transmitted bi-directionally between Germany and Austria. The main transmission channel is noise with Austrian noise lowering next day German returns whilst German noise causes an increase in next day Austrian returns. News about German price changes lead to increases in next day returns in Switzerland whereas Swiss noise raises next day returns in Germany. Information about Swiss price changes spills over to Austria and lowers returns whereas noise from Austria raises next day returns in Switzerland. There is a bi-directional interaction between Austria and Italy that is transmitted mainly through noise with innovations leading to increases in returns in both markets.

Table 7 here

Generally speaking, information spillovers increase over time with news being transmitted more through noise rather than price changes. For instance, there is a bi-directional interaction between Austria and Switzerland after 1999 that is transmitted via price changes and noise. However, noise is the more powerful transmission channel with innovations in Austria lowering Swiss returns and innovations in Switzerland increasing Austrian returns. This contrasts to uni-directional interactions in 1987-1998. Noise is the only transmission channel between Germany and Switzerland in 1999-2003. In this bi-directional interaction, innovations in each market lead to higher next day returns in the other, which contrasts with 1987 to 1998 when noise transmission is from Switzerland to Germany.

Information spills over to Switzerland from Italy (via price changes and noise) after 1999 and from Italy to Austria (via price changes and noise). Again, noise is the more important transmission channel with innovations causing an increase in next day returns in both instances. Whereas information spillovers are observed from Austria to Italy in 1987-1998, this interaction is not observed after 1999. There are several relatively large transmission effects that have greater magnitude in 1999-2003. For instance, innovations in Germany concerning price changes and noise have a larger effect on next day returns in Austria whilst noise in the Italian market leads to greater next day returns in Austria and Switzerland.

5.6: Model 6 - Germany, Ireland, UK and Luxembourg

Our final model shows stock market interdependencies across Germany, Ireland, the UK and Luxembourg. The selection of this group is based on several facets. Germany is selected because of her dominant economic position in the EC. Ireland and Luxembourg operate regional offshore financial centres whilst the UK is an international financial centre. *A priori* one might expect the Irish and UK markets and the Luxembourg and German markets to be integrated because of geographical and business links. The estimates of stock market interaction suggest that stock market integration increases over time.

The strongest interaction is between Germany and the UK. News is transmitted between the two countries via price changes and noise. There are several differences in the transmission of volatility over time. In 1987-1998, news concerning price changes in Germany and the UK had relatively large effects on next day returns. News about UK price changes lead to higher next day returns in Germany and information about UK prices exerted a greater effect on German returns than UK noise. The opposite is true for information spilling over from Germany to the UK although we find that news regarding German prices has a relatively large effect on UK returns but not as large as German noise. After 1999, news about German prices becomes more important for UK returns whereas the effect of German noise on UK returns is considerably lessened. Information spillover from the UK to Germany is transmitted through both channels although the coefficient on the transmission of returns implies that UK price changes are more important than UK noise in influencing next day returns in Germany.

However, the effects of UK information on German returns are noticeably smaller in 1999-2003 compared to 1987-1998.

Table 8 here

Stock market interdependence between Germany and Ireland has increased over time from a uni-directional interaction transmitted through price changes to bi-directional interactions transmitted through price changes and noise. There are relatively large volatility transmission coefficients from Germany to Ireland with price changes just about being the main transmission channel. News regarding Irish price changes affects (increases) next day German returns to a much greater extent than Irish noise. Whereas interdependence increases between Germany and Ireland, there is little change in interactions between Ireland and the UK over time. Furthermore, stock market interactions between Ireland and the UK are weaker than the above case. After 1999, news concerning UK prices affects (increases) Irish returns but the coefficient is four times smaller than the respective transmission coefficient from Germany to Ireland. However, information about UK prices influences Irish returns more than UK noise. Whilst, noise in the Irish market affects (increases) UK returns in 1987-1998, there is no visible volatility spillover from Ireland to the UK between 1999 and 2003.

Like the interaction between Ireland and the UK, interdependence between the UK and Luxembourg reduces over time. In 1987-1998, volatility spillover is bi-directional and transmitted through price changes but after 1999 there are no significant interactions. Interactions between Luxembourg and Germany and Luxembourg and Ireland are marginally stronger after 1999. Information about German and Irish price changes affects (lowers) next day returns in Luxembourg but news about Luxembourg prices does not significantly affect returns in the two former countries. However, noise in the Luxembourg market does affect next day returns in Germany and Ireland but the impact of volatility transmission (shown by the coefficients on the transmission of noise) is very small indeed.

6. Conclusions

This paper investigates stock market interdependencies in the EC. Our approach allows interactions to vary over time. Specifically, we estimate the sources of information spillover between stock markets before and after the introduction of the euro.

