Quantifying domestic and international linkage of financial assets

Bachelor Thesis

Econometrics and Operations Research

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Abstract

In this paper, we research the linkage of domestic and international financial assets by analyzing the spillovers between short-term interest rates, bond yields and stock returns from American and European asset markets. We do this using two methods. The first is based on estimating the significance of the structural parameters of a vector autoregressive model that measure the contemporaneous relation between these assets. The second relies on computing forecast error variance decompositions to create spillover indices with which the relations of interest can be quantified. Our results show that in general transmission within individual asset types is the strongest and that US assets tend to influence European assets more than vice versa. Furthermore, spillovers between asset classes increase during financial crises and recessions compared to tranquil periods.

Contents

1 Introduction

Since the advent of globalization international financial markets have grown increasingly intertwined. A prime example of this is the 2008 financial crisis, when subprime lending in the American mortgage market lead to a crash, resulting in subsequent crises in both domestic and international asset markets. Consequently, considerable research has been devoted to analyzing the complexities and interdependence of financial markets within and between countries.

Early papers regarding transmission across assets focused on investigating relations between domestic assets. For example, Shiller and Beltratti (1992) and Barsky (1989) have shown generally positive linkages between US equity and bond markets using low-frequency data. Interestingly, Rigobon and Sack (2003) discovered that the direction of the transmission process might be time-variant. Meaning that the results of Barsky (1989) and Shiller and Beltratti (1992) might not be applicable when either stock prices or bond rates are dominant during a certain period. Indeed, more recently Baele et al. (2007) have shown negative correlation between stock and bond returns. Pertaining to the research of international transmission, papers that initially focused on this topic did so by analyzing a single asset in isolation. To name a few, Hamao et al. (1990) and Lin et al. (1994) used reduced-form GARCH models to conclude that there are spillovers from the US equity market to those of the UK and Japan. Regarding foreign exchange markets, Andersen and Bollerslev (1998) and Engle et al. (1990) detect significant spillovers among said markets. Two similar papers that both take into account multiple asset classes and international markets are those of Andersen and Bollerslev (1998) and Ehrmann et al. (2011). Both papers research contemporaneous linkage across international markets. However, Andersen and Bollerslev (1998) use higher frequency data compared to Ehrmann et al. (2011) limiting the availability. In addition, their sample size is much smaller and they estimate subsystems separately rather than the entire model as a whole. Therefore, Ehrmann et al. (2011) in general is more advanced and consequently is of particular interest to us. The main objective of their paper was to provide a framework with which transmission across multiple international markets can be quantified. They did so by using a structural vector autoregressive model (SVAR) to estimate the magnitude and significance of the cross-market parameters. They applied this framework to American and European short-term interest rate, equity, and bond markets and concluded that indeed a considerable amount of European market movement can be explained through American and vice versa. Their methodology requires certain assumptions however, that may not hold.

As an alternative to using parameter estimates to measure the level of financial spillovers, Diebold and Yilmaz (2009) introduced a spillover index for VAR models that utilizes variance decompositions and illustrated its usefulness by computing the spillovers between international equity markets. In their subsequent paper Diebold and Yilmaz (2012), they improved upon their existing spillovers by allowing for more detailed analysis and resolving some of the issues the previous index suffered from. However, rather than using international data, this time they applied their index by using only domestic American assets. While there have been earlier papers pertaining to volatility spillovers such as those of Edwards and Susmel (2001) and M. King et al. (1994), theirs is more tractable and allows for the production of continuous time-varying indices.

In this paper, we further research transmission among domestic and international markets by first attempting to reaffirm the results of Ehrmann et al. (2011) through replicating parts of their methodology. Then we contribute to the existing strand of literature by approaching the analysis of international transmission differently than what has been done by Ehrmann et al. (2011) and other existing papers. We do so by analyzing the domestic and international linkage between multiple financial assets using the spillover index proposed in Diebold and Yilmaz (2012), which has not yet been used for this purpose. We apply this method to the reduced-form VAR model of Ehrmann et al. (2011) and their respective variables.

Our results show significant spillovers across markets and for bonds and stocks that transmission occurs mostly within the same asset class, while short-term interest rates are more affected by domestic bond yields. Furthermore, they show that the transmission effect from the US to the EU is stronger than the other way around and finally that spillovers increase during times of economic downturn. Our research underscores the importance of the dependence of international markets and advises investors to take these relations into account.

The remainder of the paper is structured as follows. In section 2 we go into the details of the methodology as in Ehrmann et al. (2011). In section 3 we describe the spillover index of Diebold and Yilmaz (2012) and explain how we apply this to the VAR model of Ehrmann et al. (2011). In section 4 we present the data we use and the source. In section 5 we showcase the results and in section 6 we draw conclusions and discuss the limitations of our paper and suggest avenues for future research.

2 Ehrmann et al. (2011) framework

2.1 The model

Firstly, to analyze the contemporaneous effect of assets across financial markets we revisit the paper of Ehrmann et al. (2011). In their paper, they construct a SVAR model containing seven European and American assets. Namely, from each of these two economies, they include the short-term interest rate r_t, the long-term interest or bond yields b_t and the stock returns s_t. Arranging these in a vector $y_t = (r_t^{US}, b_t^{US}, s_t^{US}, r_t^{EU}, b_t^{EU}, s_t^{EU}, e_t)$ gives the following VAR model in its structural form.

$$Ay_t = \zeta + \Pi(L)y_{t-1} + \Phi(L)z_t + \mu_t \tag{1}$$

Where z_t is a vector of exogenous variables that controls for common shocks. The parameter matrices $\Pi(L)$ captures the lagged effects of the endogenous variables and $\Phi(L)$ captures both the contemporaneous and lagged effects of the exogenous variables. Here (L) indicates the lag polynomial. The parameters of chief interest are those that measure the contemporaneous transmission and are contained in the 7x7 matrix A, which is given as follows.

$$A = \begin{pmatrix} 1 & \alpha_{12} & \alpha_{13} & \beta_{14} & \beta_{15} & \beta_{16} & \gamma_{17} \\ \alpha_{21} & 1 & \alpha_{23} & \beta_{24} & \beta_{25} & \beta_{26} & \gamma_{27} \\ \alpha_{31} & \alpha_{32} & 1 & \beta_{34} & \beta_{35} & \beta_{36} & \gamma_{37} \\ \beta_{41} & \beta_{42} & \beta_{43} & 1 & \alpha_{45} & \alpha_{46} & \gamma_{47} \\ \beta_{51} & \beta_{52} & \beta_{53} & \alpha_{54} & 1 & \alpha_{56} & \gamma_{57} \\ \beta_{61} & \beta_{62} & \beta_{63} & \alpha_{64} & \alpha_{65} & 1 & \gamma_{67} \\ \gamma_{71} & \gamma_{72} & \gamma_{73} & \gamma_{74} & \gamma_{75} & \gamma_{76} & 1 \end{pmatrix} \tag{2}$$

As A is multiplied on the left-hand side of equation (1), the parameters α represent the domestic spillovers, the parameters β equal the international transmission and the γ parameters the transmission to and from the euro-dollar exchange rate. The elements of the matrix are represented in basis points, meaning that element ij is equal to the percentage increase in variable i as a result of a 1% increase of variable j. Clearly then the diagonal elements are 1. Since this matrix is not diagonal the parameters are simultaneously determined and therefore endogenous. Consequently, the true values of these parameters cannot be estimated accurately through standard techniques, meaning they are unidentified. The first step towards identification is to rewrite the structural

VAR in equation (1) in its reduced-form, which results in the following.

$$y_t = A^{-1}\zeta + A^{-1}\Pi(L)y_{t-1} + A^{-1}\Phi(L)z_t + A^{-1}\mu_t \quad (3)$$

$$y_t = C_0 + B_0(L)y_{t-1} + B_1(L)z_t + \epsilon_t \quad (4)$$

Although the parameters of the reduced-form VAR can be estimated through OLS, they bear no economic interpretation and therefore it is still necessary to recover the structural parameters.

