Volatility and Return Spillovers in International Financial Markets

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Abstract

Globalization of financial markets has led to stronger relations among different markets and asset classes. As a result, information across financial markets is transmitted almost instantaneously with potential implications for domestic and international economies. Understanding how information is transmitted across different markets and assets is essential for investors, risk managers, and policy makers. In that respect, the focus of this thesis is to study the relations among financial markets through three different empirical studies.

The third chapter of this thesis examines the instantaneous transmission of volatility, namely, contemporaneous spillover effects between the US and UK stock markets. It investigates these effects using high frequency data and focuses on the overlapping trading hours among stock markets. This study points out that when markets trade simultaneously, US volatility has a stronger impact on UK volatility than the other way around.

The fourth chapter contributes to our understanding of the time-varying contemporaneous spillovers between the stock markets in Germany and four peripheral European countries that were most affected by the European Debt Crisis. The chapter shows the existence of higher spillover effects from the German market to the peripheral markets than the other way around. We further observe a reduction in the magnitude of the contemporaneous spillover effects during the European Debt Crisis in contrast to the Global Financial Crisis.

The fifth chapter explores the contemporaneous spillovers among the US and Saudi Arabia stock markets, and the oil market taking into account its continuous trading hours. This chapter emphasizes the important role of oil volatility for both stock market volatilities. Particularly, it shows that during the overlapping trading hours, the volatility of the US and Saudi Arabia stock markets is more affected by the volatility of oil than the other way around. In addition, we document an increase in volatility transmission when accounting for the indirect effects which occur via third markets. All in all, the above findings shed light on how information is transmitted among different markets and assets.

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Attestation of Authorship

I, Marinela Adriana Finta, hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person (except where explicitly defined in the acknowledgements), nor material which to a substantial extent has been submitted for the award of any other degree or diploma of a university or other institution of higher learning.

Signed: ______________________________

Date: ______________________________

Acknowledgements

Murphy's law *"Whatever can go wrong, will go wrong"* is what has defined most of times my PhD voyage. Although at the beginning it wasn't easy, during this journey I have learned to expect the unexpected and that nothing is impossible as long as I believe in myself. Looking back over these three years I still can't believe how fast they pasted and that the PhD journey has come to an end. This exciting and challenging adventure would not have been possible without the support and involvement of several amazing and special people. Here, I would like to express my sincere gratitude to those people, as well as those that in a way or another, have been there for me and contributed to this enjoyable experience.

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Life isn't about waiting for the storm to pass. It's about learning how to dance in the rain. [Vivian Greene]

Auckland, November 2016.

Chapter 1

Introduction

1.1 Motivation

Spillover effects in finance are concerned with the process of information transmission among financial markets. Particularly, these effects explore the transmission of shocks among markets across same and different regions at volatility and return level. As such, research on spillover effects helps shed light on how shocks occurring in one market are incorporated into other markets, thus improving our knowledge regarding the relations among financial markets. Given that spillover effects provide a better understanding of the volatility and returns among financial markets, their investigation is of great importance to both domestic and international economies.

The expansion of financial markets, e.g., transition from an open outcry trading platform to a computer/electronic order matching platform, together with globalization has led to faster transmission of information across the globe. As such, financial markets are more exposed to market-wide shocks which are influencing almost instantaneously their volatility and returns (Andersen et al., 2007). Investigating the impacts of volatility and return shocks is essential, especially considering the recent Global Financial Crisis, European Debt Crisis and oil crisis which have caused periods of high instability in financial markets. Specifically, the Global Financial Crisis started with Lehman Brothers' collapse on September 2008 and has led to a collapse of equity markets around the world who experienced sharp declines in their prices. Dimpfl and Peter (2014), for instance, show that during the Global Financial Crisis there is a considerable increase in information transmission between the US and European stock markets.

Following the Global Financial Crisis, the European Debt Crisis originated in Greece on October 2009 when Greek government revealed that its deficit is twice of the previous expected estimates. This has raised concerns among the Eurozone policy makers, multilateral oranizations and investors about the spread of the debt crisis to other countries with similar weaknesses such as, high public debt and high budget deficit. Indeed, European Debt Crisis has rapidly spread and affected several peripheral Eurozone countries, Italy, Portugal and Spain, which have confronted with similar problems and have required that their governments to implement various economic and fiscal reforms. These crises clearly emphasize the relevance of spillover effects, namely, shocks occurring in one market not only influence that specific market but are also transmitted to other markets. On the whole, the faster transmission of information highlights the need to adequately address and understand the time-varying relations among markets.

One important aspect of the spillover effects that is addressed in this thesis is attention that is paid to the overlapping trading hours among financial markets across the same or different regions. In this case, there exist two different situations, namely, when financial markets have partial overlapping trading hours and total overlapping trading hours. If we are aware of the overlapping trading hours and ignore them then this could lead to inaccurate spillovers, both in volatility and mean (Hamao et al., 1990). This is because it is hard to disentangle the impacts of shocks occurring in the foreign market from the impacts of the own shocks. First, we consider the situation when markets have partial overlapping trading hours, for instance, the US and UK stock markets. Given the fact that the US market opens on the same global day but ahead of the UK market and these markets trade simultaneously up to three hours, then what occurs in the former market may instantaneously spill-over the latter market. This is due to the fact that these markets trade simultaneously for a period of time. As such, there are contemporaneous spillover effects. Instead, information that is created after the overlapping trading period when US market is closed and the UK market is open, can only be transmitted on the next trading day. In this case, we state that there exist dynamic spillover effects. Second, European markets, for instance, have total overlapping trading hours. Thus, there exist contemporaneous spillovers among them which given the recent developments and their high level of integration might not entirely be captured by the dynamic spillovers. Therefore, it is essential to investigate and distinguish between both contemporaneous and dynamic (lead-lag) spillover effects at the volatility and return level. Moreover, since financial markets respond to shocks differently, namely, with different sign and magnitude, these spillover effects may be asymmetric (Ehrmann et al., 2011). In other words, the asymmetry concept that we use in this thesis refers to the differences regarding the direction of spillovers among financial markets. Namely, the spillover effects could be higher in one direction than the other way around.

The topic investigated in this thesis is primarily related to these spillover effects among financial markets at the volatility and return level. A clear understanding of how these effects change over time is of particular relevance to investors, risk managers and policy makers. Investors and risk managers need to know how shocks to one market affect other markets since changes in one market are driven not only by its own shocks, but also by its reaction to shocks in other markets (Rigobon and Sack, 2003). Knowledge of these spillover effects has implications for the efficient implementation of hedging strategies and for Value-at-Risk calculations. Policy makers and monetary authorities are interested in the stability of their financial system. The relations among financial markets affect this stability and therefore need to be better understood, especially during financial crises, such as the Global Financial Crisis and the European Debt Crisis. Moreover, the return spillover effects can provide a good measure of integration among financial markets. Particularly, how one market responds to return shocks into another market, and vice versa, how integrated is the second market with the first market. In that respect, the findings in this thesis highlight that instantaneous transmission of information matters across trading venues and considering both dynamic and contemporaneous effects leads to more valuable inferences with respect to their magnitude and direction.

1.2 Outline

This section provides a short overview of the chapters in this thesis.

Chapter 2 presents a primer on spillover effects among international financial markets. The chapter commences with a discussion on spillover effects and continues with an explanation on the endogeneity issue and how it is related to transmission of information among different markets and assets. We then provide an example to illustrate this endogeneity problem, which occurs when markets trade simultaneously, namely, there are bidirectional and different effects from one market to other market and vice versa. This chapter also provides different solutions to the identification issue which are employed in the literature on spillover effects, and how these solutions shed light on the relations among financial markets.

Chapter 3 examines the contemporaneous spillover effects between equity markets in the US and the UK. We model these interactions concentrating on the period when markets trade simultaneously, taking into consideration dynamic and contemporaneous relations at volatility level. Specifically, using high frequency data, we split the trading periods of both stock markets in three, namely, the period when the US stock market is closed, the overlapping trading period and finally, the period when the UK stock market is closed. This allows us to assess the instantaneous transmission of volatility among the stock markets. We find that during the time when trading hours overlap, higher stock market volatility in the US leads to higher volatility in the UK. Moreover, these volatilities have higher impacts on the US stock market volatility, when the UK market is closed, on the same trading day. Overall, this study clearly reveals that contemporaneous relations matter across trading venues and ignoring them leads to inappropriate conclusions regarding the magnitude and direction of volatility spillovers among the stock markets.

In Chapter 4, we assess the dynamics of contemporaneous spillover effects between the German equity market and the peripheral Greek, Italian, Portuguese and Spanish equity markets. It takes into account both the Global Financial Crisis and the European Debt Crisis and examines how financial assistance programs and credit rating downgrades, impact these relations. We document that there is asymmetry and time-variation in these contemporaneous spillover effects. Particularly, the spillover effects from the German to the peripheral equity markets is greater than the other way around. We also show that the European Debt Crisis actually induced a decrease in contemporaneous spillover effects, versus the Global Financial Crisis which caused an increase in their magnitude. Financial assistance programs and credit rating downgrades, instead, have mixed impacts on the contemporaneous spillover effects.

In Chapter 5, we investigate contemporaneous spillover effects between oil market and stock markets in the US and Saudi Arabia. This study takes into account the continuous trading of oil prices and provides a better understanding regarding the direct and indirect volatility transmission among these assets. We observe that during the time when trading hours of oil overlap with those of stock markets, higher volatility in the oil market causes higher volatility in the US and Saudi Arabia stock markets. In addition, we provide evidence of an increase in the magnitude of spillover effects when allowing for the indirect effects, namely, the effects which are transmitted through third markets. Overall, our results show the relevance of taking into consideration the information present during the simultaneous trading, and both direct and indirect volatility transmission.

On the whole, this thesis is aimed to provide a better understanding of the relations among financial focusing on their overlapping trading hours. The chapters in this thesis address several important issues regarding the volatility and return spillover effects, such as the instantaneous transmission of volatility when stock markets share overlapping trading hours, the impacts of financial crises, the announcement of financial assistance programs and credit rating downgrades on the return spillover effects, and the volatility transmission between oil and stock markets when oil trades continuously.

Chapter 6 summarizes the main findings of this thesis and concludes.

Chapter 2

A Primer on Spillover Effects Among Financial Markets

2.1 Introduction

This chapter presents a primer on spillover effects among financial markets. We briefly discuss the literature on spillover effects and their different definitions. Thus, we provide a better understanding and overview regarding the spillover effects addressed in the literature and this thesis. We further address the endogeneity issue which arises when investigating the contemporaneous spillover effects and provide a simple example to better explain this issue. Finally, we present various ways to deal with the identification problem which have been used in the literature.

2.2 Overview of the Spillover Effects

The literature on how different markets and assets interact over time is extensive, both at the international and domestic level. Given the importance and attention received by the spillover effects in the literature over time and recently, during financial crises (Fayyad and Daly, 2011; Dimpfl and Jung, 2012; Awartani et al., 2013; Bhanot et al., 2014; Ludwig, 2014), we provide an overview on their definitions and possible channels through which can occur. The literature goes back to Engle et al. (1990) who introduced the notions of "heat waves" and "meteor showers" to measure information transmission from one period to the next within markets and respectively, across markets. Using these concepts, some studies investigate the spillover effects within same markets in different regions (Koutmos and Booth, 1995; Lee and Rui, 2002; Melvin and Melvin, 2003). These studies show that information from one market is transmitted to other markets even if these markets are geographically distant. Other studies examine the interactions not only within same markets but also across different markets over different regions (Fang et al., 2006; Hakim and McAller, 2010; Clements et al., 2014). These studies find that although the strongest transmission takes place within asset classes, the international transmission across financial markets is also significant at both domestic and international level. On the whole, the literature finds evidence of both "heat waves" and "meteor showers" effects.