We consider our results support the finding in the established literature of stock market interdependence between the leading European markets and the US. However, our study contributes to the literature because it adds important aspects of the dynamics of stock market interactions. For instance, the model specification of two sub-periods allows us to conclude that stock market interdependencies have increased over time and, more specifically, in the period following the introduction of the single European currency. We observe there are different transmission mechanisms of volatility spillover between European markets and the US, which leads us to suggest the information content of European exchanges is not homogeneous. Specifically, price changes is the most important transmission channel between the US and the UK with US information having a relatively larger effect on next day UK returns. However, interactions between the US and Germany are transmitted mainly via noise and, furthermore, news concerning German price changes has a relatively greater impact on US returns than vice-versa. Indeed, the interaction from Germany to the US via price changes increases in importance after 1999.

The European stock market interdependence literature suggests that stock market integration is positively related to the introduction of the euro (and the elimination of foreign exchange risk for participating countries). In general, our results support this finding whilst allowing us to identify variation in the levels of interdependence across different groups of stock markets. Whereas stock market interdependence generally increases in 1999-2003 compared to 1987-1998, it is stronger across groups of northern European markets, such as the Benelux countries and Scandinavia, compared to interdependencies among southern European markets. For southern European markets such as Greece and Spain, their interaction with Germany increases after 1999, which may reflect more general economic convergence. The same is true of the interaction between Ireland and Germany.

In the main, news is transmitted across markets to a greater extent through noise compared with price changes and this is common to both sub-periods. There are several notable exceptions. For instance, interdependence between Germany, Europe's leading economic power, and the UK, Europe's leading financial centre. Information spillover between Germany and the UK is mainly transmitted through price changes after the introduction of the euro in 1999 whereas previously UK returns were influenced more by noise from Germany. The effect of news regarding UK price changes on German returns, on the other hand, becomes less after 1999.

Our results offer evidence that the financial deregulation programme in the EC is producing the desired effect of closer integration between domestic stock markets. We note that integration increases over time but is still variable between different groups of stock markets. Nevertheless, deregulatory acts like the Financial Services Action Plan can be expected to realise further stock market integration within the EC and between European and other international stock markets.

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Table 1: Descriptive Statistics of Stock Market Returns; by Country, 1987-2003

Exchange	Sample Mean	Standard error	T-statistic	Skewness	Kurtosis	Variance	Std error of sample mean
Austria	0.0059***	0.0822	4.6858	-0.4187***	14.0765***	0.0068	0.0013
Belgium	0.1246***	0.0780	104.8004	-0.2484***	12.8265***	0.0061	0.0012
Denmark	0.0947***	0.1365	45.4949	-0.3132***	4.3316***	0.0186	0.0021
Finland	0.0730***	0.0882	54.2872	-0.4527***	9.4837***	0.0078	0.0013
France	0.0714***	0.1204	38.9107	-0.2007***	5.4660***	0.0145	0.0018
Germany	0.2332***	0.1116	137.0185	-0.4893***	6.1313***	0.0125	0.0017
Greece	-0.0984***	0.1100	-58.6855	0.1290***	6.2573***	0.0121	0.0017
Ireland	0.2269***	0.0753	197.6744	-1.1390***	16.3181***	0.0057	0.0011
Italy	0.0494***	0.1413	22.9152	-0.2206***	2.8939***	0.0200	0.0022
Luxembourg	0.1349***	0.0537	164.6264	-1.5334***	49.7395***	0.0029	0.0008
Netherlands	0.1323***	0.0954	90.9810	-0.4593***	7.8452***	0.0091	0.0015
Portugal	0.1421***	0.0781	119.3277	-0.6192***	14.7767***	0.0061	0.0012
Spain	0.1000***	0.1128	58.1622	-0.3589***	4.9271***	0.0127	0.0017
Sweden	-0.0085***	0.1084	-5.1418	-0.0309	6.0988***	0.0118	0.0017
UK	0.2121***	0.0847	164.2212	-0.7730***	10.5756***	0.0072	0.0013
Switzerland	0.2485***	0.0949	171.7421	-1.1415***	13.0408***	0.0090	0.0014
Norway	0.6827***	0.0265	1686.8119	-40.7031***	2265.0105***	0.0007	0.0004
New York	0.3405***	0.0536	416.5829	-2.5164***	52.9405***	0.0029	0.0008

Note: *** statistically significant at the 1% level. ** at the 5% level.