2.2 Identification through heteroskedasticity

Comparing equation (2) to (3) and (4) we can see that the structural residuals are related to the reduced-form residuals through A^{-1} and therefore it holds that $A^{-1}\mu_t = \epsilon_t$. From this, it follows that we can obtain the parameters of A through solving the equation $A'\Sigma A = \Omega$, where Ω is the covariance matrix of the reduced-form residuals and Σ the covariance matrix of the structural shocks. However, because in general, the covariance matrix of the reduced-form provides fewer equations than the number of unknown parameters, the system is undetermined. Possible solutions to the problem are sign restrictions as discussed in Fry and Pagan (2010) or exclusion restrictions as used in Kilian (2009). Neither of these can always be justified however, according to Rigobon (2003). For example in our case sign restrictions would result in a parameter space that is too large and regarding exclusion restrictions, there are no variables that clearly should be excluded. Therefore instead Ehrmann et al. (2011) use Identification through Heteroksedasticity (IH) developed by Rigobon (2003) to address the problem. The involved technicalities of this method are given in appendix A. Here to shortly summarize, IH relies on heteroskedasticity in financial variables to solve the problem at hand. Because under the assumptions of stable structural parameters and zero correlation between the shocks, each new heteroskedastic regime adds more equations than unknowns. In fact, two different regimes are sufficient to identify our model.

However, usually there are more heteroskedastic regimes present than necessary, which results in overidentifcation. To limit the possible parameter space Ehrmann et al. (2011) impose a number of overidentification restrictions based on the economic interpretation of the equations. Namely, they assume that the short-term interest rate can be regarded as the markets expectation of the short to medium term development of monetary policy, the long-term interest rate or bond rate represents the expectation of the inflation rate, the stock returns can be understood as a proxy for domestic demand and the changes in exchange rate can be seen as changes in demand between the two regions. Relying on these interpretations Ehrmann et al. (2011) first impose the following restrictions on domestic transmissions. Note that since we multiplied A on the left-hand side of equation (1) the sign of the restrictions are the opposite of what we expect.

1. α_{12}, $\alpha_{45} < 0$, because we expect an inflationary shock to result in a tightening of monetary policies and therefore an increase in short-term rates.

2. α_{31}, $\alpha_{64} > 0$, since a rise in the discount price is caused by an increase in short-term interest rates, which in turn decreases the demand for goods and consequently should result in lower equity prices.

3. α_{32}, $\alpha_{65} > 0$, similarly long-term rates should have the same effect and ergo also cause a decline in equity prices.

Before we continue with the restrictions on international transmission, Ehrmann et al. (2011) posit that A solely captures the direct effects, while A^{-1} includes both direct and indirect spillovers. Indirect spillovers are defined as effects from one asset to another that occur through a third party asset. For example, variable 1 positively affects variable 2, which positively affects variable 3. An increase in variable 1 would consequently result in an increase in variable 3 through the second variable. Because they assume that these arguments for the first 3 sets of restrictions should hold for both direct and overall effects they restrict A^{-1} equivalently. Continuing with international transmission and effects of exchange rates, the parameters are restricted in the following way.

1. β_{14}, β_{41}, β_{25}, $\beta_{52} < 0$, because domestic and international money and bond markets should be positively correlated.

2. As a result of all variables being expressed in basis points, they assume that a domestic shock should not have an augmented effect on markets abroad. Therefore, $0 <| \beta_{14} |, | \beta_{41} |, | \beta_{25} |, | \beta_{52} |, | \beta_{36} |, | \beta_{63} |< 1$

3. $\gamma_{72} > 0$,$\gamma_{75} < 0$, because they assume that an increase of the long rates of a certain area results in a shift towards the assets of that region. Causing an appreciation of the exchange rate relative towards the other currency.

These assumptions can be considered reasonable as they are supported by significant empirical evidence. Finally, since the structural matrix A is only supposed to capture the effects of direct spillovers, they impose zero restrictions on the international transmission from an asset to that of another type. The full of set of restrictions written into matrix form is given in appendix C.

2.3 Estimation

As what has been done in Ehrmann et al. (2011) we first estimate the VAR in equation (3) using OLS by including 6 lags of both the endogenous and exogenous variables. Using the residuals of this regression we compute the variances using a rolling window of 20 2-day observations. An asset is considered to be in the elevated state when the variance of its residuals exceeds its mean by more than a single standard deviation. Otherwise, it is said to be in the tranquil state. A regime is defined as when a single asset is in its elevated state for more than 16 consecutive observations while all the other assets are in their tranquil state. Using this we define 8 heteroskedastic regimes. One for each individual asset and a final one where all assets are in their tranquil state. Recall from section 2.2 that we cannot recover the structural parameters by solving the unidentified system of equations $A'\Sigma A = \Omega$, where Ω is known. However, because we now have defined 8 distinct heteroskedastic regimes we can instead solve for $A'\Sigma_i A = \Omega_i$. Where Σ_i is the covariance matrix of the structural innovations for each regime and Ω_i is the covariance matrix of the reduced-form residuals for each regime. Because we have defined more regimes than necessary, we needed 2, the system is overidentified and we cannot solve it exactly. Instead we minimize the following distance.

$$\begin{aligned} \min \quad & g'g \text{ with } g = \text{vec}(A'\Sigma_i A - \Omega_i) \\ \text{s.t.} \quad & \Sigma_i \text{ is diagonal} \\ & A \text{ restrictions} \end{aligned} \tag{5}$$

This boils down to minimizing the squared difference between each element of $A'\Sigma_i A$ and the corresponding element in Ω_i.

The last step is to bootstrap the significance of the parameters. We do this by using the estimated structural parameters and covariance matrices to generate new artificial data by sampling the error variances with replacement from the covariance matrices of the structural shocks from the different regimes. In each bootstrap replication we estimate the model using the newly created data. The significance is computed as the percentage of estimates that have the opposite sign of the point estimate.

3 Spillover index

To identify the structural parameters Ehrmann et al. (2011) have imposed overidentifying restrictions based on several assumptions regarding the economic interpretation of the equations. Assumptions that, while supported by empirical evidence, may not hold. Diebold and Yilmaz (2009) first introduced an index for measuring volatility spillovers. Their method differs from that of Ehrmann et al. (2011) in that it relies on measuring forecast error variance decomposition rather than the analysis of the parameter estimates. This approach does not require the retrieval of the structural parameters and ergo the assumptions Ehrmann et al. (2011) made are not necessary. This index has as another advantage that it allows for the analysis of among others trends and cycles of financial transmission, while the framework of Ehrmann et al. (2011) only results in a single estimate for the entire sample. However, because Diebold and Yilmaz (2009) use Cholesky decompositions to orthogonalize the error terms before computing the variance decompositions the decompositions depend on the order of the variables. Consequently, they improve on this by introducing a new spillover index in their ensuing paper Diebold and Yilmaz (2012) that does not suffer from the same problem. While in both papers they used this index exclusively to measure volatility spillover it can be applied to a variety of variables including asset returns, which we do.