To provide a better understanding of the relations among financial markets, we further review the contagion concept that is closely related to the shock transmission. As proxies for spillover effects, many studies (Karanasos et al., 2014; Syllignakis and Kouretas, 2011; Samitas and Tsakalos, 2013; Gjika and Horvath, 2013) use the correlation coefficients and follow Forbes and Rigobon's (2002) definition of contagion, that is, a significant increase in the correlations after a crisis event. Bekaert et al. (2014), instead, define contagion as excess comovements, namely, the unexplained increases in factor exposures (the US factor, a global financial factor and a domestic factor). Furthermore, the studies of Alter and Bayer (2014) and of Ehrmann and Fratzscher (2015) describe contagion as an intensification in transmission of shocks across markets, namely, an increase in spillover effects.

As to the transmission channels of shocks, empirical research has emphasized the important role of bank linkages, globalization and "wake-up call" hypotheses (Bekaert et al., 2014; Gorea and Radev, 2014; Ahrend and Goujard, 2014; Gómez-Puig and Rivero, 2013). According to the globalization hypothesis, crises hit hardest those economies that are integrated through trade and financial linkages. The "wake-up call" hypothesis, instead, holds that a crisis in one country can trigger a crisis in another country even if the countries are not interconnected through bank, trade or debt linkages. This is the case when market participants take the initial crisis as a signal to update information in other countries, they re-evaluate the risk (Moser, 2003, Bekaert et al., 2014). For instance, the reassessment of the functioning of financial markets or policies of international institutions could cause investors to sell assets across countries (Forbes, 2012), thereby causing contagion (Arghyrou and Kontonikas, 2012; Ludwig, 2014; Samitas and Tsakalos, 2013). Thus, contagion occurs when the increase in co-movement among markets is driven by a crisis shock to one market.

A common feature of the above literature is that although it uses different concepts in investigating the relations among financial markets and their determinants, essentially, all these notions refer to the extent by which shocks are transmitted across financial markets. At the same time, from an empirical perspective, the majority of studies examine the spillover effects using univariate/ multivariate GARCH and VAR models. Thus, these studies solely look at the information transmitted among markets on the next trading day, namely, dynamic effects, that partly explain the spillover effects. Such a limited approaches can be problematic since they may not pick up the effects of instantaneous shocks, namely, the contemporaneous spillovers. These contemporaneous spillover effects are particularly relevant since many financial markets share partial or total overlapping trading hours. We therefore need to adequately investigate both contemporaneous and dynamic (lead-lag) effects which together define the total spillover. Using a basic example, we next show how the spillover effects are modelled in this thesis.

2.3 Modelling Spillover Effects

2.3.1 Basic Model

In this section, we introduce a structural vector autoregressive (SVAR) model which is a convenient way to analyze the linkages among financial markets. Assuming that we are interested in the contemporaneous spillover effects between two markets, y_1 and y_2, this model allows us to assess them, namely, it shows the impact of a shock occurring in the y_1 on the y_2 and the other way around.

To assess these relations, we implement the following SVAR,

$$\mathbf{A}y_t = c + \mathbf{\Phi}(\mathbf{L})y_t + \varepsilon_t \tag{2.1}$$

where $y_t = \begin{pmatrix} y_{1,t} & y_{2,t} \end{pmatrix}'$, c is a (2×1) vector of constants and ε_t is (2×1) vector of structural shocks/innovations. The spillover effects between our markets are captured by the matrices $\mathbf{\Phi}(\mathbf{L})$ and $\mathbf{A}$. Specifically, $\mathbf{\Phi}(\mathbf{L})$ is a (2×2) matrix capturing the dynamic spillover effects, i.e.,

$$\mathbf{\Phi}(\mathbf{L}) = \begin{pmatrix} \phi_{11}(L) & \phi_{12}(L) \\ \phi_{21}(L) & \phi_{22}(L) \end{pmatrix} \tag{2.2}$$

where considering the first lag ϕ_{12} shows the dynamic spillover from $y_{2,t-1}$ to $y_{1,t}$, that is, the impact of a shock originating in $y_{2,t-1}$ previous's day on $y_{1,t}$. The other parameters are defined likewise. The $(2{\times}2)$ matrix $\mathbf{A}$ captures the contemporaneous effects between our markets and has the following structure,

$$\mathbf{A} = \begin{pmatrix} 1 & \alpha_{12} \\ \alpha_{21} & 1 \end{pmatrix}, \tag{2.3}$$

where α_{12} captures the contemporaneous spillover from the second market to the first market and α_{21} captures the contemporaneous spillover from $y_{1,t}$ to $y_{2,t}$.

The main aim of this thesis is to investigate the relations among financial markets. As such, it is important to assess and distinguish between the contemporaneous and dynamic spillover effects, namely, the information that is transmitted among markets within the same trading day and next trading day. However, when investigating the contemporaneous relations between $y_{1,t}$ and $y_{2,t}$ markets, we face a problem that also exists in simultaneous equations models, i.e., endogeneity. Next, we address in more detail this problem.

2.3.2 Endogeneity Issue

Endogeneity is a major issue that occurs when we have multiple variables whose behaviours are interrelated such that they are effectively simultaneously determined. That is, each asset price is likely to respond instantaneously to other asset prices included in the model, e.g., $y_{1,t}$ shocks affect $y_{2,t}$ and $y_{2,t}$ shocks affect $y_{1,t}$ at the same time. As such, we are unable to identify contemporaneous spillover effects, matrix $\mathbf{A}$.

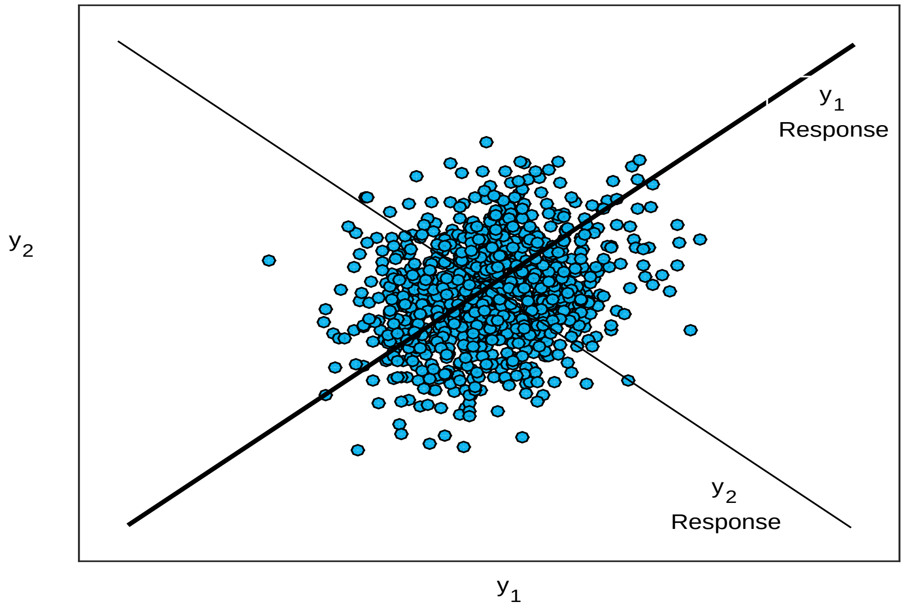
To better illustrate this issue we consider the SVAR model from Equation (2.1) with one lag and rewrite it as the following system of two equations:

$$y_{1,t} = c_1 - \alpha_{12} y_{2,t} + \phi_{11} y_{1,t-1} + \phi_{12} y_{2,t-1} + \varepsilon_{1,t} \tag{2.4}$$

$$y_{2,t} = c_2 - \alpha_{21} y_{1,t} + \phi_{21} y_{1,t-1} + \phi_{22} y_{2,t-1} + \varepsilon_{2,t} \tag{2.5}$$

As is well known, if α_{12} and α_{21} are different from zero, Equation (2.4) and (2.5) cannot be estimated consistently using OLS due to simultaneity. Essentially, this occurs due to the failure of the OLS conditions, i.e., $\mathrm{E}[\varepsilon_{1,t}\, y_{2,t}] = 0$ and $\mathrm{E}[\varepsilon_{2,t}\, y_{1,t}] = 0$. For instance, if we run an OLS regression on Equation (2.4) then the former condition fails, namely, the shock term $\varepsilon_{1,t}$ is correlated with the $y_{2,t}$. This arises as a result of the responses of $y_{2,t}$ to $y_{1,t}$, as given by parameter α_{21} in Equation (2.5). Similarly, when estimating Equation (2.5) the shock term $\varepsilon_{2,t}$ is correlated with the $y_{1,t}$ due to the responses of $y_{1,t}$

Figure 2.1: Joint Determination of $y_{1,t}$ and $y_{2,t}$



to $y_{2,t}$, as given by parameter α_{12} in Equation (2.4). As such, this example illustrates that the estimated coefficients are biased.

This identification problem is demonstrated in Figure 2.1, which shows that the realizations of both $y_{1,t}$ and $y_{2,t}$ prices (i.e., the outcomes of shocks to both $y_{1,t}$ and $y_{2,t}$ markets) are determined by the intersection of these two equations. Due to the fact that shocks are continuously hitting both curves these intersects are moving and thus, might not give any information regarding the slope of either equation.

Given the fact that our markets trade simultaneously, their prices are instantaneously affected by shocks occurring in either of them. Indeed, Figure 2.1 emphasizes the endogeneity issue that is due to the instantaneous transmission of shocks to our markets. As a result, the outcomes of these shocks presented in Figure 2.1 are distributed around the centre of the intersection and not around the schedules. This is because shocks which are affecting the $y_{1,t}$ equation are also affecting the $y_{2,t}$ equation and the other way round. Thus, we are unable to identify whether the impacts of $y_{1,t}$ shocks to $y_{2,t}$ are higher than the impacts of $y_{2,t}$ shocks to $y_{1,t}$ or the other way around. By looking at this figure we can only state that there is a spillover between our markets but we are unable to infer the direction of this spillover which can go in both sides. In next section, we discuss how to address the simultaneity problem.

2.3.3 Solving the Identification Problem

To address the endogeneity problem, many studies have typically focused on imposing sign and exclusion restrictions, thus, solely allowing for unidirectional spillover effects (Dimpfl and Jung, 2012; Clements et al., 2015; Alter and Bayer, 2014; Louzis, 2015). For instance, these studies assume that there is no spillover from one market to other market, i.e., either $\alpha_{12} = 0$ or $\alpha_{21} = 0$. In this case, the OLS conditions are fulfilled, namely, structural shocks $\varepsilon_{1,t}/\varepsilon_{2,t}$ are uncorrelated with $y_{2,t}/y_{1,t}$. However, from an economic point of view, these assumptions might be inappropriate. Furthermore, the purpose of this thesis is to precisely investigate and take into consideration the contemporaneous spillover effects among markets. As such, the above solutions could be unreasonable.

There are, however, alternative solutions which allow us to properly deal with the identification problem presented in Figure 2.1. For instance, Rigobon (2003) and Lütkepohl (2012) propose the "identification through heteroskedasticity" approach and respectively, identification through changes in volatility approach.

The initial point for the estimation of these approaches is to estimate the reduced-form VAR between $y_{1,t}$ and $y_{2,t}$ as bellow:

$$\begin{aligned} y_t &= \mathbf{A}^{\mathbf{-1}} c + \mathbf{A}^{\mathbf{-1}} \mathbf{\Phi}(\mathbf{L}) y_t + \mathbf{A}^{\mathbf{-1}} \varepsilon_t \\ y_t &= c^* + \mathbf{\Phi}(\mathbf{L})^* y_t + u_t \end{aligned} \tag{2.6}$$

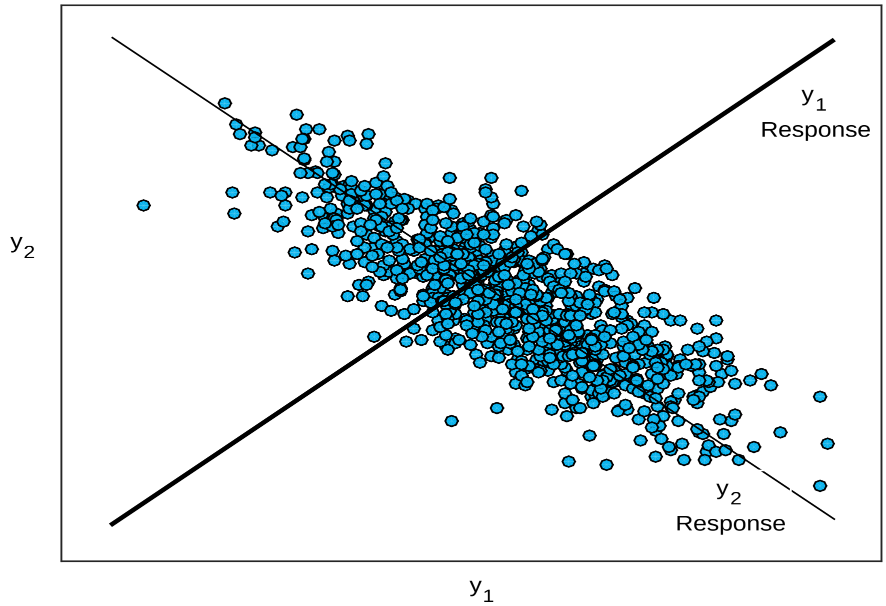
where the coefficients of Equation (2.6) can be estimated by OLS and are related to the structural coefficients of Equation (2.1) through matrix $\mathbf{A}$. We then essentially make use of the non-proportional shifts in volatility which enable us to recover and identify the contemporaneous relations. In particular, for the implementation of these approaches we have to impose two restrictions. That are, the structural shocks, ε_t from Equation (2.1) are uncorrelated and parameters from Equation (2.6) are time-invariant. If these restrictions hold, then we are able to capture and identify the instantaneous transmission of information among financial markets.