Table 2a: Ljung-Box Q Statistics – Returns, Squared Returns 8, 16, 24, 32 lags

	Returns				Squared Returns			
	Q(8)	Q(16)	Q(24)	Q(32)	Q(8)	Q(16)	Q(24)	Q(32)
Austria	214.379*	264.121*	273.192*	279.482*	598.289*	747.005*	880.013*	911.976*
Belgium	199.851*	245.817*	256.124*	285.538*	273.225*	405.470*	437.008*	460.333*
Denmark	40.790*	60.941*	71.727*	78.340*	762.115*	1153.038*	1468.566*	1710.218*
Finland	26.644*	43.590*	61.571*	87.748*	335.450*	574.486*	883.469*	1220.514*
France	35.823*	59.263*	77.608*	88.498*	1217.321*	2346.054*	3141.388*	3743.080*
Germany	26.760*	38.067*	51.105*	68.464*	26.967*	78.160*	102.559*	130.837*
Greece	119.389*	143.483*	152.280*	162.025*	432.717*	577.760*	646.535*	743.765*
Ireland	81.849*	116.603*	136.047*	152.457*	84.872*	116.018*	147.713*	160.927*
Italy	41.112*	56.489*	77.051*	83.400*	646.278*	982.831*	1169.625*	1251.466*
Luxembourg	276.873*	330.378*	367.001*	398.656*	988.146*	1089.503*	1255.674*	1425.196*
Netherlands	41.330*	63.193*	91.541*	110.282*	441.782*	879.412*	1096.282*	1192.281*
Portugal	261.058*	300.608*	310.398*	341.687*	349.773*	418.311*	498.445*	564.235*
Spain	55.416*	75.821*	85.733*	92.241*	458.511*	661.529*	762.518*	827.601*
Sweden	49.403*	81.895*	100.079*	119.431*	1361.432*	1823.823*	2016.364*	2123.265*
UK	36.781*	49.522*	67.559*	71.264*	124.625*	189.516*	208.180*	216.318*
Switzerland	27.036*	48.207*	68.267*	84.770*	56.640*	112.657*	132.856*	154.828*
Norway	5.174	8.512	9.782	10.718	47.861*	70.965*	83.856*	92.873*
New York	28.226*	33.260*	43.388*	65.839*	46.558*	53.922*	62.028*	73.048*

Table 2b: Ljung-Box Q Statistics – Residuals, Squared Residuals 8, 16, 24, 32 lags

	Residuals				Squared residuals			
	Q(8)	Q(16)	Q(24)	Q(32)	Q(8)	Q(16)	Q(24)	Q(32)
Austria	8.916	31.847*	39.133*	43.623*	630.675*	742.307*	817.084*	836.578*
Belgium	32.734*	68.247*	78.573*	103.547*	1431.841*	1923.311*	2077.859*	2206.600*
Denmark	16.066*	35.811*	46.818*	54.408*	1391.276*	2117.135*	2657.864*	3091.942*
Finland	17.109*	32.473*	49.924*	73.779*	517.103*	821.448*	1243.528*	1648.257*
France	24.788*	45.224*	63.443*	73.611*	2001.047*	3526.633*	4672.295*	5562.504*
Germany	26.760*	38.067*	51.105*	68.464*	1197.877*	1851.513*	2156.173*	2399.755*
Greece	14.585*	34.356*	42.430*	50.836*	625.911*	882.072*	1009.945*	1199.356*
Ireland	19.672*	48.563*	64.611*	81.830*	811.854*	1059.862*	1208.289*	1273.170*
Italy	18.121*	31.371*	51.296*	57.798*	876.157*	1281.663*	1469.059*	1554.512*
Luxembourg	32.631*	68.814*	107.890*	133.820*	1459.672*	1720.208*	1883.358*	2051.946*
Netherlands	41.330*	63.193*	91.541*	110.282*	2763.943*	4234.447*	5096.322*	5496.175*
Portugal	26.554*	51.141*	65.183*	90.131*	355.960*	425.205*	505.106*	606.206*
Spain	13.561*	31.150*	42.167*	49.194*	1449.424*	1935.778*	2127.111*	2245.583*
Sweden	17.461*	43.731*	58.821*	74.649*	1354.593*	1797.812*	1979.725*	2084.771*
UK	36.781*	49.522*	67.559*	71.264*	1958.436*	2240.566*	2359.398*	2442.879*
Switzerland	27.036*	48.207*	68.267*	84.770*	1578.775*	2149.948*	2314.967*	2410.670*
Norway	5.174	8.512	9.782	10.718	0.001	0.000	0.000	0.014
New York	28.226*	33.260*	43.388*	65.839*	307.816*	321.709*	326.584*	334.629*

* statistically significant at 5%.