3.1 Forecast Error Variance Decomposition

Suppose that we have the following covariance-stationary vector autoregressive model.

$$y_t = \sum_{i=i}^{p} \Phi_i y_{t-i} + \epsilon_t \tag{6}$$

Where y_t is a vector of m simultaneously determined variables, Φ_i are the related autoregressive parameter matrices and ϵ_t are i.i.d. innovations. Under the assumption that the y_t are covariance-stationary then equation (6) can be rewritten into the infinite moving average (MA) representation given as follow.

$$y_t = \sum_{i=0}^{\infty} A_i \epsilon_{t-i} \tag{7}$$

Where ϵ_t is the same as in equation (6) and the $m \times m$ matrices A_i are related through the recursion:

$$A_i = \zeta_1 A_{i-1} + \zeta_i A_{i-2} +, ..., +\zeta_p A_{i-p} \tag{8}$$

Variance decompositions indicate the proportion of the forecast error variance of a variable that is explained through shocks to other variables. To obtain variance decompositions from the moving average form it is necessary for the innovations to be orthogonal, which is generally not the case. As mentioned before, the innovations can be orthogonalized through Cholesky decomposition however these are order-dependent. Therefore, in Diebold and Yilmaz (2012) they utilize the variance decompositions as in Koop et al. (1996) and Pesaran and Shin (1998), which are indifferent to ordering. Define $\theta^g(H)$ as the matrix of variance decompositions. Then as in Pesaran and Shin (1998) the share of H-step forecast error variance of y_i that is a result of a shock in y_j is given by the following equation.

$$\theta_{ij}^g(H) = \frac{\sigma_{jj}^{-1} \sum_{h=0}^{H-1} (e_i' A_h \Sigma e_j)^2}{\sum_{h=0}^{H-1} (e_i' A_h \Sigma e_j)} \tag{9}$$

Here Σ is the covariance matrix of the innovations in equation (6), A_h is the H$^{\text{th}}$ moving average parameter matrix in equation (7), σ_{jj} is the standard deviation of the innovation of the jth equation in the VAR model and e_i is a zero vector of which the i^{th} element is 1, such that it selects the element of which we want to compute the variance decomposition. We compute these variance decompositions for the reduced-form model in equation (3) and (4) using the same assets. However, we omit the exogenous variables, because as stated in Ehrmann et al. (2011), they are included solely for the purpose of orthogonalizing the error terms as this is a requirement for identification through heteroskedasticity. However, since the decomposition by construction already achieves orthogonality the inclusion of exogenous variables is no longer necessary. In addition, the matrix of exogenous variables is near-singular for smaller samples, which will prove troublesome when later in this paper we analyze the development of the spillovers over the years through rolling window estimates of the VAR model.

3.2 Spillover index

Using the method in the previous subsection, although the errors are indeed orthogonalized they do not sum up to 1, meaning $\sum_{j=1}^{m} \theta_{ij}^g(H) \neq 1$. In order to interpret them as percentages Diebold and Yilmaz (2012) normalize them by dividing each element of the matrix $\theta^g(H)$ by the sum of the entire row it is in. Written as a formula we have:

$$\tilde{\theta}_{ij}^g(H) = \frac{\theta_{ij}^g(H)}{\sum_{j=1}^{m} \theta_{ij}^g(H)} \tag{10}$$

Obviously doing this results in $\sum_{j=1}^{N} \tilde{\theta}_{ij}^g(H)$ being equal to 1. These normalized variance decompositions are the first and basis of the spillovers that are proposed in Diebold and Yilmaz (2012).

3.3 Total spillover index

Utilizing the spillovers from 3.2, Diebold and Yilmaz (2012) compute the total spillovers by summing all the off diagonal elements of the normalized variance decomposition or spillover matrix $\tilde{\theta}_{ij}^g(H)$

and divide it by the sum of all decompositions. This results in the following.

$$S^G(H) = \frac{\sum_{i,j=1;i\neq j}^{m} \tilde{\theta}_{ij}^{g}(H)}{\sum_{i,j=1}^{m} \tilde{\theta}_{ij}^{g}(H)} \cdot 100 = \frac{\sum_{i,j=1;i\neq j}^{m} \tilde{\theta}_{ij}^{g}(H)}{m} \cdot 100 \tag{11}$$

The second equality holds because the sum of all elements of $\tilde{\theta}_{ij}^{g}(H)$ by construction is equal to the number of variables m. The total spillovers can be interpreted as the total variance that is explained through other variables across all variables.

3.4 Directional spillovers

In contrast to the initial spillover measure in Diebold and Yilmaz (2009), the current one, in addition, allows for the computation of the directional spillovers variable i received from all other variables $j \neq i$, which is given as follows.

$$S_{i\cdot}^G(H) = \frac{\sum_{j=1;i\neq j}^{m} \tilde{\theta}_{ij}^{g}(H)}{\sum_{i,j=1}^{m} \tilde{\theta}_{ij}^{g}(H)} \cdot 100 = \frac{\sum_{j=1;i\neq j}^{m} \tilde{\theta}_{ij}^{g}(H)}{m} \cdot 100 \tag{12}$$

Similarly, we can compute the total directional spillovers from variable i transferred to all other variables $j \neq i$, which written as formula is equal to:

$$S_{\cdot i}^G(H) = \frac{\sum_{j=1;i\neq j}^{m} \tilde{\theta}_{ji}^{g}(H)}{\sum_{i,j=1}^{m} \tilde{\theta}_{ji}^{g}(H)} \cdot 100 = \frac{\sum_{j=1;i\neq j}^{m} \tilde{\theta}_{ji}^{g}(H)}{m} \cdot 100 \tag{13}$$

3.5 Net spillovers

Additionally, it is possible for us to measure the net spillover from one variable to another. This is equivalent to the difference between what market i has transmitted to all other markets and what it has received from the others. This is given by:

$$S_i^g(H) = S_{\cdot i}^g(H) - S_{i\cdot}^g(H) \tag{14}$$

In addition to analyzing the net spillovers for a single market relative to all other markets, we can also analyze the net spillover between two markets. This net pairwise spillover is given as follows.

$$S_{ij}^G(H) = \left(\frac{\tilde{\theta}_{ji}^{g}(H)}{\sum_{i,k=1}^{m} \tilde{\theta}_{ik}^{g}(H)} - \frac{\tilde{\theta}_{ij}^{g}(H)}{\sum_{i,k=1}^{m} \tilde{\theta}_{jk}^{g}(H)} \right) \cdot 100 = \left(\frac{\tilde{\theta}_{ji}^{g}(H) - \tilde{\theta}_{ij}^{g}(H)}{m} \right) \cdot 100 \tag{15}$$

This is simply the difference between the spillovers emitted and received from market i and j.

3.6 Development of spillovers

Aside from computing the average of the spillovers over our entire sample, it is interesting to investigate the development of the spillovers throughout the years. Due to a myriad of events, such as the increased movement of labor and capital, the faster travel of news due to the internet and the introduction of the Euro it can be expected that international linkage has increased. To illustrate this development similarly to as in Diebold and Yilmaz (2012) we use a moving window of 200 observations to estimate the parameters of our VAR and use these to compute the variance decomposition and to plot the spillovers over the sample.

4 Data

The aim of the first part of this paper is to replicate the methodology and the results of Ehrmann et al. (2011) and therefore we use the same data set. The source for the time series they have used is Datastream, but the entire collection is provided by the authors and can be found in the Journal of Applied Econometrics. In our research, the purpose is also to highlight the interdependencies of the same group of assets. Consequently, we use the same set of data to compute the spillover indices, however, we exclude the exogenous series for the reasons mentioned in the methodology.

The sample ranges from 1989 to 2008. To serve as the short-term interest rates, bond rate, and the stock returns in the US they have used, the 3-month Treasury bill, the 10-year Treasury bond rate, and the S&P 500 stock market index respectively. Similarly, to represent the European bond and equity markets they have used the 10-year German government bonds and S&P Euro index respectively. However, due to the introduction of the Euro in 1999 for the short-term interest rate they have used 2 separate series. Namely, for rates before 1999 they have used the FIBOR rate and for data after they have used the EURIBOR rate. While the short-term interest and bond rates are already given in returns, the stock indices and exchange rates are not. To transform these we take the first difference of the natural logarithm and multiply these by 100.