The main idea of both approaches is to make use of the non-proportional shifts in volatility to recover and identify the contemporaneous relations. As such, an important first step for the examination of contemporaneous spillover effects between our markets, i.e., $y_{1,t}$ and $y_{2,t}$ is to capture these non-proportional changes in volatility. Given the fact that the reduced-form residuals reflect the structural shocks and contemporaneous relations, we use these residuals to identify different volatility regimes. Essentially, the idea in choosing these regimes is to find periods in which the variance of residuals in one market, i.e., $y_{1,t}$, is higher than the variance of residuals in another market, i.e., $y_{2,t}$, and the other way around. In other words, a shock to one market is the defined as a period when volatility in this market is high while volatility in the other markets is low. This period can then be used to estimate contemporaneous spillover from this market to other markets.

The intuition why these changes in the variances allow the identification of contemporaneous relations is closely related to the instrumental variable intuition. For instance, if we are interested in finding the $y_{2,t}$ equation, the intuition for the instrumental variable approach is to find some variable or shock that moves the $y_{1,t}$ equation without affecting the $y_{2,t}$ curve. As such, this variable measures the slope of the $y_{2,t}$.

The approaches of Rigobon (2003) and Lütkepohl (2012) work in a similar way. In these approaches, we look for a regime change that shifts the variance of residuals. This change in the variance rotates the ellipse where the residuals are distributed, namely, along the equation we are interested in estimating. If, for instance, the shift in variances of the $y_{1,t}$ and $y_{2,t}$ shocks is the same then the shape of the ellipse across the

Figure 2.2: Contemporaneous Spillover from $y_{1,t}$ to $y_{2,t}$



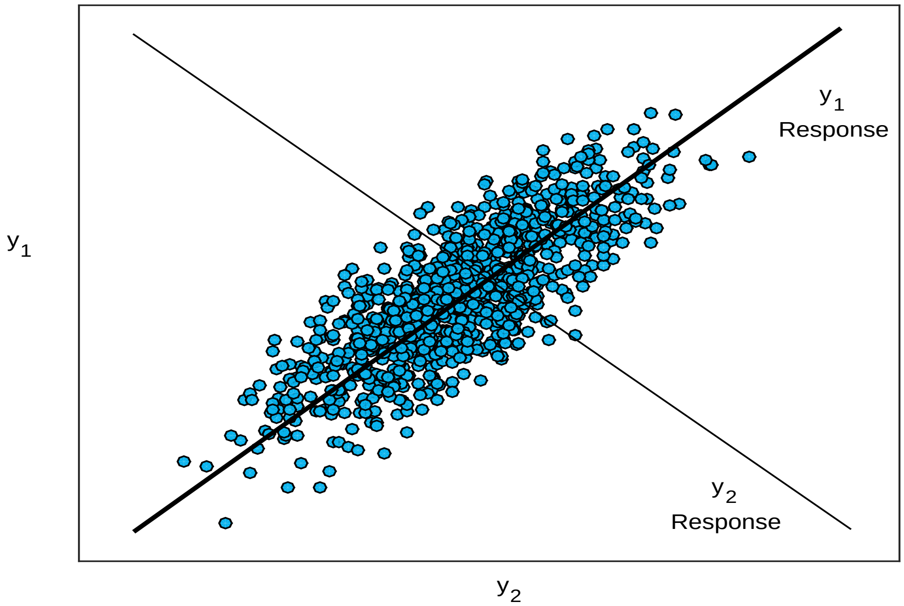
regimes is the same and we cannot identify the contemporaneous relations. That is due to the fact that we do not know which shock becomes more important across the regimes.

The simplest intuition is to split the sample from Figure 2.1 into two sub-samples as shown in Figure 2.2 and Figure 2.3 such that the volatility of one of the variables is high while volatility of the other variable is low. Specifically, we assume that the variance of the $y_{1,t}$ residuals is higher in Figure 2.2 than Figure 2.3, while the variance of the $y_{2,t}$ residuals is lower in Figure 2.2 than Figure 2.3.

Figure 2.2 implies that $y_{1,t}$ shocks are more volatile in the first sub-sample and $y_{2,t}$ shocks have a constant variance. As is noticeable in this figure, the increase in the variance of $y_{1,t}$ shocks implies that the pattern of realized observations shifts more closely along the $y_{2,t}$ equation. This shift in the variance implies a rotation in the ellipse along the $y_{2,t}$ equation and thus, allows us to capture the $y_{2,t}$ responses to shocks occurring in the $y_{1,t}$.

The intuition behind this is that a shift in the variance of $y_{1,t}$ shocks relative to the $y_{2,t}$

Figure 2.3: Contemporaneous Spillover from $y_{2,t}$ and $y_{1,t}$



shocks influences their covariance in a way that depends on the reaction of market $y_{2,t}$ to market $y_{1,t}$ shocks. In other words, given the fact that the volatility of $y_{1,t}$ is high, we get more information on the $y_{2,t}$ equation. As such, we are able to estimate the contemporaneous spillover from $y_{1,t}$ to $y_{2,t}$, namely, how shocks occurring in market $y_{1,t}$ affect market $y_{2,t}$.

Figure 2.3, assumes that $y_{2,t}$ shocks are more volatile than in the first sub-sample, Figure 2.2, and $y_{1,t}$ shocks have a constant variance. This rise in the variance of $y_{2,t}$ shocks implies a tilting of the realizations towards the $y_{1,t}$ equation and allows us to examine the $y_{1,t}$ responses to shocks occurring in the $y_{2,t}$. In other words, due to the fact that the volatility of the market $y_{2,t}$ is higher than the volatility of market $y_{1,t}$, we obtain more information on the impacts that shocks to $y_{2,t}$ have on the market $y_{1,t}$. Specifically, we can identify contemporaneous spillover from $y_{2,t}$ to $y_{1,t}$. From the instrumental variable point of view, this rise in the variance of $y_{2,t}$ shocks becomes a probabilistic instrument which allows to assess how shocks to market $y_{1,t}$ influence market $y_{2,t}$.

The main difference between the approach of Rigobon's (2003) and Lütkepohl's (2012) consists in how are obtained the changes in volatility which allow the identification of contemporaneous spillover effects.

Rigobon (2003) captures these shifts in volatility from the reduced-form residuals. The basic idea of this approach is to find in which periods the residuals of one variable are very volatile, while residuals of the other variable are less volatile. To do this we define a reasonable volatility threshold that is, the average standard deviation over the full sample plus the threshold value of 0.8. We then compute variances of reduced-form residuals for each of our variables over fixed windows of 50 days. Whenever the residuals of one variable are above this threshold while the residuals of other variable are bellow threshold, we consider the residuals of the first variable to be volatile. We define the number of regimes as the number of variables plus one. For instance, in our example, we are interested in finding three regimes, namely, a high $y_{1,t}$ volatility regime, a high $y_{2,t}$ volatility regime and a regime where both variables show lower than threshold volatility. If during some period more than one of the variables has residuals above volatility threshold then we do not use these residuals since would not much contribute to the identification of contemporaneous relations.

In sum, in Chapter 3 of the thesis we capture the changes in volatility by computing rolling window variances from the reduced-form VAR residuals from which we then define volatility regimes that have different variance covariance matrices.

The approach of Lütkepohl (2012) also relies on the fact that the existence of different volatility regimes allows us to identify the contemporaneous relations. However, the main important characteristic of this approach is that only requires to decompose the variance covariance matrix of the reduced-form residuals to uniquely identify the contemporaneous spillover effects. As such, contrary to the approach of Rigobon (2003) we do not need to define the volatility regimes from the reduced form residuals. Instead, we are defining their variance covariance matrix such that this matrix is different across the volatility regimes.

In sum, Lütkepohl (2012) provides a definition of the different variance covariance matrices. These changes in the variance of residuals allow in Chapter 4 and 5 the identification of the contemporaneous spillover among financial markets.

As regards the implementation of these approaches in the literature on spillover effects, there are several studies who apply Rigobon's (2003) approach and show the existence of contemporaneous spillovers. For instance, Andersen et al. (2007) find that there are contemporaneous interactions among the equity markets in the US, Germany and UK and that the US macroeconomic news affect them. Ehrmann et al. (2011) show that the US money, bond and equity markets are explaining a proportion of 30% the European money, bond and equity markets movements, whereas the European markets are only explaining around 6% of the US movements. Recently, Ehrmann and Fratzscher (2015) provide evidence of larger contemporaneous return spillovers from Germany to peripheral European countries during the Global Financial Crisis compared to the European Debt Crisis. On the whole, these studies clearly show that endogeneity issue can be addressed such that it allows the exploration of contemporaneous spillover effects among different markets and assets.

The SVAR model together with these two techniques form an integral part of this thesis, which assesses the relations among financial markets with a special emphasis on the overlapping trading hours among them. Particularly, these techniques allows us to examine the contemporaneous spillover effects from three different important perspectives. In Chapter 3, we examine these relations paying attention to the partial overlapping trading hours among stock markets. In Chapter 4, we evaluate the contemporaneous spillover effects when stock markets are entirely trading simultaneously. Finally, Chapter 5 explores the contemporaneous relations taking into consideration the continuous trading hours of oil market.

Chapter 3

Contemporaneous Volatility Spillover Effects Between the US and the UK

3.1 Introduction

The Global Financial Crisis, which originated in the US and rapidly spread to other countries, has triggered a resurgence in research on the international transmission of volatility (Louzis, 2015; Dimpfl and Jung, 2012; Singh et al., 2010; Diebold and Yilmaz, 2009). This crisis caused a period of high volatility and instability in financial markets, and had a strong negative impact in terms of economic growth for many economies around the world. The crisis once again highlighted that economic shocks originating in one market not only affect that particular market, but are also transmitted to other markets with serious implications for financial markets. Moreover, their globalization and expansion have led to stronger relations among different markets and asset classes. As a result, volatility shocks to one market are reflected almost instantaneously into other markets. Given the fact that there are trading time differences among the financial markets from different trading zones, the impacts of these shocks could be transmitted on the same global trading day, in addition to the next trading day. Understanding these "spillover effects" among markets is therefore of great importance especially during financial crises and when markets share overlapping trading hours.

While many studies consider the dynamic aspect of volatility spillover, the total volatility spillover between markets and across different regions can be explained by both dynamic and contemporaneous effects. The dynamic effects refer to spillovers that occur over time. This is the case, for example, when one market is open while the other is closed, and information from one market can only affect the other market in the next trading period. Contemporaneous spillover may be seen as the spillover that takes place at the same time. This can occur, for example, when markets have overlapping trading hours, and information from one market can be transmitted to another market instantaneously. Given that many markets share overlapping trading hours, capturing these contemporaneous spillovers is important. However, a major issue that we face when investigating the spillover effects is that contemporaneous effects cannot be identified using standard VAR and GARCH models (Savva et al., 2009; Hakim and McAller, 2010), as these focus purely on lead-lag dynamics. Therefore, several studies assume that the transmission of shocks is in one direction and not in the other, and impose sign restrictions based on prior economic knowledge. Unfortunately, these assumptions cannot always be justified.