Table 3: Estimated BEKK GARCH (1,1) Model Germany, France, UK, US

Variable	Coefficient	T-Statistic	Variable	Coefficient	T-Statistic
Transmission of returns 1987-1998			*Transmission of returns 1999-2003*		
GER → GER	0.9190*	28.1099	GER → GER	0.9328*	71.7654
FRA → FRA	1.1561*	40.8110	FRA → FRA	0.9242*	122.0173
FRA → GER	0.0302	0.6312	FRA → GER	-0.0026	-0.4206
GER → FRA	0.0751*	2.8297	GER → FRA	-0.0450*	-3.6737
UK → UK	0.6248*	14.3459	UK → UK	0.7938*	26.7885
UK → GER	-0.0331	-1.1463	UK → GER	0.0316*	3.2938
GER → UK	-0.0252	-0.4504	GER → UK	0.1529*	3.1731
UK → FRA	0.2246*	10.1982	UK → FRA	0.0078	1.0065
FRA → UK	-0.3847*	-5.8077	FRA → UK	0.0214	0.9170
US → US	0.9251*	64.9496	US → US	0.8894*	50.6399
US → GER	-0.0275	-1.5387	US → GER	-0.0259*	-2.5280
GER → US	-0.0861*	-2.4412	GER → US	-0.0972*	-3.9221
US → FRA	0.0546*	3.5055	US → FRA	-0.0337*	-3.8821
FRA → US	-0.1895*	-3.5005	FRA → US	-0.0210	-1.8837
US → UK	0.0076	0.2373	US → UK	0.1526*	4.6503
UK → US	0.0173	0.4215	UK → US	0.0578*	3.5177
Transmission of noise 1987-1998			*Transmission of noise 1999-2003*		
GER → GER	0.3035*	5.2439	GER → GER	0.2421*	9.1784
FRA → FRA	0.0614	1.0175	FRA → FRA	0.4834*	20.6223
FRA → GER	0.0868	1.2473	FRA → GER	0.0182	1.3408
GER → FRA	-0.0807	-1.7635	GER → FRA	0.1079*	4.4606
UK → UK	0.4066*	6.7469	UK → UK	0.2758*	12.5336
UK → GER	0.0826	1.8721	UK → GER	0.0277*	2.7548
GER → UK	0.0360	0.4866	GER → UK	0.0792*	2.0987
UK → FRA	-0.1237*	-3.3409	UK → FRA	0.1432*	8.7677
FRA → UK	0.2556*	2.7962	FRA → UK	0.0023	0.1019
US → US	0.2424*	6.1233	US → US	0.2545*	11.4294
US → GER	-0.0252	-0.9020	US → GER	0.1372*	9.2182
GER → US	0.0609	0.7678	GER → US	-0.1474*	-5.5220
US → FRA	-0.0116	-0.4325	US → FRA	-0.0090	-0.5625
FRA → US	0.0833	0.8204	FRA → US	-0.0231	-1.7205
US → UK	-0.0493	-1.2740	US → UK	-0.1300*	-4.6157
UK → US	-0.1664*	-2.4634	UK → US	0.0347*	2.5109
		Diagnostic Statistics			
LR(48) Ho = 0	562811.54	p-value	0.0000		
Log-likelihood	39375.3				
Observations	4297				

Note: * significant from zero at the five percent level of significance.

Table 4: Estimated BEKK GARCH (1,1) Model Belgium, Luxembourg, France, Netherlands

Variable	Coefficient	T-Statistic	Variable	Coefficient	T-Statistic
Transmission of returns 1987-1998			*Transmission of returns 1999-2003*		
BEL → BEL	0.2426*	9.0383	BEL → BEL	0.2609*	11.2228
LUX → LUX	0.5487*	31.1154	LUX → LUX	0.5522*	32.8514
LUX → BEL	0.0007	0.1474	LUX → BEL	-0.0454*	-8.3641
BEL → LUX	0.0239	0.3378	BEL → LUX	0.4944*	8.2858
FRA → FRA	0.4604*	24.1462	FRA → FRA	0.5116*	32.3230
FRA → BEL	-0.0260*	-4.0818	FRA → BEL	-0.0054	-0.5690
BEL → FRA	0.1044*	2.2686	BEL → FRA	-0.0752*	-2.7088
FRA → LUX	0.1108*	6.1367	FRA → LUX	0.0914*	5.2096
LUX → FRA	-0.0273*	-3.1901	LUX → FRA	-0.0113	-1.8216
NLD → NLD	0.4297*	21.6005	NLD → NLD	0.4966*	28.3371
NLD → BEL	-0.0238*	-5.5532	NLD → BEL	-0.0109	-1.7304
BEL → NLD	0.0269	0.3982	BEL → NLD	-0.2063*	-3.8393
NLD → LUX	0.0434*	4.3509	NLD → LUX	0.0745*	7.5535
LUX → NLD	-0.0397*	-3.0753	LUX → NLD	-0.0266*	-2.4705
NLD → FRA	0.0226*	3.1709	NLD → FRA	-0.0140*	-2.3008
FRA → NLD	-0.1218*	-6.5187	FRA → NLD	0.0198	1.3899
Transmission of noise 1987-1998			*Transmission of noise 1999-2003*		
BEL → BEL	1.4125*	9.6988	BEL → BEL	0.7383*	11.5280
LUX → LUX	0.8199*	22.4659	LUX → LUX	0.8327*	23.2891
LUX → BEL	0.0069	0.6036	LUX → BEL	0.0499*	6.3499
BEL → LUX	-0.5770*	-2.3735	BEL → LUX	-0.2278	-1.5183
FRA → FRA	1.1031*	18.0259	FRA → FRA	0.9536*	24.9892
FRA → BEL	0.0669*	3.2972	FRA → BEL	-0.0329*	-2.9415
BEL → FRA	-0.2632	-1.2809	BEL → FRA	0.1932*	2.1211
FRA → LUX	-0.2493*	-5.6362	FRA → LUX	-0.0705*	-2.4044
LUX → FRA	0.0629*	3.2089	LUX → FRA	0.0444*	3.7545
NLD → NLD	1.1644*	17.5256	NLD → NLD	1.0106*	22.2137
NLD → BEL	0.0559*	3.7587	NLD → BEL	-0.0245*	-3.0248
BEL → NLD	-0.0258	-0.0842	BEL → NLD	0.4809*	3.0381
NLD → LUX	-0.1422*	-5.2689	NLD → LUX	-0.0987*	-6.4170
LUX → NLD	0.0828*	2.9374	LUX → NLD	0.0641*	2.8401
NLD → FRA	-0.0762*	-3.2813	NLD → FRA	0.0301*	2.4322
FRA → NLD	0.2531*	4.5962	FRA → NLD	-0.0497	-1.7909
		Diagnostic Statistics			
LR(48) Ho = 0	1164931.35	p-value	0.0000		
Log-likelihood	43672.25				
Observations	4297				