An issue that arises from using data on assets is that of different trading hours. As a result of the time difference European markets trade earlier than their American counterparts. Consequently, innovations in European assets are transmitted to American markets on the same day, while the opposite obviously does not hold true. Instead, innovations in the American markets do not exert influence on European assets until the day after when their markets open again. To diminish this problem Ehrmann et al. (2011) have opted to use 2-day returns for all series.

Recall that a crucial assumption for IH is zero correlation between the structural shocks. This condition might be violated if the shocks in the time series are the result of common shocks. Consequently, to manage these common shocks, Ehrmann et al. (2011) first include an array of macroeconomic news in the Euro area and the US to function as exogenous variables. This news consists of 'unexpected' news and is determined as the discrepancy between the actual announcement and the previously held expectations. The expectations are based on a survey composed by the Money Marketing Service. Furthermore, because based on empirical data, European markets show insufficient reaction to news announcements, it could be possible that these variables alone do not completely capture the common shocks. Therefore, Ehrmann et al. (2011) in addition include fluctuations in oil prices.

5 Results

This section presents the empirical results from the two different approaches to measuring transmission across assets. First, in section 5.1, we present the estimation results from applying the Ehrmann et al. (2011) framework. The remainder of section 5 showcases the results from the second method, in which we applied the spillover index of Diebold and Yilmaz (2012).

5.1 Ehrmann et al. (2011)

In this subsection, we primarily compare the results of Ehrmann et al. (2011) and the results of our replication shown in Table 1. For the sake of brevity, we will not go into the details of the economic interpretation of these results, since these can be found in great detail in Ehrmann et al. (2011). For direct domestic and international transmission, the signs of the parameters are generally the same with varying magnitudes. Notable exceptions are β_{63} and β_{36}. These measure the transmission between European and American equity markets and for both it holds that the sign is the opposite of that in Ehrmann et al. (2011). The effects of exchange rate seem to not closely match that of the comparison paper. These changes can be attributed to a number of reasons. First, a heteroskedastic regime was defined when a single asset was in the elevated state for at least 16 consecutive days, while all others remained in the tranquil state. Ω_i in equation (5) was computed as the covariance of the observations in a period for which the requirements of a regime were satisfied. However, there were various periods for which these requirements were fulfilled and it could be possible that different periods were chosen as regimes. Furthermore, in their paper Ehrmann et al. (2011) they did not provide starting values nor the algorithm used

Table 1: Structural parameter estimates illustrating the direct effects and bootstrap results

	Point estimate	Bootstrap		
		Mean	SD	p-value
Domestic transmission				
USA				
α_{12}	-0.1242	-0.2747	0.2979	0.0000
α_{13}	0.2851	-1.0393	3.0624	0.7067
α_{21}	-0.2653	0.1200	0.8518	0.5067
α_{23}	-0.9227	-1.8140	3.2134	0.2133
α_{31}	0.0158	0.0403	0.0407	0.0000
α_{32}	0.0235	0.0346	0.0341	0.0000
Euro area				
α_{45}	-0.1292	-0.5110	0.43538	0.0000
α_{46}	-0.3249	-1.9670	2.7302	0.2533
α_{54}	-0.2371	-0.1072	0.5060	0.3200
α_{64}	0.0105	0.0208	0.0245	0.0000
α_{65}	0.0027	0.0229	0.0244	0.0000
International transmission				
USA to Euro area				
β_{41}	-0.1269	-0.3131	0.2797	0.0000
β_{52}	-0.1855	-0.1418	0.1841	0.0000
β_{63}	0.3065	0.0969	0.3399	0.4667
Euro area to USA				
β_{14}	-0.0712	-0.1471	0.1383	0.0000
β_{25}	-0.1808	-0.1940	0.2201	0.0000
β_{36}	0.2881	0.4936	0.5102	0.2133
Exchange rate effects				
γ_{17}	-0.9772	0.0834	1.5655	0.4133
γ_{27}	-3.4273	0.0350	2.0012	0.5733
γ_{37}	0.0434	-0.0337	0.1942	0.4667
γ_{47}	1.3346	0.0254	1.8960	0.4800
γ_{57}	-0.1427	-0.0331	2.2521	0.5467
γ_{67}	-0.1626	0.0405	0.2103	0.5733
γ_{71}	0.0658	-0.0563	0.2479	0.5200
γ_{72}	0.1127	0.1466	0.1415	0.0000
γ_{73}	-0.9058	0.0720	2.62200	0.4933
γ_{74}	-0.0180	0.0155	0.1624	0.5733
γ_{75}	-0.0676	-0.889	0.0880	0.0000
γ_{76}	0.7686	0.7607	2.2051	0.6800

for the minimization. Both of these are provided in our code, for which instructions are provided in appendix F. Pertaining to the bootstrapped significance. To ease computational time we have only used 75 replications, which is a small number. Consequently, the standard deviations of our estimated parameters are considerably greater than that of Ehrmann et al. (2011) and therefore our p-values are also generally larger. The overall effects are obtained by simply inverting A, the matrix of structural parameters. The results of these are provided in appendix B. It seems that for some reduced-form parameters, through possibly poorly estimated values in the structural form or errors in the bootstrap, even greater deviations occur in the reduced-form. Resulting in an extremely high standard-deviation.

5.2 Full sample spillovers

The spillover results are presented in Table 2. the ijth entry represents the spillover of variable i received from variable j, while the final column shows the total amount of spillovers received from other markets and the last row showcases the total spillovers transmitted to other markets. All results in this section use a forecast horizon of 10 observations. Firstly, from the table we can

Table 2: Spillover table in percentages, entry i, j shows the spillover of asset i received by asset j

	r^{us}	b^{us}	s^{us}	r^{eu}	b^{eu}	s^{eu}	e	Directional received
r^{us}	83.52	11.24	2.27	0.09	1.11	1.2	0.58	16.48
b^{us}	7.34	81.67	0.02	0.06	9.15	0.18	1.59	18.33
s^{us}	0.85	0.24	81.72	0.14	0.47	15.82	0.75	18.28
r^{eu}	0.95	1.44	0.05	90.61	6.76	0.18	0.03	9.38
b^{eu}	1.35	29.26	0.98	1.14	67.79	0.10	0.26	32.21
s^{eu}	0.62	0.21	29.89	0.32	0.07	63.02	5.87	36.98
e	0.54	1.81	0.63	0.15	0.61	11.22	85.04	14.96
Directional transmitted	11.65	44.20	32.96	1.89	18.16	28.70	9.05	total spillover = 26.06

see that the spillovers between American and European short-term interests are very low. With shocks in European short-term interest rates only amounting to 0.09% of the error variance of US short-term interest rates. It seems that short-term interests rates are more related to domestic bond yields as the spillovers are considerably larger. Goode and Birnbaum (1959) show that indeed domestic short and long-term interest rates or bond yields are closely connected and state that long-term interest rates are a reflection of future short-term interests. The parameter that measures the direct effect between European and American short-term interest in Ehrmann et al. (2011) is also not significant, while the parameter for the relation between American bonds and short-term interest is. However, both these parameters that measure the total effect are significant. In contrast to the transmission of international short-term interest rates, for both bond yields and stock returns, there were appreciable amounts of spillovers between European and American markets. For example, 29.89% of the variance in European stocks were due to shocks in American stock returns. Another noteworthy result is that there were significantly more spillovers from the US bond and stock markets to European than vice versa, as we can see from the directional spillovers

[1]. For example, American bonds contributed 29.26% to European bonds, while the opposite effect is only 9.15%. Furthermore, the exchange rate seems to both contribute and receive little spillovers from other assets, except for from European stocks. There appears to be no clear reason for this remarkable result. Although, Ehrmann et al. (2011) have shown that European equity receives significantly more spillovers from the exchange rate than American, which is also shown in our results, the opposite does not hold true based on their results. Finally, the total spillovers of 26.06 % indicate the average spillovers over our entire sample and across all assets and the exchange rate. This number states that of all the variation in asset returns on average 26.06% were caused by other assets. These results, in general, are in alignment with what we would have expected based on the results in Ehrmann et al. (2011). Importantly, we reaffirm the result that spillovers primarily occur from within one asset type and that American markets affect European more than vice versa. However, our results show minor spillovers from short-term interest rates to other assets. One important result of Ehrmann et al. (2011) that our spillover table does not support is that of significant international cross-market spillovers. The greatest of these spillovers in Table 2 is from American bonds to European short-term interest rate, which is only 1.44%.