As an alternative method to solve the identification issue, Rigobon (2003) proposes the "identification through heteroskedasticity" approach. This technique relies on the existence of non-proportional changes in volatility over time and makes use of these changes to identify the contemporaneous interactions without any a priori assumptions regarding the direction of causality. This approach has recently been employed by Andersen et al. (2007) and Ehrmann et al. (2011) who provide evidence that there are contemporaneous spillover effects among different markets and assets at the return level.

In this study, we analyze the instantaneous transmission of volatility, namely, contemporaneous spillover effects. We examine these spillover effects using a structural VAR and the "identification through heteroskedasticity" approach of Rigobon (2003) focusing on the period when markets trade simultaneously. This period is particularly relevant as it is the only time when information can be transmitted simultaneously among markets. Specifically, we estimate the contemporaneous spillover effects that occur in the US and the UK stock markets.[1]

We contribute to the existing literature in three ways. First, we investigate volatility transmission between the US and UK stock markets taking into consideration the overlapping trading hours. Trading in the UK stock market starts while the US stock market is closed and continues for two hours after the US stock market opens, when both markets trade simultaneously. This implies that during the overlapping trading hours, shocks arriving from the US and UK stock markets can be incorporated instantaneously into the other market, while part of the US shocks can only affect the UK stock market on the next trading day. In particular, we use high frequency data and split the trading period in three: the period before the US market opens, the overlapping trading period and the period when the UK market is closed. For each of these trading periods, we compute the realized volatility which enables us to examine the contemporaneous spillover effects as the effects of, for example, the US volatility onto the UK volatility and the other way around. In doing so, our approach differs from the studies of Andersen et al. (2007) and of Ehrmann et al. (2011), which examine the

[1] There are several reasons for the choice of the US (S&P 500) and the UK (FTSE 100) stock markets. First, these markets share up to three hours of overlapping trading that allow us to examine the contemporaneous spillover effects, namely, the spillover effects that are transmitted on the same day. The use of the stock market indices, instead of futures, is motivated by the availability of the information during the simultaneous trading. A drawback of using the futures is the unavailability of information during the simultaneous trading for open outcry exchanges. As the main focus is the overlapping trading period, in contrast to the studies of e.g. Dimpfl and Jung (2012) and of Clements et al. (2014), we do not include Japan in our analysis. The US and the UK markets open/close after the Japanese market, therefore any information would be incorporated in these markets and would affect the Japanese market only on the following trading day. Second, the US and the UK are integrated (Morana and Beltratti, 2008) and related through trade and investments, so that any news in one country most likely has implications for the other country, hence, investors are able to trade simultaneously in both markets in response to shocks in either of the markets. For instance, Andersen et al. (2007) show that news is transmitted faster and there is direct spillover effect among the US and European equity markets.

contemporaneous effects at the return level and do not consider the partial overlap in trading times. Second, we use Rigobon's (2003) approach, which solves the identification problem allowing us to identify the contemporaneous and the dynamic spillover effects separetaly. By using this technique, our study differs from the existing studies on volatility transmission across stock markets like those of Clements et al. (2014) and of Dimpfl and Jung (2012), which solely investigate the lead-lag relations. Our investigation aims to highlight that although there are only up to three hours of overlapping trading between the US and UK, there is a strong instantaneous transmission of volatility between them that is necessary to be taken into account. Third, we highlight the implications of our model by comparing the dynamic relations, impulse responses and variance decomposition generated by our structural VAR with those of a traditional VAR.

Our investigation leads to several important results. First, we find that there are asymmetric contemporaneous spillover effects, where a shock occurring in the US market has a stronger effect on the UK volatility than vice versa. These finding highlight the important role played by the US market for the UK market. Second, we show that on the previous trading day, when the UK market is closed, the US volatility has a stronger effect on the volatilities of both US and UK during the overlapping trading period than the other way around. This is due to the fact that when the US and UK markets are trading simultaneously, their volatilities have stronger impacts on the US volatility on the same trading day. Third, we observe that during the overlapping trading period, UK volatility indirectly affects US volatility over the following trading days via its contemporaneous volatility spillover with the US. Overall, our findings clearly reveal that contemporaneous relations matter and not taking these into account leads to very different interpretations regarding volatility transmission among stock markets.

Our results have several important implications. First, we show that volatility shocks are transmitted instantaneously when US and UK trade simultaneously. As such, capturing these contemporaneous spillovers is useful for high frequency traders and could contribute to a better implementation of hedging strategies. Second, volatility serves as a proxy measure of risk and thus, is of relevance in financial applications that rely on conditional volatility. Our findings show that shocks causing volatility in the US and UK during the overlapping trading period have significant effects on the US volatility. This implies that the volatility of shocks hitting the markets when they are simultaneously trading is affecting both markets on the same trading day. Therefore, the estimation of the Value-at-Risk when contemporaneous spillover effects are not taken into account may not adequately capture the uncertainty faced, for instance, by a hedge fund. Moreover, we can expect that the Value-at-Risk calculations to be overestimated since the dynamic effects are overestimated in the reduced-form VAR.

The rest of the chapter is organized as follows. Section 2 reviews the literature on spillover effects and its applications. Section 3 presents the empirical setting. Section 4 discusses the data and Section 5 outlines the results. We conclude in Section 6.

3.2 Literature Review

The literature on the transmission of spillover effects can be classified into three groups. The first group includes papers that rely on traditional methods, such as GARCH and VAR models to identify lead-lag dynamics at the return and volatility level. The second group focuses on sampling at higher frequencies when analysing volatility transmission between markets across regions in an attempt to estimate contemporaneous spillovers. The last group uses a different estimation technique that relies on heterogeneity in the data to solve the problem of simultaneity and identify the contemporaneous relations. These studies have the ability to examine the instantaneous transmission of spillover effects when markets trade simultaneously. However, they do not investigate these dynamics by explicitly focusing on the overlapping trading hours between markets.

3.2.1 Traditional Methods

Among the first studies addressing the spillover effects in volatility is Engle et al. (1990) who introduce the concepts of "heat wave" and "meteor shower". A "heat wave" implies that financial asset volatility is influenced by the previous day's volatility in the same region. For instance, a hot day in New York, is likely to be followed by another hot day in New York, but not typically by a hot day in Tokyo. From another perspective, volatility is closely related to information flow, meaning that shocks are transmitted across borders. The transmission of volatility from one market to another in different regions refers to the concept of a "meteor shower". This is the case when, for example, a meteor shower in New York is likely to be followed by one in Tokyo. Using a GARCH model, Engle et al. (1990) test whether news in the yen/dollar exchange rates in the New York market can predict volatility in Tokyo and find a "meteor shower" effect. This finding contradicts the more natural expectation that volatility would instead continue in the same market the next day, the "heat wave" effect. Instead, Melvin and Melvin (2003) analyse the volatility transmission of exchange rates over different regions and find evidence of both effects, but the "heat wave" effects are larger in magnitude.

Hamao et al. (1990) propose one of the first methods to quantify the volatility spillover effects among different capital markets. They study the effects of volatility in three markets:[2] Tokyo, London and New York using a GARCH-M model. To measure the volatility transmissions from one period to the next within markets ("heat waves") and across markets ("meteor showers") the daily close-to-close returns are divided into close-to-open and open-to-close. They find volatility spillover effects from the US and the UK stock markets to the Japanese market and from the US to the UK market. Vice versa, the spillover effects are weaker from the Japanese market to the US and the UK

[2]See also, Koutmos and Booth (1995) and Lee and Rui (2002) who analyze the same regions. The former study estimates a multivariate E-GARCH model to test for spillover effects between the conditional first and second moments of returns and finds evidence of a "meteor shower" effect. The latter examines the dynamic relationship between the stocks and volume. Lee and Rui (2002) find a positive relation between the volumes and return volatility, therefore conclude that the US trading volume has a predictive power for the other two stock markets.

markets.

A similar approach is adopted by Lin et al. (1994), who investigate how returns and volatility are correlated between Tokyo and New York[3]. They use data which are divided into daily (open-to-close) and overnight (close-to-open) returns, and compare their results with those of Hamao et al. (1990). The results show the existence of bi-directional spillovers, i.e., daily returns of New York are correlated with Tokyo's overnight returns and vice versa. In contrast to Hamao et al. (1990), they find minor evidence of spillovers from daily returns in one market to daily returns in the other market.

Other studies measure volatility transmission from one period to the next within ("heat waves") and across markets ("meteor showers") at both return and volatility level using different extensions of GARCH models.

Kanas (2000) uses an EGARCH model and assumes a constant conditional correlation over time[4], in analyzing the volatility spillover between stocks and exchange rates in the US, Canada and several European countries (Germany France and the UK). He finds evidence of volatility spillover from stock returns to exchange rates in all countries except Germany. However, the reverse spillovers (exchange rates to stock returns) are insignificant. Using a BEKK-GARCH[5], Fang et al. (2006) analyze the causal transmission between stocks and bonds in the US and Japan. Their results show a bi-directional transmission of volatility, in the sense that volatility of the stock market has a greater influence on bond volatility.

The RiskMetrics approach of J. P. Morgan (1996) is another technique similar to the

[3]See also Karolyi (1995) who investigates the return and volatility spillovers between the New York and Toronto stock exchanges.

[4]See, Hakim and McAller (2010) who study the interactions between different assets and regions assuming conditional correlations are constant. They find evidence of mean and volatility spillover from each market to all other markets. However, they acknowledge that conditional correlations are not constant and future research might consider models that capture the time variation in the correlations.

[5]The BEKK model was defined in Engle and Kroner (1995) and is among the first parametric multivariate GARCH models. Its main advantage is that the conditional covariance matrices are positive definite by construction.

BEKK model of Engle and Kroner (1995) that imposes the same dynamics on all elements in a multivariate GARCH model. This model has been used by Martens and Poon (2001) to investigate the return and volatility spillover between European (France and the UK) and the US stock markets. Although they find no spillover at the return level, vice versa, at the volatility level there exists a spillover from the US to European stock markets. Savva et al. (2009) use the ADCC-GARCH model[6] and daily closing prices to analyze the spillover effects between the US and European (Germany, France and the UK) stock markets. Their results are in line with previous studies and show that domestic stock prices and their volatilities are influenced by the foreign market. However, they find larger spillover effects from the European markets to the US market than the reverse.

Diebold and Yilmaz (2009, 2012) use a different technique, the forecast error variance decomposition framework of a generalized VAR model to examine both return and volatility spillover effects among several different markets[7]. This model uses the contribution of spillovers of shocks to the total forecast error variance to compute the total spillover index which allows to identify the directional spillover indices, i.e., the markets as the transmitters and receivers of spillovers (Louzis, 2015). Several other studies use the so called "spillover index" in their analysis (Antonakakis, 2012; Fengler and Gisler, 2015; Louzis, 2015).

A common characteristic of the above studies is that they analyze the spillover effects focusing on the lead-lag relations among financial markets. Moreover, as these studies are mostly based on daily data, often cannot extract the volatility effects that are incorporated on the same trading day. This is the case, for example, when contemporaneous

[6]This model was introduced by Capiello et al. (2006) and captures the asymmetric behavior of volatility, i.e, volatility tends to increase more when negative shocks occur than when positive shocks occur.

[7]While Diebold and Yilmaz (2009) investigate the return and volatility spillover effects between the developed (the US, UK, France, Germany, Hong Kong, Japan and Australia) and emerging stock markets (Indonesia, South Korea, Malaysia, Philippines, Singapore, Taiwan, Thailand, Argentina, Brazil, Chile, Mexico and Turkey), Diebold and Yilmaz (2012) examine the volatility spillovers across the US stock, bond, foreign exchange and commodities markets.

spillover effects occur, i.e., two markets trade simultaneously and information from one market could be transmitted to another market on the same trading day. The next group of studies addresses the contemporaneous spillover effects by sampling at higher frequencies.