Note: * significant from zero at the five percent level of significance.

Table 5: Estimated BEKK GARCH (1,1) Model Denmark, Finland, Sweden, Norway

Variable	Coefficient	T-Statistic	Variable	Coefficient	T-Statistic
Transmission of returns 1987-1998			*Transmission of returns 1999-2003*		
DEN → DEN	0.9226*	21.4731	DEN → DEN	0.6712*	17.8723
FIN → FIN	0.7838*	4.9855	FIN → FIN	0.5043*	10.9687
FIN → DEN	0.1617	1.7629	FIN → DEN	0.0940*	4.7313
DEN → FIN	-0.0236	-0.2429	DEN → FIN	0.0001	0.0007
SWE → SWE	0.9505*	13.6090	SWE → SWE	0.8025*	31.5828
SWE → DEN	0.0605	1.0030	SWE → DEN	-0.0016	-0.0517
DEN → SWE	0.1375	0.9730	DEN → SWE	0.0026	0.0617
SWE → FIN	0.0375	0.5672	SWE → FIN	0.0189	0.3151
FIN → SWE	0.3222	1.8250	FIN → SWE	0.0930*	3.9785
NOR → NOR	-0.9916*	-7.9161	NOR → NOR	0.0978*	3.6835
NOR → DEN	0.0573*	3.4944	NOR → DEN	0.0615*	8.0712
DEN → NOR	-3.6943	-1.9229	DEN → NOR	-0.5753*	-3.4029
NOR → FIN	-0.0220	-0.7608	NOR → FIN	0.1039*	6.8248
FIN → NOR	-7.5023*	-4.4094	FIN → NOR	-0.8592*	-9.7590
NOR → SWE	0.0609*	2.0093	NOR → SWE	-0.0112	-1.2998
SWE → NOR	-3.0949*	-1.9817	SWE → NOR	-0.6757*	-5.3269
Transmission of noise 1987-1998			*Transmission of noise 1999-2003*		
DEN → DEN	0.2300*	5.0831	DEN → DEN	0.3363*	10.5039
FIN → FIN	0.1805*	2.8090	FIN → FIN	0.2772*	9.3039
FIN → DEN	-0.0630	-1.5226	FIN → DEN	-0.1064*	-6.1500
DEN → FIN	-0.0278	-0.3595	DEN → FIN	-0.1673*	-2.6465
SWE → SWE	0.2890*	6.3910	SWE → SWE	0.3221*	12.6106
SWE → DEN	-0.0153	-0.4421	SWE → DEN	-0.0335	-1.2543
DEN → SWE	0.0312	0.4116	DEN → SWE	-0.0887*	-2.3022
SWE → FIN	-0.1064*	-2.6790	SWE → FIN	-0.1855*	-4.6141
FIN → SWE	0.1239	1.8169	FIN → SWE	-0.0485*	-2.7498
NOR → NOR	0.3039*	4.9605	NOR → NOR	1.2028*	44.3364
NOR → DEN	-0.0036	-0.7050	NOR → DEN	-0.0756*	-19.5588
DEN → NOR	1.6946*	2.3595	DEN → NOR	1.8594*	6.8969
NOR → FIN	0.0087	1.2339	NOR → FIN	-0.1556*	-25.3744
FIN → NOR	1.2550*	2.2333	FIN → NOR	1.4366*	9.9459
NOR → SWE	-0.0061	-1.0552	NOR → SWE	0.0070	1.2810
SWE → NOR	1.6434*	3.3978	SWE → NOR	1.1252*	5.9984
		Diagnostic Statistics			
LR(48) Ho = 0	84446.88	p-value	0.0000		
Log-likelihood	41272.18				
Observations	4297				

Note: * significant from zero at the five percent level of significance.