5.3 Development of total spillovers

Figure 1 shows the level of total spillovers throughout the years of our sample. We can see that in the decade leading up to the 21st century the spillovers varied between approximately 30% and 50% with a positive spike in 1991. Diebold and Yilmaz (2012) posited that spillovers increase during times of crisis. Therefore this period of high spillovers may be attributed to the recession that was widespread among western countries in the early 90s. Continuing with our spillovers, at the inception of the 2000s the total spillovers surged, reaching almost 60%. The reason for this is the burst of the dot-com bubble on March 11th of 2000 that lasted till late 2002. The ensuing years are marked by relatively low spillovers again until 2007, when due to subprime lending in the US the spillovers increased again up until the collapse of the Lehman brothers in 2008, when the spillovers peaked at over 55% at the end of our sample. The main conclusion we can draw from this plot is that total international spillovers come in cycles. Namely, spillovers increase substantially during crises and then return to lower levels until the next crisis, which is in line with the results

[1]In Table 2, the spillover table, of Diebold and Yilmaz (2012) the directional spillovers were not divided by the number of variables, despite this being specified in the formula, while for the remainder of the paper they did adhere to the formula. No particular reason was given for this nevertheless we do the same, as dividing by this constant does not change the interpretation of the results in a meaningful way.

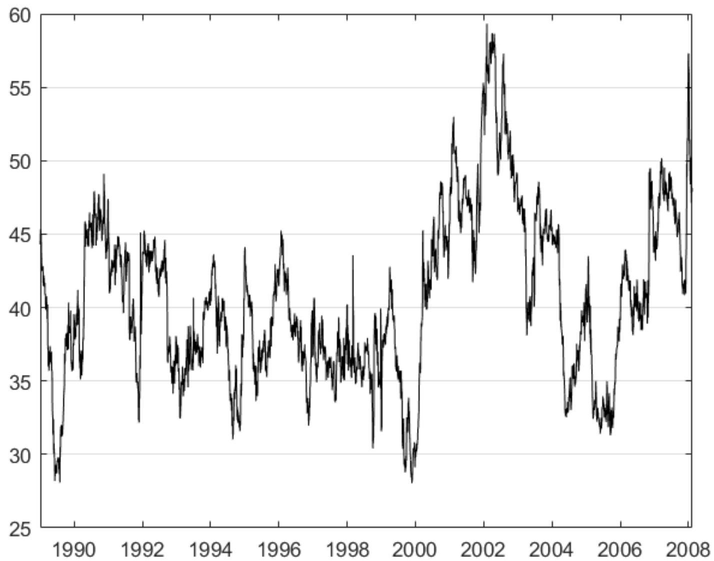


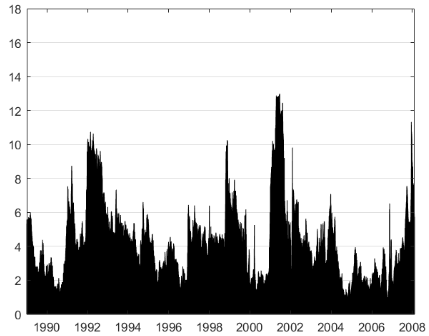
Figure 1: Development of $S^G(H)$, the total spillovers of the 7 assets in percentage, through time.

of Diebold and Yilmaz (2012), who have shown this for domestic assets.

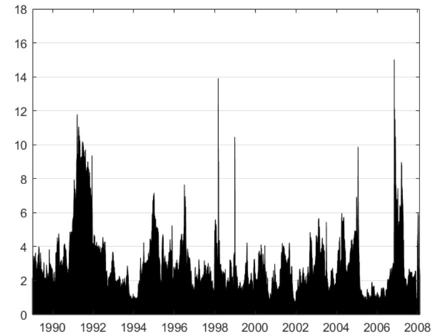
5.4 Development of directional spillovers

Figure 2 showcases how the directional spillovers from market i to all other markets $j \neq i$ differs over time. We are mostly interested in the effects between asset markets and therefore the results of the exchange rates will be presented in appendix D.

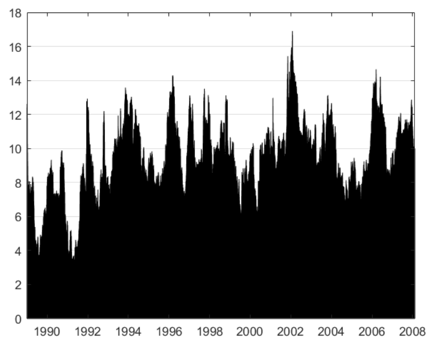
For both European and American assets, the level of spillovers varies greatly for different periods, going as low as 1.5% to as high as approximately 17%. Similar to what we have observed earlier from the full-sample variance decompositions presented in Table 2, it appears that individual American assets transmit more spillovers to other markets than European. A possible explanation for this result is the common view of the US economy as the primary driver behind the global economy. This notion is further elaborated on in Dées et al. (2009). Despite this being a compelling explanation this result in itself is not sufficient evidence to conclude that European markets are more affected by the US than the other way around. It could be that American domestic markets are more integrated amongst themselves than European and therefore emit more spillovers. Pertaining to the effects of crises on spillovers. Although the effects of the dot-com bubble still result in a considerable increase in directional spillovers, albeit varying for different markets, European markets do not express as much of an increase in directional spillovers as we would have expected during the great recession



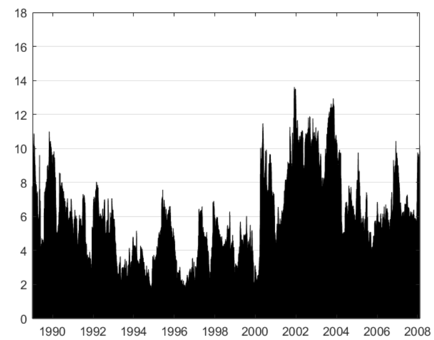
(a) American short-term interest rate



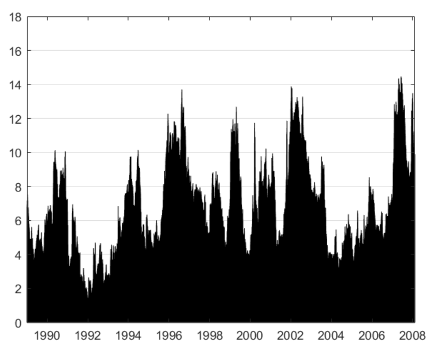
(b) European short-term interest rate



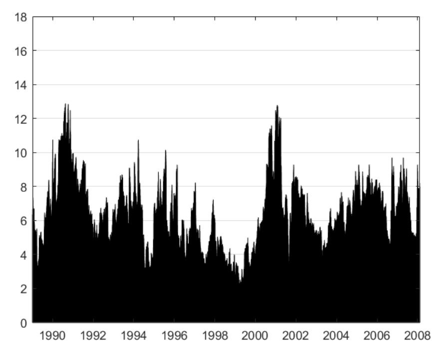
(c) American bonds yield



(d) European bonds yield



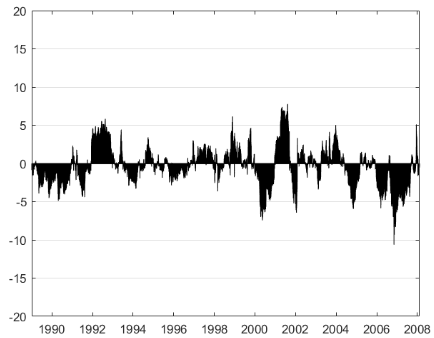
(e) American equity



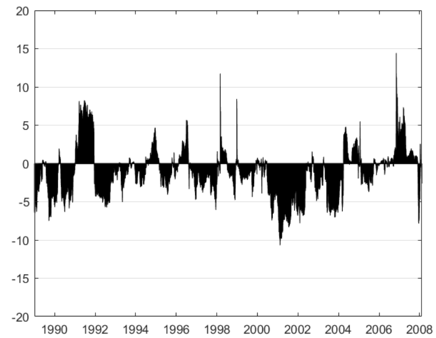
(f) European equity

Figure 2: The development of $S^G_{.i}(H)$, the directional spillovers from market i transmitted to all markets $j \neq i$ in percentage, through time.