3.2.2 Sampling at Higher Frequencies

As a solution to identify the contemporaneous spillover effects, various studies split the returns into smaller periods, i.e., they increase the sampling frequency. For instance, Kim (2005) investigates the spillover effects between the US and Asia-Pacific stock markets by splitting the daily returns ($\text{close}_{\text{t-1}} - \text{to} - \text{close}_{\text{t}}$) into the overnight ($\text{close}_{\text{t-1}} - \text{to} - \text{open}_{\text{t}}$) and intradaily ($\text{open}_{\text{t}} - \text{to} - \text{close}_{\text{t}}$) returns. This study defines contemporaneous effects as the spillover effects that occur when there is an overlap between the daily, overnight and intradaily return periods in the US and Asia-Pacific markets. For example, the US intradaily return period on the previous day overlaps with the overnight period on the next day in the Asia-Pacific markets. The analysis reveals that this contemporaneous spillover is significant and the intraday Japanese returns have a positive contemporaneous effect on all overnight returns. These findings suggest that contemporaneous effects are actually treated as lagged effects, i.e., the spillover effects that are transmitted on the next trading day. Baur and Jung (2006) follow Kim's (2005) method of splitting daily returns to capture contemporaneous correlations and spillover effects between the US and German stock markets. They use high frequency data and the Aggregate-Shock model of Lin et al. (1994) for spillovers. Their main findings are that daytime returns significantly influence overnight returns in both markets and there is no spillover from the previous daytime stock returns of US to the morning German stock market.

Other studies use high frequency future data which capture more information and help in better estimating the spillover effects when there are no overlapping trading periods among markets. At the same time, the use of high frequency data is expected to result in improved inference on volatility transmissions across markets and asset classes over a short period. For instance, Martinez and Tse (2007) analyze volatility transmissions among the foreign exchange, equity and bond future markets in different regions using data sampled at a 1-minute frequency. They find evidence in all markets of both interregional ("meteor shower") and intraregional ("heat wave") volatility effects but as Melvin and Melvin (2003) found, the latter one is more pronounced. Similarly, Clements et al. (2014) use high frequency data sampled at a 10-minute frequency and show the presence of both "meteor shower" and "heat wave" effects between the foreign exchange, equity and bond future markets in the US, Japan and Europe.

To solve the problem with overlapping periods, Dimpfl and Jung (2012) restrict the observations to some relevant points in time. They employ a structural VAR model[8] and estimate the volatility transmission in Japanese, European and US equity future markets[9]. Their results indicate that there are mean spillovers from the US stock market to Japanese stock market and from the Japanse stock market to European stock market. In regard with volatility spillovers, they found all markets react more intensely to the previous market.

3.2.3 Heteroskedasticity Approach

One of the first studies investigating the identification problem when having simultaneous equation models is Rigobon (2003) who introduces the "identification through heteroskedasticity" technique. This technique allows us to properly identify the contemporaneous relations by making use of the data's heteroskedasticity. Practically, if in a simultaneous equation model, we observe non-proportional changes in volatility over time, then we can use these changes to identify the contemporaneous spillover effects. Using this method Rigobon (2003) examines the contemporaneous relations

[8]This model is used together with restrictions that reflect the chronological ordering of the financial markets and the fact that no spillover effects can occur on the same day among the markets.

[9]The Nikkei 225, Dow Jones Euro Stoxx 50 and the S&P 500 indices are used for Asia, Europe and respectively, United States.

among Argentina, Brazil and Mexico sovereign-bond yields and finds strong linkages across emerging markets.

Several studies use this "identification through heteroskedasticity" approach to estimate the contemporaneous spillover effects at the return level. For instance, Rigobon and Sack (2003b) use a structural GARCH model to examine the contemporaneous interactions between short-term interest rates, long-term interest rate and the stock market in the US. Their findings show that there are strong contemporaneous spillover effects between these variables.

Andersen et al. (2007) use a modified version of Rigobon's (2003) technique to identify the reaction of the US, German and British stock, bond and foreign exchange future markets to the real-time U.S. macroeconomic news. The study is based on high frequency data, estimating first the contemporaneous relations and then in a separate analysis the spillovers between bonds, stocks and exchange rates. The results show that there is a direct spillover between the equity markets and that bad news has negative impact during contractions, respectively, positive impact during expansions.

Ehrmann et al. (2011) study the transmission between money, bond and equity markets within and between the US and Europe using a multifactor model and the "identification through heteroskedasticity" approach. To avoid and reduce the importance of the overlapping trading hours between the US and Europe, they calculate the returns over a 2-day window. The results show the existence of spillovers within asset classes but also international cross-market spillovers. For instance, there is a spillover from the US equity market to the European money and bond markets but also an opposite spillover from the European money market to the US bond market. The US markets are explaining a proportion of 30% the European markets movements, whereas the European markets are only explaining around 6% of the US movements.

The previous literature investigates the return and volatility transmission of spillover effects among different markets and assets. These studies demonstrate that information revealed during trading hours in one market is transmitted to same market and to other markets on the next day. However, many markets around the world have overlapping trading hours. While some studies address the simultaneity issue by sampling at a higher frequency, others make use of the heterogeneity in the data. The latter technique together with the high frequency data allows us to estimate the contemporaneous spillover effects. Our study contributes to the related literature in that we analyze the spillover effects by distinguishing between the contemporaneous and dynamic spillover effects at volatility level. To estimate the spillover effects we combine Rigobon's approach based on the heteroskedasticity and the high frequency dataset with daily returns split in overlapping and non-overlapping trading periods.

3.3 Model

In this study, we explore the stock markets in the US and the UK.[10] We follow the approach of Rigobon (2003) and implemented by Ehrmann et al. (2011) in assessing volatility spillover effects among our markets.

We define the total trading day by splitting each day into three periods: UK non-overlapping ($\mathrm{UK^{NO}}$), UK/US overlapping ($\mathrm{UK^{O}}/\mathrm{US^{O}}$) and the US non-overlapping ($\mathrm{US^{NO}}$). All times are taken to be Greenwich Mean Time as follows:

$$\underbrace{\begin{array}{lll} \overbrace{8am \dots 2:30pm}^{\mathrm{UK^{NO}}} & \overbrace{2:30pm \dots 4:30pm}^{\mathrm{UK^{O}}} & \\ & \underbrace{2:30pm \dots 4:30pm}_{\mathrm{US^{O}}} & \underbrace{4:30pm \dots 9pm}_{\mathrm{US^{NO}}} \end{array}}_{\text{Total Trading Day}}$$

[10] We do not convert the indices into a common currency since this conversion would also incorporate the currency exchange rate risk. In other words, the converted indices might reveal some behaviour due to the behaviour of the common currency. Moreover, the behaviour of the exchange rate might offset changes in the domestic equity market and thus hide the underlying behaviour of the domestic market. As such, our investigation focuses on the contemporaneous spillovers among equity markets at a global rather than local level.

When creating the total trading day, we account also for Daylight Saving Time, i.e., the number of overlapping/non-overlapping trading hours is changing, e.g., from three hours overlapping trading to two hours overlapping trading.

We calculate the intraday returns for all assets based on the formula: $\Delta P_i = log(P_i) - log(P_{i-1})$, where the P_i is the intraday price. Once we have the intraday returns, we construct realized variances[11] as $RV_t^j = log(\sum_{i=1}^{N}(\Delta P_i)^2 \frac{T}{t_j})$, with $j = \{UK^{NO}, UK^{O}, US^{O}, US^{NO}\}$, $T = 24$ and t_j is the number of trading hours in the j^{th} trading period. We implement the scaling by T/t_j to have all volatility measures expressed on the same time interval (in our case we express volatility on a 24 hour basis).

We model the realized variances using a structural VAR (SVAR) process:

$$\mathbf{A}RV_t = c + \mathbf{\Phi}(\mathbf{L})RV_t + \varepsilon_t \tag{3.1}$$

where RV_t is a (4×1) vector consisting of the realized variances for different periods, i.e.,

$$RV_t = \begin{pmatrix} RV_t^{UK^{NO}} & RV_t^{UK^{O}} & RV_t^{US^{O}} & RV_t^{US^{NO}} \end{pmatrix}', \tag{3.2}$$

where $RV_t^{UK^{NO}}$ is the UK stock market volatility during the non-overlapping trading period, $RV_t^{UK^{O}}$ is the UK stock market volatility during the overlapping trading period, $RV_t^{US^{O}}$ is the US stock market volatility during the overlapping period, $RV_t^{US^{NO}}$ is the US stock market volatility during the non-overlapping trading period, c is a (4×1) vector of constants and $\mathbf{\Phi}(\mathbf{L})$ is a (4×4) matrix polynomial in the lag operator. The (4×4) matrix $\mathbf{A}$ captures the contemporaneous effects between the realized variances and has the following structure,

$$\mathbf{A} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ \alpha_{21} & 1 & \alpha_{23} & 0 \\ \alpha_{31} & \alpha_{32} & 1 & 0 \\ \alpha_{41} & \alpha_{42} & \alpha_{43} & 1 \end{pmatrix}, \tag{3.3}$$

[11] Andersen et al. (2003) demonstrate that by taking the logarithm of volatility the series will become close to the normal distribution allowing us to conduct the estimation in a straightforward manner.

where, e.g., α_{23} captures the contemporaneous spillover from $RV_t^{US^O}$ to $RV_t^{UK^O}$ and α_{32} captures the contemporaneous spillover from $RV_t^{UK^O}$ to $RV_t^{US^O}$. The other parameters are defined likewise. We set exclusion restrictions on matrix **A** according to the trading day, allowing for spillovers in one direction, forward. The spillovers from both overlapping trading periods to UK^{NO} as well as from the US^{NO} to $\text{UK}^{\text{NO}}/\text{US}^{\text{O}}$ and UK^{NO} to UK^{O} are set to zero.

An initial point to the identification strategy is to estimate the reduced-form VAR by premultiplying Equation (3.1) by $\mathbf{A^{-1}}$:

$$RV_t = c^* + \mathbf{\Phi}(\mathbf{L})^* RV_t + u_t \tag{3.4}$$

The coefficients of Equation (3.4) can be estimated by OLS and are related to the structural coefficients by: $c^* = \mathbf{A^{-1}}c, \mathbf{\Phi}(\mathbf{L})^* = \mathbf{A^{-1}}\mathbf{\Phi}(\mathbf{L}), u_t = \mathbf{A^{-1}}\varepsilon_t$ and $u_t \sim N(0, \mathbf{\Omega_t})$ where $\mathbf{\Omega_t} = \mathbf{A^{-1}}\mathbf{\Sigma_t}\ \mathbf{A^{-1}}'$.

When analyzing the contemporaneous spillover effects between the US and UK stock market volatilities which are captured by **A**, we face a problem that is also present in simultaneous equations models, i.e., endogeneity. That is, the volatility transmission between the US and UK overlapping periods occurs at the same point in time. Therefore, matrix **A** cannot be identified from Equation (3.1) through estimation of the reduced-form VAR in Equation (3.4).

Many studies (Baur and Jung, 2006; Antonakakis, 2012; Louzis, 2015) focus on lead-lag relations to identify the spillover effects between different markets/assets and regions and are not able to capture the contemporaneous spillover effects. Others (Dimpfl and Jung, 2012; Diebold and Yilmaz, 2009; Clements et al., 2015) use Cholesky decompositions and sign restrictions for the identification of the contemporaneous spillover effect. However, orthogonalization is an assumption on the direction of causality. Given that markets trade simultaneously assuming unidirectional spillovers may be unreasonable. In addition, imposing a large number of restrictions might be unreasonable from an economic point of view since might require a priori information with regard to, for instance, the sign of spillover effects.

Rigobon (2003) proposes a way to solve the simultaneity issue, namely, the "identification through heteroskedasticity" approach. In this approach, the existence of heteroskedastic regimes can solve the identification problem when having a simultaneous equation model. Essentially, to identify matrix **A** which captures the contemporaneous spillover effects, we have to impose three assumptions. First, we assume that the structural shocks, ε_t, from Equation (3.1) are uncorrelated. The variance of ε_t shows conditional heteroskedasticity. Namely, $\varepsilon_t \sim N(0, \mathbf{\Sigma_t})$, where $\mathbf{\Sigma_t}$ is a diagonal matrix based on the first assumption. Second, the matrix **A** is constant across regimes. Third, there must exist at least two regimes of distinct variances $\mathbf{\Omega_t}$.