Table 6: Estimated BEKK GARCH (1,1) Model Germany, Greece, Spain, Portugal

Variable	Coefficient	T-Statistic	Variable	Coefficient	T-Statistic
Transmission of returns 1987-1998			*Transmission of returns 1999-2003*		
GER → GER	0.9664*	96.7349	GER → GER	0.9489*	176.4848
GRE → GRE	0.9730*	256.6483	GRE → GRE	0.9135*	341.8926
GRE → GER	0.0045	0.6393	GRE → GER	0.0002	0.1166
GER → GRE	0.0042	0.7196	GER → GRE	-0.0210*	-6.6532
SPA → SPA	0.9305*	68.8050	SPA → SPA	0.9493*	115.1000
SPA → GER	0.0190	1.9357	SPA → GER	-0.0131	-1.7365
GER → SPA	-0.0326*	-2.3267	GER → SPA	-0.0085	-1.2003
SPA → GRE	0.0059	0.9553	SPA → GRE	-0.0157*	-3.7741
GRE → SPA	-0.0226*	-2.6591	GRE → SPA	0.0001	0.0425
POR → POR	0.8636*	58.8463	POR → POR	0.7357*	49.9331
POR → GER	0.0055	0.5435	POR → GER	-0.0149	-1.4333
GER → POR	0.0191	0.8345	GER → POR	-0.0275	-1.8812
POR → GRE	0.0082	1.3816	POR → GRE	-0.0143*	-4.3108
GRE → POR	0.0566*	5.0662	GRE → POR	-0.0001	-0.0233
POR → SPA	0.0158	1.0589	POR → SPA	0.0103	0.9547
SPA → POR	0.0306	1.1922	SPA → POR	-0.0509*	-2.8087
Transmission of noise 1987-1998			*Transmission of noise 1999-2003*		
GER → GER	0.2786*	7.9137	GER → GER	0.2801*	21.6771
GRE → GRE	0.2127*	14.4276	GRE → GRE	0.5381*	41.4940
GRE → GER	0.0191	1.0137	GRE → GER	-0.0008	-0.1831
GER → GRE	-0.0178	-0.9664	GER → GRE	0.1198*	10.2517
SPA → SPA	0.1920*	6.0539	SPA → SPA	0.2637*	16.6695
SPA → GER	0.0149	0.5384	SPA → GER	0.0568*	3.2496
GER → SPA	0.0180	0.4867	GER → SPA	0.0483*	3.4384
SPA → GRE	0.0049	0.2363	SPA → GRE	0.1098*	6.8868
GRE → SPA	0.0032	0.1558	GRE → SPA	-0.0014	-0.3781
POR → POR	0.3056*	9.5219	POR → POR	0.4839*	23.1879
POR → GER	0.0127	0.5834	POR → GER	0.1217*	9.3967
GER → POR	-0.0336	-0.7837	GER → POR	-0.0117	-0.5266
POR → GRE	-0.0083	-0.4929	POR → GRE	0.1490*	21.3741
GRE → POR	-0.1232*	-4.1931	GRE → POR	0.0018	0.2764
POR → SPA	-0.0206	-0.7786	POR → SPA	0.0301*	2.3876
SPA → POR	0.0267	0.6027	SPA → POR	0.0715*	2.5561
			Diagnostic Statistics		
LR(48) Ho = 0	2823156.74	p-value	0.0000		
Log-likelihood	35931.64				
Observations	4297				

Note: * significant from zero at the five percent level of significance.