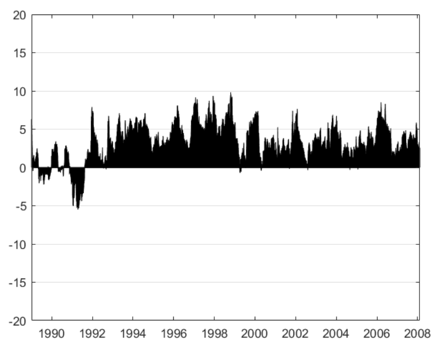
of 2007-2008, based on the total spillovers. However, this could possibly be explained by the fact that the crisis originated in the US. As a result, its gravest effects were not felt in Europe until late 2008 or early 2009, where our sample ends. Regarding the directional spillovers market i received from all other markets $j \neq i$, similar patterns can be observed and the same conclusions can be drawn. These figures have been included in appendix E.



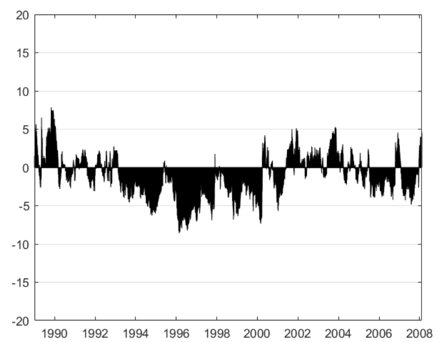
(a) American short-term interest rate



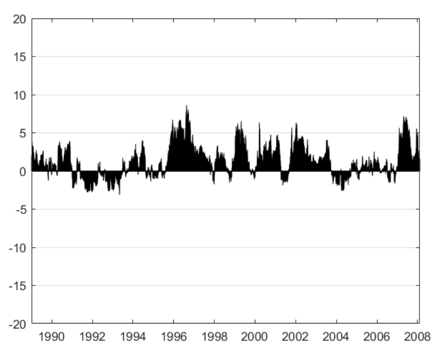
(b) European short-term interest rate



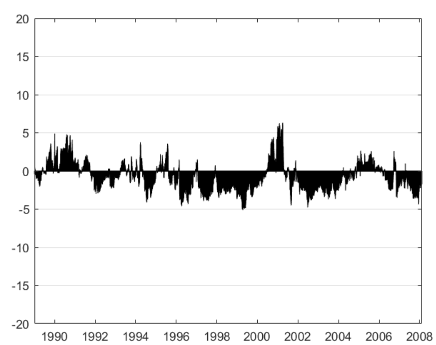
(c) American bonds yield



(d) European bonds yield



(e) American equity

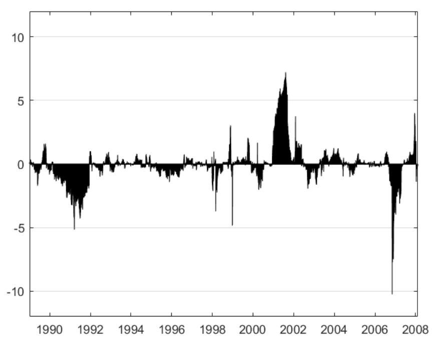


(f) European equity

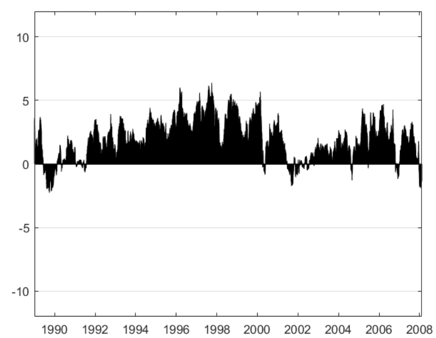
Figure 3: Development of $S_i^g(H)$, the net spillovers in percentage of market i, through time.

5.5 Development of net spillovers

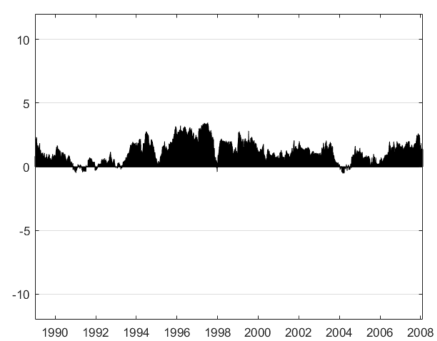
Our earlier results already hinted that American markets have more influence on European markets than vice versa. This phenomenon becomes more apparent when we graph the net spillovers. As shown in figure 3 it holds for almost the entire sample for American bonds and stocks that the net spillovers are positive, contrasting their European counterparts which are mostly negative. On the contrary, short-term interest rates in both regions appear to oscillate and do not show a clear pattern. At the inception of the second millennia European equity and bond net spillovers experience a sudden large positive surge. This coincides with the burst of the dot-com bubble, however, this does not seems to be a logical reason for the sudden increase. Another possible explanation could be the introduction of the Euro which was gradually implemented by its member countries starting in 1999. Cappiello et al. (2006) have shown that since the introduction of the Euro, cross-Atlantic markets did indeed become more integrated. In its initials years, this may have caused positive net spillovers that we observe coming from the Euro side.



(a) American-European short-term interest



(b) American-European bonds yield



(c) American-European equity

Figure 4: Development of $S^G_{ij}(H)$, the net pairwise spillovers between market i and j in percentage, through time.

5.6 Development of net pairwise spillovers

The net pairwise spillovers between American short-term interest rate, bond rates, stock returns, and their European counterparts are presented in Figure 4. For the sake of brevity, we have not included the others, because there are simply too many combinations of pairwise spillovers to include in this paper. The net-spillovers between the European and American short-term interest rates fluctuate throughout time and does not favor a certain direction. The net pairwise spillovers confirm that in general there are more spillovers from the US to the EU than vice versa. In the late 20^{th} century and early 2000's, it does seem that this difference is somewhat tempered, but increases again later into the century. Again this may be a result of the introduction of the euro.

6 Conclusion

In this paper, we have researched the linkage of domestic and international financial markets. We have done this by approaching the topic of interest using two methods. First, we estimated the parameters of the SVAR model in Ehrmann et al. (2011) containing 6 American and European assets and the Euro-Dollar exchange rate to analyze the significance and magnitude of cross-market transmission. As an alternative to tackle the same question we have used the reduced-form VAR of Ehrmann et al. (2011) without the exogenous variables to measure spillovers using the index designed by Diebold and Yilmaz (2012). Although we have not managed to identically replicate the results of Ehrmann et al. (2011), the results of our computed spillovers generally match those of Ehrmann et al. (2011) in economic interpretation. Most importantly, we have reaffirmed that for equity and bond yields spillovers occur mostly within the same type of asset and that American markets exert more influence over European markets than vice versa. We, however, did not find significant cross-market spillovers between assets of the two regions. Finally, we have shown that international spillovers tend to increase during recessions and crises. This is in line with the conclusion of Diebold and Yilmaz (2012) who have shown this for domestic spillovers.