Following Ehrmann et al. (2011) we compute 50-day rolling windows variances from the reduced form residuals, u_t, that contain only the contemporaneous effects. We define five volatility regimes based on when the 50 day variances are higher than the residuals average standard deviation over the full sample plus the threshold value of 0.8. The first regime consists of observations where all variables show lower than normal volatility. The other four regimes are defined as: a high $\mathrm{UK}^{\mathrm{NO}}$ volatility regime, a high UK^{O} regime, a high US^{O} regime and a high $\mathrm{US}^{\mathrm{NO}}$ regime. These five regimes allow to obtain the non-proportional shifts among our variances, which we need to identify the parameters in **A**. For example, if we observe non-proportional changes in the variance of the stock market volatility shocks in the $\mathrm{US}^{\mathrm{NO}}$, that will affect the covariance between volatilities in the $\mathrm{US}^{\mathrm{NO}}$ and $\mathrm{UK}^{\mathrm{NO}}$, i.e., we are able to better examine the responsiveness of the $\mathrm{UK}^{\mathrm{NO}}$ volatility to the $\mathrm{US}^{\mathrm{NO}}$ stock market volatility shocks. If there is no significant change between variances or they shift proportionally then the system is not identified.

The covariance matrices of each regime are then used in the GMM estimation of the spillover coefficients.

$$min\ \mathbf{d}'\ \mathbf{d}\ with\ \mathbf{d} = \mathbf{A}'\mathbf{\Omega_t}\mathbf{A} - \mathbf{\Sigma_t} \tag{3.5}$$

where $\mathbf{\Sigma_t}$ is the variance of the structural shocks assumed to be uncorrelated, which we are interested in, and $\mathbf{\Omega_t}$ is the variance-covariance matrix that we estimate in each regime t.

To assess the significance of the structural dynamic spillover effects, $\mathbf{\Phi(L)}$ and matrix $\mathbf{A}$ from Equation (3.1) we implement a bootstrap procedure similar to Ehrmann et al. (2011). Specifically, we simulate the residuals for each of the five regimes, by drawing random variables from a standard normal distribution. We then premultiply these random variables for each of the five regimes by the Cholesky decomposition of our residuals from our original regimes. These simulated residuals will have the same covariance structure for each of the regimes that they belong to. Next, using the simulated residuals we simulate the dependent variable, RV_t, and re-estimate the VAR model, and re-estimate the coefficients in matrix $\mathbf{A}$ by GMM. We repeat this process 1,000 times which allows us to calculate the empirical p-values and confidence intervals for the parameter estimates.

3.4 Data

We use high frequency data sampled at a 5-minute[12] frequency for the US and UK stock markets. The data are obtained from Thomson Reuters Tick History and cover the period from 3 January 2007 to 31 December 2013. Days where one market is closed, as well as public holidays are eliminated from the sample. For our analysis, we employ the S&P500/FTSE 100 indices for the US/UK stocks traded on New York Stock Exchange (NYSE), respectively, London Stock Exchange (LSE).[13]

In Table 3.1, we provide summary statistics for realized volatilities in the US and UK

[12]See Liu et al. (2015) which consider almost 400 realized measures, across seven different classes of estimators, and compare them with the simple "realized variance" (RV) estimator. They found that it is difficult to significantly beat the 5-minute RV.

[13]In addition to the S&P500 index, we have also conducted our analysis using the Dow Jones and Nasdaq indexes. The results for these alternative US indices are in line with those presented in this paper, showing that the results are robust to the choice of the index. The use of alternative indexes also safeguards our results from the effects of companies that might be included in the indexes of both markets. The results for this additional analysis are available on request.

Table 3.1: Summary Statistics

	$V_t^{UK^{NO}}$	$V_t^{UK^{O}}$	$V_t^{US^{O}}$	$V_t^{US^{NO}}$
Mean	0.0147	0.0182	0.0191	0.0159
Max	0.1874	0.1215	0.1863	0.1245
Min	0.0042	0.0037	0.0043	0.0031
Std.Dev.	0.0104	0.0111	0.0130	0.0134
Skew.	5.46	2.46	3.49	3.30
Kurt.	63.07	13.11	27.15	18.61
ADF	-6.36^{***}	-5.00^{***}	-5.61^{***}	-4.98^{***}

Note: This Table reports summary statistics for the equity volatilities defined as $V_t^j = \sqrt{\sum_{i=1}^{N}(\Delta P_i)^2}$, i.e., $V_t^{UK^{NO}}$, $V_t^{UK^{O}}$, $V_t^{US^{O}}$ and $V_t^{US^{NO}}$, in all four trading periods. ADF is the t-statistics for the Augmented Dickey-Fuller test. *** denote the significance at the 1% level.

during both overlapping and non-overlapping trading periods. These realized volatilities are computed as follows

$$V_t^j = \sqrt{\sum_{i=1}^{N}(\Delta P_i)^2 \times \frac{T}{t_j}}, \tag{3.6}$$

where $T = 24$, and t_j is the time in hours of the j^{th} trading period. This scaling ensures that all realized volatilities are expressed as volatilities per 24 hours and makes them comparable.[14] As can be seen, the highest level of volatility is during the trading period when only the US market is open, followed by the US and UK overlapping trading periods. The highest mean volatility and variability is in the US overlapping trading period. Skewness is positive in all trading periods. This implies that positive changes in equity markets occur more often than negative changes. The excess kurtosis in all four series implies that large changes occur more often than is the case of normally distributed series. Augmented Dickey Fuller tests reject the null hypothesis of a unit root and confirm the stationarity of equity volatilities.

[14]Note that in the main analysis, we model the log of realized variances as presented in Section 3.3. We report the realized volatilities in the Table 3.1, as volatilities are more commonly reported than variances.

Table 3.2: Correlation Matrix between Realized Variances

	$RV_t^{UK^{NO}}$	$RV_t^{UK^{O}}$	$RV_t^{US^{O}}$	$RV_t^{US^{NO}}$
$RV_t^{UK^{NO}}$				
$RV_t^{UK^{O}}$	0.8472			
$RV_t^{US^{O}}$	0.8203	0.9088		
$RV_t^{US^{NO}}$	0.8160	0.8306	0.8553	

Note: This Table reports the correlation matrix among the realized variances, $RV_t^{UK^{NO}}$, $RV_t^{UK^{O}}$, $RV_t^{US^{O}}$ and the $RV_t^{US^{NO}}$.

Table 3.2 presents the correlations between the realized variances in all four trading periods. We notice the existence of a positive relation between the volatilities of both the US and UK trading periods. Moreover, we can see that the correlation between the volatilities of both, the US and UK overlapping trading periods is higher than the correlation between the volatilities of the US and UK non-overlapping trading periods. This suggests that there are contemporaneous spillover effects between the US and UK overlapping trading periods. However, the correlation matrix does not give us the direction of causality which can run in both sides. For instance, when markets trade simultaneously the spillover from UK stock market volatility to US stock market volatility is different than the spillover from the US stock market volatility to UK stock market volatility. The next section addresses these relations.

3.5 Results

3.5.1 Granger Causality

We start our analysis with the estimation of the reduced form VAR using Equation (3.4). To select the optimal lag length we use the Akaike Information Criterion which is equal to 5.26 and find a lag length of 5 days to be optimal. As such, we carry out all our analysis with a 5-day lag length. We examine the relations among the realized variances performing Granger causality tests.

Table 3.3: Granger Causality for Realized Variances

Null Hypothesis	5 lags	
	F-statistics	P-value
$RV_t^{UK^O}$ does not Granger cause $RV_t^{UK^{NO}}$	36.28***	0.00
$RV_t^{UK^{NO}}$ does not Granger cause $RV_t^{UK^O}$	7.85***	0.00
$RV_t^{US^O}$ does not Granger cause $RV_t^{UK^{NO}}$	20.25***	0.00
$RV_t^{UK^{NO}}$ does not Granger cause $RV_t^{US^O}$	6.71***	0.00
$RV_t^{US^{NO}}$ does not Granger cause $RV_t^{UK^{NO}}$	44.36***	0.00
$RV_t^{UK^{NO}}$ does not Granger cause $RV_t^{US^{NO}}$	2.92**	0.01
$RV_t^{US^O}$ does not Granger cause $RV_t^{UK^O}$	2.29**	0.04
$RV_t^{UK^O}$ does not Granger cause $RV_t^{US^O}$	6.55***	0.00
$RV_t^{US^{NO}}$ does not Granger cause $RV_t^{UK^O}$	25.79***	0.00
$RV_t^{UK^O}$ does not Granger cause $RV_t^{US^{NO}}$	7.18***	0.00
$RV_t^{US^{NO}}$ does not Granger cause $RV_t^{US^O}$	47.26***	0.00
$RV_t^{US^O}$ does not Granger cause $RV_t^{US^{NO}}$	5.07***	0.00

Note: This Table reports the results for the Granger causality tests on the reduced-form VAR. The reduced-form VAR is estimated using 5 lags. We present F-statistics and their associated P-values. *** and ** denote significance at the 1% and 5% levels, respectively.

The results of the Granger causality tests for realized variances of stocks markets are presented in Table 3.3 with corresponding values of F-tests. We observe strong, significant bidirectional Granger causalities between stock market volatilities in all trading periods. The US^{NO} stock market volatility Granger causes the volatility in both overlapping trading periods, UK^{O} and US^{O}, stronger than the other way around. This significant causality highlights the importance of US^{NO} stock market volatility and its spillover effect on UK^{O} and US^{O} stock market volatilities. Strong Granger causality can also be observed between the volatilities of both the US and the UK overlapping trading periods. This suggests that there are causal effects between the volatilities during the overlapping trading period. Interestingly, the Granger causality running from the volatility of the UK overlapping trading period to the volatility of the US overlapping trading period is stronger than the other way around. This implies that past UK^{O}

volatility, in addition to past US^{O} volatility, explains the future volatility of US^{O}.

In sum, our results imply that in both overlapping and non-overlapping trading periods stock market volatilities significantly Granger cause the volatilities in every other trading period. We find that the US non-overlapping stock market volatility has a significant effect on the volatilities of both overlapping trading periods. Moreover, the volatility of the US overlapping trading period has a lower effect on the volatility of the UK overlapping trading period than the other way around.

The Granger causality tests provide information only about which variable we can use in the future as explanatory variable, to clarify the behaviour of other variables in the VAR. Moreover, these Granger causality tests capture the dynamic relations, namely, the lead-lag relations, and might not reflect all the causal effects among our realized variances. For instance, Table 3.3 indicates that the bidirectional Granger causality between the US^{NO} and UK^{NO} stock market volatilities is stronger than the bidirectional Granger causality between the volatilities of both US and UK overlapping trading periods, whereas Table 3.2 shows a higher correlation between the US and UK volatilities during the overlapping trading period than the US and UK volatilities during the non-overlapping trading period. This implies that Granger causality tests may not capture the contemporaneous spillover effects. These contemporaneous effects are presented in next section.

3.5.2 Structural Form Results

In this section, we present the findings for the model explained in Section 3.3. Further, we present the results regarding both, contemporaneous and dynamic spillover effects. In addition, we emphasize the implications of the SVAR model by comparing the dynamic relations, impulse responses and variance decomposition with the results generated by the reduced-form VAR model.