Table 7: Estimated BEKK GARCH (1,1) Model Germany, Switzerland, Italy, Austria

Variable	Coefficient	T-Statistic	Variable	Coefficient	T-Statistic
Transmission of returns 1987-1998			*Transmission of returns 1999-2003*		
GER → GER	0.9483*	97.1179	GER → GER	0.9759*	148.4883
SWZ → SWZ	0.9645*	98.7618	SWZ → SWZ	0.9475*	127.3684
SWZ → GER	-0.0171	-1.8117	SWZ → GER	-0.0003	-0.0530
GER → SWZ	0.0466*	3.9681	GER → SWZ	-0.0045	-0.5313
ITA → ITA	0.9454*	98.3794	ITA → ITA	0.9682*	207.6584
ITA → GER	-0.0011	-0.1115	ITA → GER	0.0083	1.0351
GER → ITA	0.0162	1.7664	GER → ITA	0.0030	0.7632
ITA → SWZ	0.0064	0.4592	ITA → SWZ	-0.0365*	-3.3075
SWZ → ITA	-0.0098	-1.1326	SWZ → ITA	-0.0033	-0.8969
AUS → AUS	0.8256*	70.9839	AUS → AUS	0.7777*	75.3152
AUS → GER	0.0351*	4.3406	AUS → GER	-0.0133	-1.3970
GER → AUS	-0.0863*	-3.5562	GER → AUS	-0.1088*	-15.4811
AUS → SWZ	-0.0031	-0.2873	AUS → SWZ	0.0290*	2.4595
SWZ → AUS	-0.0421*	-2.2936	SWZ → AUS	-0.0586*	-10.7175
AUS → ITA	-0.0390*	-4.1634	AUS → ITA	0.0002	0.0425
ITA → AUS	-0.0387	-1.2694	ITA → AUS	-0.0786*	-6.9779
Transmission of noise 1987-1998			*Transmission of noise 1999-2003*		
GER → GER	0.1642*	5.3634	GER → GER	0.1997*	12.4718
SWZ → SWZ	0.1851*	6.6062	SWZ → SWZ	0.2777*	21.0012
SWZ → GER	0.1088*	4.6963	SWZ → GER	0.0443*	2.8796
GER → SWZ	-0.0202	-0.6505	GER → SWZ	0.0621*	3.7279
ITA → ITA	0.2493*	7.9480	ITA → ITA	0.1847*	16.2872
ITA → GER	0.0383	1.0819	ITA → GER	0.0286	1.2068
GER → ITA	-0.0102	-0.3956	GER → ITA	-0.0148	-1.7661
ITA → SWZ	-0.0203	-0.5387	ITA → SWZ	0.1061*	4.5933
SWZ → ITA	0.0094	0.4105	SWZ → ITA	-0.0075	-0.9752
AUS → AUS	0.3514*	17.7577	AUS → AUS	0.5776*	30.6267
AUS → GER	-0.1328*	-7.3544	AUS → GER	0.0558*	3.4343
GER → AUS	0.1271*	3.0444	GER → AUS	0.1836*	11.5738
AUS → SWZ	0.0607*	3.5325	AUS → SWZ	-0.0451*	-2.8746
SWZ → AUS	0.0514	1.8864	SWZ → AUS	0.0853*	6.5062
AUS → ITA	0.1188*	6.0393	AUS → ITA	-0.0024	-0.2635
ITA → AUS	0.0836*	2.0106	ITA → AUS	0.1394*	5.5253
		Diagnostic Statistics			
LR(48) Ho = 0	2253903.45	p-value	0.0000		
Log-likelihood	35739.58				
Observations	4297				

Note: * significant from zero at the five percent level of significance.

Table 8: Estimated BEKK GARCH (1,1) Model Germany, Ireland, UK, Luxembourg

Variable	Coefficient	T-Statistic	Variable	Coefficient	T-Statistic
Transmission of returns 1987-1998			*Transmission of returns 1999-2003*		
GER → GER	1.0438*	84.8578	GER → GER	0.8979*	76.6692
IRL → IRL	0.8408*	62.3352	IRL → IRL	0.6863*	53.2306
IRL → GER	0.0334*	2.2933	IRL → GER	0.1014*	10.8068
GER → IRL	-0.0396	-1.4948	GER → IRL	-0.2581*	-13.3386
UK → UK	0.7647*	36.3696	UK → UK	0.5705*	28.4095
UK → GER	0.1050*	8.5632	UK → GER	-0.0309*	-3.1233
GER → UK	-0.1406*	-5.4544	GER → UK	-0.1789*	-7.6273
UK → IRL	-0.0512	-1.6319	UK → IRL	0.0631*	4.5533
IRL → UK	-0.0203	-0.6738	IRL → UK	-0.0242	-1.0573
LUX → LUX	0.9574*	181.8007	LUX → LUX	0.0000	0.0123
LUX → GER	-0.0078	-1.6191	LUX → GER	0.0000	-1.5303
GER → LUX	0.0388*	3.1406	GER → LUX	-263.8371*	-2.2734
LUX → IRL	-0.0220	-1.6028	LUX → IRL	0.0000	0.7156
IRL → LUX	0.0338*	3.8236	IRL → LUX	-179.3672*	-2.4034
LUX → UK	-0.0337*	-3.9561	LUX → UK	0.0000	0.2761
UK → LUX	0.0413*	3.4506	UK → LUX	-126.3990	-1.0431
Transmission of noise 1987-1998			*Transmission of noise 1999-2003*		
GER → GER	0.1324*	4.7382	GER → GER	0.1925*	29.9526
IRL → IRL	0.1605*	6.0223	IRL → IRL	0.3028*	29.1532
IRL → GER	-0.0227	-0.9380	IRL → GER	-0.0231*	-4.0362
GER → IRL	-0.0212	-0.4953	GER → IRL	0.2215*	16.9514
UK → UK	0.4061*	9.4167	UK → UK	0.2290*	28.7053
UK → GER	-0.0648*	-2.5463	UK → GER	0.0277*	5.3949
GER → UK	0.1846*	4.0956	GER → UK	-0.0262*	-2.4570
UK → IRL	-0.0068	-0.1496	UK → IRL	-0.0360*	-3.9493
IRL → UK	0.1179*	3.1609	IRL → UK	-0.0047	-0.5696
LUX → LUX	0.2723*	15.9034	LUX → LUX	-0.0118	-0.2695
LUX → GER	0.1400*	8.9166	LUX → GER	0.0000*	2.0708
GER → LUX	-0.0306	-0.9941	GER → LUX	-496468.94	-0.5982
LUX → IRL	0.0115	0.4174	LUX → IRL	0.0000*	2.1047
IRL → LUX	0.0170	1.0101	IRL → LUX	-342134.19	-0.6030
LUX → UK	-0.0337	-1.4465	LUX → UK	0.0000	1.3428
UK → LUX	0.0214	0.7913	UK → LUX	-227058.23	-0.5066
		Diagnostic Statistics			
LR(48) Ho = 0	938342.81	p-value	0.0000		
Log-likelihood	91073.90				
Observations	4297				

Note: * significant from zero at the five percent level of significance.