Notwithstanding the results, comparing the approaches of Ehrmann et al. (2011) and Diebold and Yilmaz (2012) towards measuring international cross-market transmission between assets, the methodology of Ehrmann et al. (2011) has as merit that it allows for both the measurement of direct and overall effects that assets have on each other. However, it requires several assumptions to be made to identify the structural parameters. The index of Diebold and Yilmaz (2012) on the other hand, allows for the computation of time-varying spillovers and therefore the scrutiny of trends and other patterns.

Our research is not without limitations. Because we have used the same data as Ehrmann et al. (2011), we have only included time series from the two major western economies. Two economies that historically have been perceived as having strong ties politically and culturally. Regions that are not so connected to each other in these ways may show different results for financial transmission. Furthermore, our model also ignores possible effects from excluded markets on the relation between European and American assets. Given the rise of China and India in prominence to economic superpowers, including assets from these countries would provide interesting future research. Finally, we have given possible explanations to some of the phenomena we have observed. For example, we attributed the increase in net spillovers from the euro area to the US during the early 21st century to the introduction of the euro. These explanations are not clear-clut. Therefore, we also suggest future investigation into events or other factors that engender changes in spillovers.

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A Identification through heteroskedasticity

In this appendix we will go into further detail regarding IH. This method was devised by Rigobon (2003) and the complete theoretical proof is provided there. Let X be a set of k endogenous variables and suppose that the corresponding structural VAR is given as follows.

$$AX = c + \epsilon$$

Here A is the matrix of parameters, where the diagonal elements are taken be equal to 1, c is a vector of constants and ϵ are the structural shocks, which are assumed to be uncorrelated. In other words the covariance matrix of the shocks is diagonal. Rewriting the structural form into the reduced-form results in the following

$$X = A^{-1}c + A^{-1}\epsilon$$

As mentioned in section 2, despite not being able the estimate the structural parameters, we can estimate the reduced-form parameters and the covariance matrix of its residuals. These happen to be the only statistics we can retrieve. However, because we are not interested in the parameters of the reduced-form we still need to recover the structural parameters from these. Generally speaking this is not possible, because with k endogenous variables, we have $k(k-1)$ unknown parameters of interest. In addition we need to obtain the k structural shocks, meaning there are k^2 unknown variables, while the covariance matrix of the reduced-form residuals only supplies $k(k+1)/2$ equations. Consequently, $k(k-1)/2$ parameters remain unidentified. In summary, usually there are fewer equations than unknowns.

IH relies on conditional heteroskedasticity in the data to inflate the number of equations such that the system can be solved. For simplicity, assume that based on the volatility of the observations we can split the sample into two sub-samples, which we will call heteroskedastic regimes, for which the following properties hold.

$$
\begin{aligned}
AX^{s1} &= c + \epsilon^{s1} \\
AX^{s2} &= c + \epsilon^{s2} \\
\mathrm{var}(\epsilon^{s1}) &= \Sigma^{s1} \\
\mathrm{var}(\epsilon^{s2}) &= \Sigma^{s2} \\
\Sigma^{s1} &\neq \Sigma^{s2}
\end{aligned}
$$

This new model in addition to the previous assumptions, assumes that the covariance matrices of the residuals between the 2 regimes differ, while c and A remain the same or in other words they are stable across regimes. Combining these two assumptions results in each regime providing $k(k+1)/2$ new equations and only k new unknowns. This leads to $k(k+1)/2 - k = k(k-1)/2$ new free parameters, meaning one extra regime is sufficient for identification.

B Reduced-form parameter estimates

Table 3: Reduced-form parameter estimates illustrating the overall effects and bootstrap results

	Point estimate	Bootstrap		
		Mean	SD	p-value
Domestic transmission				
USA				
α_{11}	0.9616	0.9605	2.2646	0.0533
α_{21}	0.0395	-0.1691	2.1960	0.6133
α_{31}	-0.0107	-0.0278	0.0742	0.2267
α_{12}	0.0291	0.2371	1.3428	0.2267
α_{22}	0.7523	0.9208	1.7866	0.0933
α_{32}	-0.0116	-0.04596	0.0529	0.1867
α_{13}	0.6757	1.4384	36.1696	0.3200
α_{23}	3.2310	1.5120	34.2869	0.1867
α_{33}	0.9400	-0.9181	0.9324	0.0800
Euro area				
α_{44}	1.0230	1.0362	0.5861	0.0400
α_{54}	0.2708	0.0604	0.8297	0.5067
α_{64}	-0.0076	-0.0225	0.0278	0.2400
α_{45}	0.1140	0.4818	1.0413	0.1876
α_{55}	1.0667	1.0021	1.0514	0.0133
α_{65}	0.0031	-0.0348	0.0318	0.9200
α_{46}	0.8518	2.8581	42.1381	0.2677
α_{56}	-1.2024	-2.2710	36.9155	0.7876
α_{66}	0.9497	0.8865	1.1415	0.0133
International transmission				
USA to euro area				
β_{41}	0.2100	0.2847	2.9736	0.3067
β_{51}	0.0555	-0.0045	2.6435	0.6000
β_{61}	-0.0093	-0.0060	0.07457	0.2400
β_{42}	0.1211	0.1569	1.2343	0.4800
β_{52}	0.12998	0.1485	1.1377	0.4000
β_{62}	-0.0107	0.0021	0.0298	0.4933
β_{43}	-0.7146	0.3141	47.7229	0.5467
β_{53}	0.5358	0.0493	42.0596	0.4933
β_{63}	-0.1833	-0.0856	1.2257	0.4133
Euro area to USA				
β_{14}	0.1073	0.1568	0.5441	0.3067
β_{24}	0.1338	-0.0011	0.9368	0.6000
β_{34}	-0.00345	0.0030	0.0242	0.5200
β_{15}	0.0718	0.1246	1.0245	0.3467
β_{25}	0.2899	0.1873	0.9598	0.2400
β_{35}	-0.0099	0.0050	0.0309	0.5733
β_{16}	-0.8060	-0.0756	31.4485	0.5333
β_{26}	-2.6530	-0.2151	33.3388	0.4400
β_{36}	-0.1726	-0.3494	0.8122	0.2800

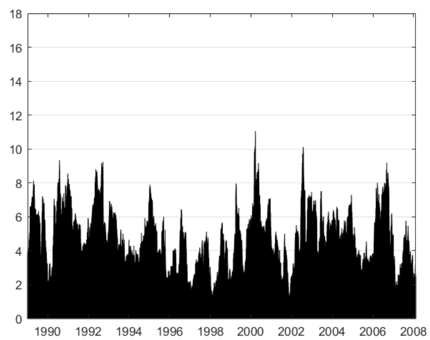
Table 3 continued

	Point estimate	Bootstrap		
		Mean	SD	p-value
Exchange rate effects				
γ_{71}	-0.06282	0.07144	0.8975	0.5733
γ_{72}	-0.0780	-0.1060	0.6470	0.3867
γ_{73}	0.6072	-0.2724	14.2943	0.6133
γ_{74}	0.0173	-0.0191	0.2831	0.5067
γ_{75}	0.0254	0.0343	0.4147	0.4133
γ_{76}	-0.6001	0.8842	13.0765	0.6667
γ_{17}	0.7463	-0.0367	7.6311	0.4667
γ_{27}	1.9155	0.0477	7.4944	0.3733
γ_{37}	-0.11628	0.0491	0.1962	0.5067
γ_{47}	-0.55800	-0.1445	11.0083	0.4933
γ_{57}	0.0728	-0.0636	9.3987	0.4933
γ_{67}	-0.1269	-0.0390	0.2718	0.6000
γ_{77}	0.5271	0.9544	2.9552	0.0933