I. Contemporaneous Relations

In Table 3.4, we present the contemporaneous relations, matrix **A** as given in Equation (3.1) together with the bootstrap results. The coefficients have negative signs as matrix **A** is on the left-hand side of Equation (3.1), as such when taken to the right-hand side the spillover effects become positive. We identify the following relations:

$$RV_t^{UK^O} = -0.14RV_t^{UK^{NO}} + 0.25RV_t^{US^O} \tag{3.7}$$

$$RV_t^{US^O} = 0.12RV_t^{UK^{NO}} + 0.18RV_t^{UK^O} \tag{3.8}$$

$$RV_t^{US^{NO}} = 0.23RV_t^{UK^{NO}} + 0.29RV_t^{UK^O} + 0.37RV_t^{US^O} \tag{3.9}$$

We notice a high and positive contemporaneous spillover of 0.25 from the volatility of the US overlapping trading period to the volatility of the UK overlapping trading period. The coefficient suggests that a 1% increase in the $\mathrm{US^O}$ volatility leads to a contemporaneous increase of 0.25% in the $\mathrm{UK^O}$ volatility. Vice versa, the $\mathrm{UK^O}$ volatility has a smaller impact on the $\mathrm{US^O}$ volatility, approximately 0.18 indicating that the $\mathrm{US^O}$ stock market volatility is less sensitive to the $\mathrm{UK^O}$ stock market volatility shocks than the other way around. These results highlight the dominant role of $\mathrm{US^O}$ in transmitting the volatility to $\mathrm{UK^O}$. Note that these results are inconsistent with Granger causality findings presented in Table 3.3, which indicated that the $\mathrm{UK^O}$ volatility has a stronger effect on the $\mathrm{US^O}$ volatility than the other way around. These differences in the results are due to the fact that Granger causality tests consider just the lagged effects without considering contemporaneous effects.

When we consider the spillover effect of the $\mathrm{UK^{NO}}$, $\mathrm{UK^O}$ and $\mathrm{US^O}$ volatilities, on the $\mathrm{US^{NO}}$ volatility, we observe the highest and most significant spillover from the $\mathrm{US^O}$ volatility to the $\mathrm{US^{NO}}$ volatility, with the coefficient of around 0.37, suggesting that a 1% increase in the $\mathrm{US^O}$ stock market volatility leads to an increase of 0.37% in the $\mathrm{US^{NO}}$ stock market volatility. This spillover is again not evident from the Granger causality tests reported in Table 3.3, which showed the opposite, namely, that the causality running from the $\mathrm{US^{NO}}$ volatility to the $\mathrm{UK^O}$ volatility is stronger than the other way

Table 3.4: Contemporaneous Relation between Realized Variances

	Parameter estimates	Bootstrap	
		Mean	Confidence Intervals
α_{21}	0.1393***	0.1379	[0.1133, 0.1583]
α_{23}	−0.2533***	−0.2530	[−0.2632, −0.2420]
α_{31}	−0.1197***	−0.1225	[−0.1479, −0.1156]
α_{32}	−0.1796***	−0.1805	[−0.1931, −0.1762]
α_{41}	−0.2286***	−0.2279	[−0.2384, −0.2137]
α_{42}	−0.2935***	−0.2934	[−0.3040, −0.2822]
α_{43}	−0.3663***	−0.3659	[−0.3754, −0.3556]

Note: This Table reports the contemporaneous relation, matrix **A** as given in Equation (3.1). We present coefficients together with their associated mean and 95% confidence intervals obtained in a bootstrap. Judging through the p-value from bootstrap all coefficients are significant at the 1% level. The vector of variables is $RV_t = \left(RV_t^{UK^{NO}} \quad RV_t^{UK^{O}} \quad RV_t^{US^{O}} \quad RV_t^{US^{NO}}\right)'$. The coefficient α_{23} indicates the spillover effect from $RV_t^{US^{O}}$ to $RV_t^{UK^{O}}$. Vice versa, the coefficient α_{32} shows the spillover effect from $RV_t^{UK^{O}}$ to $RV_t^{US^{O}}$. The other parameters are defined likewise.

around. This finding demonstrates that the reduced-form VAR model is not able to recover these spillover effects. Interestingly, if we compare the spillover from the UK^{NO} and UK^{O} volatilities to the US^{NO} volatility, we notice that the latter spillover is 0.29, greater than the former spillover, with the value about 0.23. These results underline the importance of taking into account both UK^{O} and US^{O} volatilities that have significant effects on the US^{NO} volatility simultaneously.[15]

In sum, our analysis so far implies the existence of strong contemporaneous effects that are not captured by the reduced-form VAR model. Essentially, when markets trade simultaneously a shock occurring in either the US or UK stock markets is transmitted instantaneously between the volatilities of the stock markets during the overlapping trading period and affects the US^{NO} volatility on the same day.

[15] In additional robustness tests, we split our sample in two: the period covering the global financial crisis (GFC) and the period following the GFC, to assess whether the GFC affected the spillover between markets. The main results presented in this paper are also observed in both subperiod, although we do observe that the magnitude of the spillovers decreased somewhat following the GFC (especially the effect of UK volatility on US volatility). The decrease in the magnitude of the spillover corroborates the results of Dimpfl and Peter (2014) who show that there is a reduction in information flow following the GFC. The results of this robustness test are available on request.

II. Reduced-Form versus Structural Dynamic Relations

This section aims to shed light on the transmission of volatility by comparing the dynamic reduced-form VAR effects, $\mathbf{\Phi}(\mathbf{L})^*$ as given in Equation (3.4), and the structural dynamic effects, $\mathbf{\Phi}(\mathbf{L})$ as given in Equation (3.1). Thus, by comparing these effects we aim to to highlight the importance of examining the contemporaneous effects. The reduced-form dynamic effects are a combination of the structural dynamic and contemporaneous effects, which are not identified in the reduced-form VAR model. As such, if contemporaneous spillovers are not taken into consideration, we are unable to distinguish between the impacts of volatility shocks that are transmitted on the same trading day and those impacts that are transmitted on next trading day among our stock markets. The identification of contemporaneous spillover effects allows us to determine the structural dynamic interactions between our variables. In particular, having the total spillover, i.e., $\mathbf{\Phi_1^*}$ and understanding how much of spillover is due to the contemporaneous interactions, i.e., $\mathbf{A}$, we are able to explore the structural dynamic linkages, i.e., $\mathbf{\Phi_1}$. Table 3.5 reports the 1st order dynamic reduced-form VAR effects, $\mathbf{\Phi_1^*}$ and the 1st order structural dynamic relations, matrix $\mathbf{\Phi_1}$ alongside with the bootstrap results.

When comparing the dynamic SVAR effects with the dynamic reduced form VAR effects, in Table 3.5, we observe that they lead to different results with regard to the impact of volatility shocks that are transmitted on the next trading day. We find a positive dynamic spillover from the US^{NO} previous day's volatility to the volatilities of both US and UK overlapping trading periods with the values of 0.22 and 0.32 in the reduced-form VAR, respectively, while we notice a lower dynamic spillover of 0.17 and 0.25 in the SVAR. These results imply that transmission of volatility is overestimated in the reduced-from VAR model. Moreover, the spillover effects are large as volatility present during the previous trading day in the US^{NO} can only be transmitted to the US and the UK overlapping trading periods with delay, i.e., the next trading day. Instead, if volatility can be transmitted instantaneously, namely, when markets trade simultaneously, we find there is no evidence of significant dynamic spillover effects. For

Table 3.5: The 1st order Reduced Form and Structural Effects between Realized Variances

Parameter estimates	RF VAR	SVAR	Bootstrap Mean	Bootstrap Confidence Intervals
Panel A: Dynamic transmission to $RV_t^{UK^{NO}}$				
ϕ_{11}^* and ϕ_{11}	0.2101	0.2101***	0.2096	[0.1535, 0.2671]
ϕ_{12}^* and ϕ_{12}	0.2225	0.2225***	0.2219	[0.1735, 0.2676]
ϕ_{13}^* and ϕ_{13}	−0.0637	−0.0637*	−0.0623	[− 0.1338, 0.0057]
ϕ_{14}^* and ϕ_{14}	0.2114	0.2114***	0.2112	[0.1664, 0.2564]
Panel B: Dynamic transmission to $RV_t^{UK^{O}}$				
ϕ_{21}^* and ϕ_{21}	0.1017	0.1287***	0.1300	[0.0614, 0.1992]
ϕ_{22}^* and ϕ_{22}	0.2320	0.2446***	0.2405	[0.1814, 0.2952]
ϕ_{23}^* and ϕ_{23}	−0.0538	−0.1095**	−0.1071	[− 0.1885, −0.0265]
ϕ_{24}^* and ϕ_{24}	0.2191	0.1684***	0.1682	[0.1154, 0.2210]
Panel C: Dynamic transmission to $RV_t^{US^{O}}$				
ϕ_{31}^* and ϕ_{31}	0.0087	−0.0348	−0.0342	[− 0.0828, 0.0167]
ϕ_{32}^* and ϕ_{32}	0.0727	0.0044	0.0050	[− 0.0362, 0.0463]
ϕ_{33}^* and ϕ_{33}	0.1848	0.2021***	0.2009	[0.1372, 0.2664]
ϕ_{34}^* and ϕ_{34}	0.3164	0.2517***	0.2511	[0.2114, 0.2887]
Panel D: Dynamic transmission to $RV_t^{US^{NO}}$				
ϕ_{41}^* and ϕ_{41}	−0.0248	−0.1058***	−0.1042	[− 0.1755, -0.0314]
ϕ_{42}^* and ϕ_{42}	0.0996	−0.0460	−0.0458	[− 0.1035, 0.0153]
ϕ_{43}^* and ϕ_{43}	0.0451	0.0078	0.0083	[− 0.0868, 0.0944]
ϕ_{44}^* and ϕ_{44}	0.3949	0.1664***	0.1645	[0.1088, 0.2177]

Note: This Table reports the reduced-form, matrix $\mathbf{\Phi_1^*}$ and structural, matrix $\mathbf{\Phi_1}$ dynamic relations, as given in Equation (3.4) and respectively, in Equation (3.1). We present coefficients together with their associated mean and 95% confidence intervals obtained in a bootstrap. ***, ** and * denote significance at the 1%, 5% and 10% levels, respectively. The vector of variables is $RV_t = \left(RV_t^{UK^{NO}} \quad RV_t^{UK^{O}} \quad RV_t^{US^{O}} \quad RV_t^{US^{NO}}\right)'$. The coefficient $\phi_{12}{}^*$ indicates the spillover effect from $RV_{t-1}{}^{UK^{O}}$ to $RV_t^{UK^{NO}}$. Vice versa, the coefficient $\phi_{21}{}^*$ shows the spillover effect from $RV_{t-1}{}^{UK^{NO}}$ to $RV_t^{UK^{O}}$. The other parameters are defined likewise.

instance, a 1% increase in the $\mathrm{UK^{O}}$ and $\mathrm{US^{O}}$ previous day's volatilities lead to an increase in the $\mathrm{US^{NO}}$ volatility equal to 0.10% and 0.05%, respectively, in the reduced-form, versus a decrease of -0.05% and increase of 0.01% in the structural form. This suggests that volatility is transmitted on the same day when there is simultaneous trading between the US and UK stock markets.

Overall, our analysis reveals that the volatilities of both US and UK overlapping trading periods are influenced by the $\mathrm{US^{NO}}$ previous day's volatility, whereas vice versa, the

US^{NO} volatility is less affected by previous day's volatilities of both US and UK overlapping trading periods. These findings highlight the importance of taking into account the contemporaneous spillover effects. Essentially, the volatilities of the US and UK overlapping trading periods have higher positive impacts on the US^{NO} volatility that are transmitted on the same day, and vice versa, the US^{NO} stock market volatility only affects the next trading day's stock market volatilities of the US and UK overlapping trading periods. Moreover, we find that these dynamic relations are overestimated in the reduced-form VAR model. This is because the reduced-form dynamic effects capture the total spillover without distinguishing between the share of spillover that is due to either contemporaneous or structural dynamic interactions.