Appendix 1 – Expansion of BEKK GARCH model

An expansion of the BEKK GARCH parameterisation equation [3] shows that the bivariate GARCH (p,q) model takes the form:

$$\begin{bmatrix} h_{11,t+1} & \\ h_{12,t+1} & h_{22,t+1} \end{bmatrix}_t = \begin{bmatrix} c^*_{11} & c^*_{12} \\ c^*_{21} & c^*_{22} \end{bmatrix} * \begin{bmatrix} c_{11} & c_{12} \\ c_{21} & c_{22} \end{bmatrix} + \begin{bmatrix} b_{11} & b_{12} \\ b_{21} & b_{22} \end{bmatrix} * \begin{bmatrix} h_{11,t+1} & \\ h_{12,t+1} & h_{22,t+1} \end{bmatrix}_t * \begin{bmatrix} b_{11} & b_{12} \\ b_{21} & b_{22} \end{bmatrix} +$$

$$= + \begin{bmatrix} a_{11} & a_{21} \\ a_{12} & a_{22} \end{bmatrix} * \begin{bmatrix} \varepsilon_{1,t} \\ \varepsilon_{2,t} \end{bmatrix} * \begin{bmatrix} \varepsilon_{1,t} & \varepsilon_{2,t} \end{bmatrix} * \begin{bmatrix} \varepsilon_{11} & \alpha_{12} \\ \alpha_{21} & \alpha_{22} \end{bmatrix}$$

Where,
$h_{11,\ t+1}$ = the volatility for the first portfolio of equities in period t+1,
$h_{22,\ t+1}$ = the volatility for the second portfolio of equities in period t+1,
$h_{12,\ t+1}$ = the volatility spillover from the second portfolio of equities to the first portfolio of equities in the period t+1.
c_{11} = the constant coefficient for the first portfolio of equities in period t,
c_{12} = the constant coefficient for the volatility spillovers between the two portfolios of equities in period t, and
c_{22} = the constant coefficient for the second portfolio of equities in period t.
b_{11} = the volatility coefficient for the first portfolio of equities in period t
b_{21} = the volatility spillover from the first portfolio of equities to the second portfolio of equities in period t.
b_{22} = the volatility coefficient for the second portfolio of equities in period t.
α_{11} = the squared coefficient of error term for the first portfolio equities in period t.
α_{21} = the coefficient of error transmission from the first portfolio of equities to the second portfolio of equities in period t.
α_{12} = the coefficient of error transmission from the second portfolio of equities to the first portfolio of equities in period t.
α_{22} = the squared coefficient of the error term for the second portfolio of the equities in period t.
$\varepsilon_{1,t}$ = the error term in the first portfolio of equities in period t,ε_2 is the error term in the second portfolio of equities in period t.

Table A1: European Stock Exchange Indexes & Optimal Number of Lags

COUNTRY	STOCK EXCHANGE INDEX	Optimal lag
AUSTRIA	WIENER BOERSE INDEX (WBI) - PRICE INDEX	1
BELGIUM	BRUSSELS ALL SHARE - PRICE INDEX	3
DENMARK	COPENHAGEN KFX - PRICE INDEX	1
FINLAND	HEX GENERAL - PRICE INDEX	1
FRANCE	SBF 250 - PRICE INDEX	1
GERMANY	DAX 30 PERFORMANCE - PRICE INDEX	0
GREECE	ATHENS SE GENERAL - PRICE INDEX	1
IRELAND	IRELAND - DATASTREAM MARKET	1
ITALY	ITALY - DATASTREAM MARKET	1
LUXEMBOURG	LUXEMBOURG SE LUXX - PRICE INDEX	5
NETHERLANDS	NETHERLANDS - DATASTREAM MARKET	0
PORTUGAL	PORTUGAL PSI GENERAL - PRICE INDEX	1
SPAIN	SPAIN - DATASTREAM MARKET	1
SWEDEN	STOCKHOLMSBORSEN ALL SHARE (SAX) - PRICE INDEX	1
UK	FTSE 100 - PRICE INDEX	0
SWITZERLAND	SWISS PERFORMANCE - PRICE INDEX	0
NORWAY	OSLO SE INDUSTRY DS-CALCULATED - PRICE INDEX	0
USA	NYSE COMPOSITE - PRICE INDEX	0