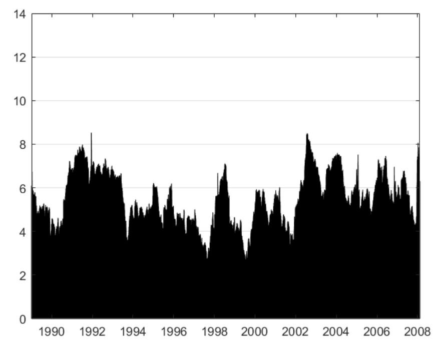
C Restriction matrix

$$A = \begin{pmatrix} 1 & \alpha_{12} < 0 & \alpha_{13} & -1 < \beta_{14} < 0 & 0 & 0 & \gamma_{17} \\ \alpha_{21} & 1 & \alpha_{23} & 0 & -1 < \beta_{25} < 0 & 0 & \gamma_{27} \\ \alpha_{31} > 0 & \alpha_{32} > 0 & 1 & 0 & 0 & -1 < \beta_{36<1} & \gamma_{37} \\ -1 < \beta_{41} < 0 & 0 & 0 & 1 & \alpha_{45} < 0 & \alpha_{46} & \gamma_{47} \\ 0 & -1 < \beta_{52} < 0 & 0 & \alpha_{54} & 1 & \alpha_{56} & \gamma_{57} \\ 0 & 0 & -1 < \beta_{63} < 1 & \alpha_{64} > 0 & \alpha_{65} > 0 & 1 & \gamma_{67} \\ \gamma_{71} & \gamma_{72} > 0 & \gamma_{73} & \gamma_{74} & \gamma_{75} < 0 & \gamma_{76} & 1 \end{pmatrix}$$

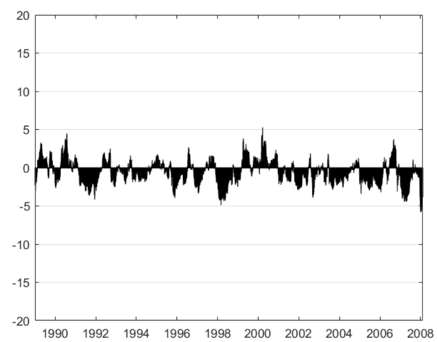
D Various spillovers for the exchange rate



(a) The development of $S^G_{\cdot i}(H)$, the directional spillovers from market i transmitted to all markets $j \neq i$ in percentage, through time.

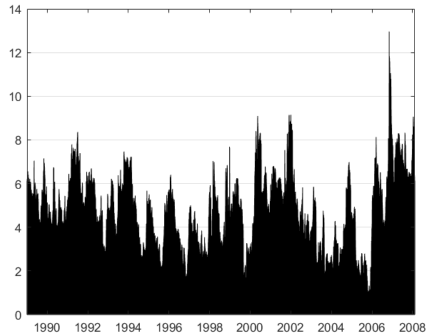


(b) The development of $S^G_{i\cdot}(H)$, the directional spillovers from market i transmitted to all markets $j \neq i$ in percentage, through time.

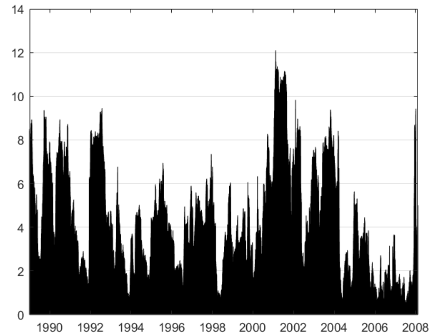


(c) Development of $S^g_i(H)$, the net spillovers in percentage of the exchange rate, through time.

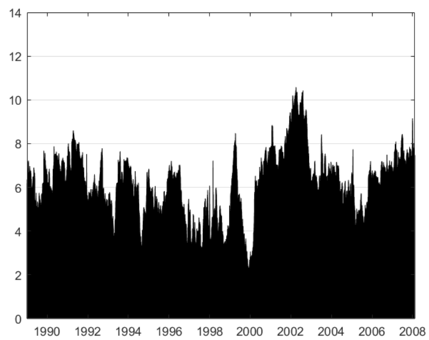
E Development of received directional spillovers



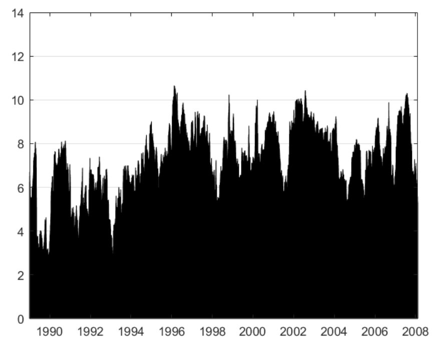
(a) American short-term interest rate



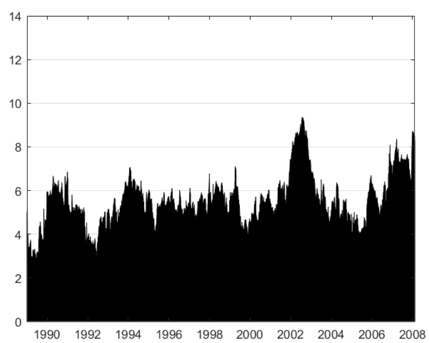
(b) European short-term interest rate



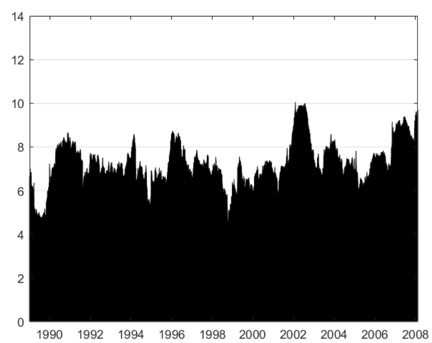
(c) American bonds yield



(d) European bonds yield



(e) American equity



(f) European equity

Figure 6: Development of $S^G_{i\cdot}(H)$, the directional spillovers market i received from all markets $j \neq i$ in percentage, through time.

F Instructions for programming code

For this paper we have written 6 separate programs all coded entirely in Matlab. The first 4 of these were used to obtain our results. For the extensions make sure to run the code in Matlab

2019a, because the function *fevd* is not included in older versions.

- var2.m contains the code for the point estimation of the parameters of Ehrmann et al. (2011). The structural parameters are given in the variable *Amatrix* and the reduced-form parameters can be found in *Ainv*. The function *fmincon* with the interior-point algorithm was used to minimize the distance. The starting values are the array *startval*.

- bootstrapping.m is the program that runs the bootstrap. It is required to run var2.m first, because it requires the parameter estimated from that code. The mean and standard deviation of the estimates are contained in *bmeanmat* and *varbootmat* respectively. And the p-values in *pvaluestruct* and *pvaluered*.

- extension1.m computes the spillovers presented in table 2. *decompn* consists out of 7 10×7 matrices. The 10^{th} row of each matrix contains the spillovers presented in the spillover table.

- extension.m calculates the moving-window spillovers such that the time-varying spillovers can be plotted.

To be able to run the codes for var2.m and bootstrapping.m first the csv file ECBdata has to be imported. To plot the spillovers against time import the last column of the excel file dates.

To verify the correctness of our code in extension.m and extention1.m we have also included replication code for Diebold and Yilmaz (2012). The programs are nearly identical, except for a few changes to accommodate the different VAR's and data.

- diebold1.m is the parallel of extension1.m. The results can also be found in decompn.

- diebold.m is the Diebold and Yilmaz (2012) counterpart of extension.m

Before executing the program, import the csv file dy2012. This file was obtained from the personal website of David Gabauer [2]

[2]URL: `https://sites.google.com/view/davidgabauer/econometric-code`