III. Impulse Response Functions and Variance Decompositions

In the previous sections, we emphasized the relevance of the contemporaneous spillover effects and the differences that are observed between the reduced-form and structural dynamic relations. In this section, we highlight the importance that these differences make for the outcomes of impulse response functions and variance decompositions.[16]

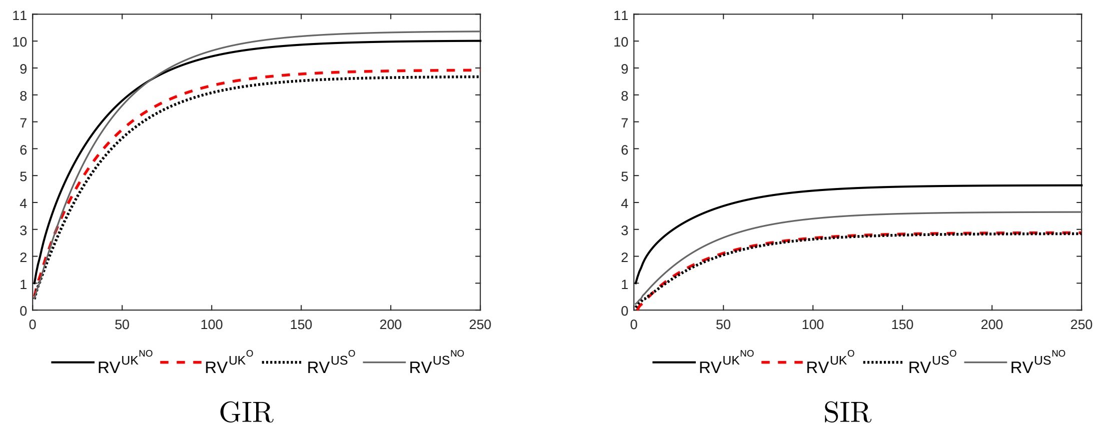
For the impulse response functions, we apply unit shocks to our variables and obtain their cumulative responses for up to 250 steps ahead. However, to compute the responses of the other variables correctly, we need to know the contemporaneous shocks that need to be applied to the other variables in the system. In the reduced-form form VAR we do this by calculating the impulse responses using the generalized impulse response functions of Pesaran and Shin (1998) which are invariant to the ordering of the volatilities in the reduced-form VAR. For the structural VAR, the initial shock vectors is known, and is based on the structural parameters of matrix $\mathbf{A}$. Specifically, the initial shock vector is given by $\mathbf{A}^{-1}$.

In Figure 3.1, we plot the cumulative impulse response functions for up to 250 steps

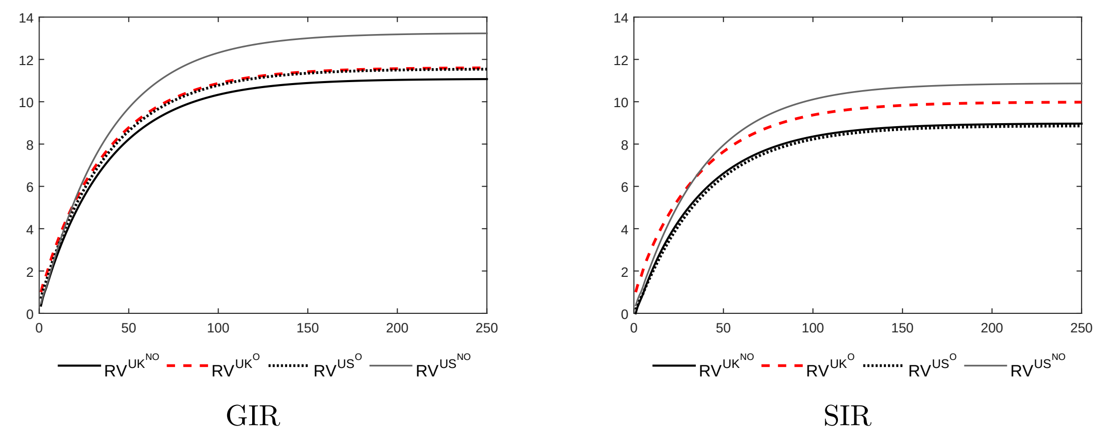
[16]Given that many studies (e.g., Louzis, 2015; Baur and Jung, 2006; Clements et al., 2015) rely only on reduced-form model to estimate the spillover effects, we feel that it is important to highlight the implications of the structural model with the results generated by the reduced-from model.

Figure 3.1: Generalized vs. Structural Impulse Response Functions

Panel A: Responses to a Unit Shock to $RV^{UK^{NO}}$



Panel B: Responses to a Unit Shock to $RV^{UK^{O}}$

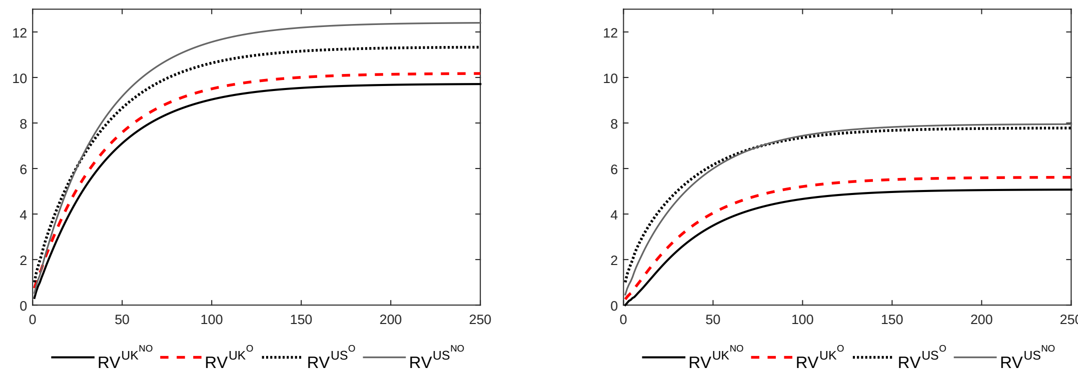


ahead for the generalized impulse responses (GIR) in the first column, and for the structural impulse responses (SIR) in the second column. As we can see from the graphs, the results from the reduced form and the structural VAR can differ considerably. We note that 1. the GIR tends to overestimate the overall long-run reaction compared with the SIR; and 2. the orderings of the long-run impacts differ frequently between the GIR and SIR (e.g. in Panel A, we observe that according to the GIR, a unit shock to $RV^{UK^{NO}}$ has the largest long-run impact to $RV^{UK^{O}}$, while the SIR shows that the largest impact will be on $RV^{UK^{NO}}$).

In addition to the impulse response functions, we can also consider a long-run vari-

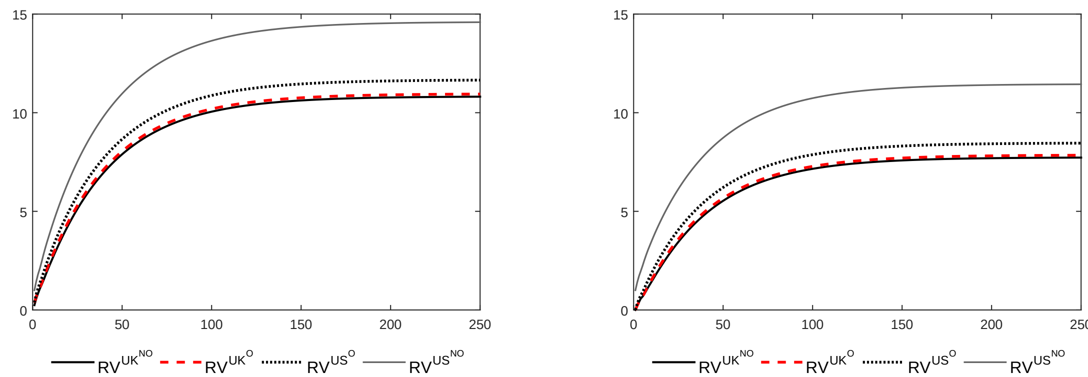
Figure 3.1 (cont.): Generalized vs. Structural Impulse-Response Functions

Panel C: Responses to a Unit Shock to $\mathrm{RV}^{\mathrm{US}^{\mathrm{O}}}$



GIR SIR

Panel D: Responses to a Unit Shock to $\mathrm{RV}^{\mathrm{US}^{\mathrm{NO}}}$



GIR SIR

Note: This Figure shows the generalized and structural impulse response functions. In particular, Panel A, B, C and D show the responses to a unit shock in $RV^{UK^{NO}}$, $RV^{UK^{O}}$, $RV^{US^{O}}$ and respectively, $RV^{US^{NO}}$. The left column plots the generalized impulse responses based on the reduced-form VAR, whereas the right column plots the structural impulse responses based on the structural VAR. The x-axis is the number of days ahead and the y-axis is the accumulated responses.

ance decomposition, i.e., the share of the total variance of the $\mathrm{UK}^{\mathrm{NO}}$, UK^{O}, US^{O} and $\mathrm{US}^{\mathrm{NO}}$ volatilities that is explained by the reduced-form and structural shocks to each of the stock market volatilities. Table 3.6 reports the 250-day ahead forecast error variance decomposition, where each cell indicates the percentage contribution of shocks in explaining the share of the total variance of each stock market volatilities.

Table 3.6: Variance Decomposition

		Reduced Form shock				Structural shock			
		$RV_t^{UK^{NO}}$	$RV_t^{UK^{O}}$	$RV_t^{US^{O}}$	$RV_t^{US^{NO}}$	$RV_t^{UK^{NO}}$	$RV_t^{UK^{O}}$	$RV_t^{US^{O}}$	$RV_t^{US^{NO}}$
Variance	$RV_t^{UK^{NO}}$	33.65%	25.35%	18.51%	22.49%	37.66%	31.92%	8.17%	22.24%
	$RV_t^{UK^{O}}$	17.51%	35.71%	24.22%	22.56%	4.18%	61.31%	11.41%	23.08%
	$RV_t^{US^{O}}$	13.90%	27.37%	33.64%	25.09%	2.81%	25.48%	45.61%	26.08%
	$RV_t^{US^{NO}}$	15.34%	24.65%	22.72%	37.29%	3.91%	28.71%	18.02%	49.36%

Note: This Table reports the share of the variance of each realized variances, $RV_t^{UK^{NO}}$, $RV_t^{UK^{O}}$, $RV_t^{US^{O}}$ and $RV_t^{US^{NO}}$, that is explained by the reduced-form and structural shocks. The variance decomposition are computed at the 250-day ahead response to a unit structural shock.

As with the impulse-response functions, we observe clear differences between the reduced form and structural shocks. We find that the largest shares of the stock market variances are due to their own shocks. When comparing the contribution of the own reduced-form and structural shocks, we notice that reduced-form shocks explain a smaller amount of the stock market volatilities ranging between 34% and 37%, versus the structural shocks that vary between 38% and 61%. The impacts of shocks on the variances of other markets also differ substantially between the reduced form and structural model. For instance, a shock to $RV^{UK^{NO}}$ has a much larger impact on the variances of the other markets according to the reduced form model than compared with the structural model.

In sum, our results clearly show that impulse-response functions and variance decompositions based on the reduced-form VAR and SVAR lead to very different conclusions regarding the magnitude of the spillover. Overall, the reduced-form model tends to overestimate the long-run impact of shocks, and the variance decomposition clearly shows the difference contributions of variances that we obtain.

3.6 Conclusion

In this chapter, we analyze the contemporaneous spillover effects focusing on the overlapping trading hours between the US and UK stock markets. Using high frequency data split into overlapping and non-overlapping trading periods and employing Rigobon's (2003) approach, we explain complexities of these relations at the volatility level. We highlight the implications of our structural VAR model by comparing the dynamic relations, impulse responses and variance decomposition with those of a reduced-form VAR model.

Our analyses yield several interesting findings. First, we provide evidence of asymmetric contemporaneous spillover effects. We find that when markets trade simultaneously an increase in US stock market volatility has a greater impact on UK stock market volatility than the other way around. Second, we show that during the overlapping trading period the US and UK stock market volatilities react more intensively to the US non-overlapping previous days's stock market volatility than the other way round. This suggests that the volatilities of both US and UK overlapping trading periods are affecting the US non-overlapping volatility on the same day. Third, we demonstrate that ignoring the contemporaneous relations, leads to different conclusions regarding the magnitude and direction of volatility spillovers among our stock markets.

Our findings have several important implications. First, we show that volatility is transmitted instantaneously when markets trade simultaneously. Thus, contemporaneous relations are useful for the high frequency trading and may contribute to better prediction of volatility across markets, which can be used, for instance, for hedging purposes. Second, we find that dynamic relations and impulse responses are overestimated in the traditional VAR. As such, investors and risk managers who do not consider the contemporaneous effects may inadequately evaluate volatility transmission between the US and UK stock markets. All in all, our analyses highlight the relevance of taking into account the simultaneous information transmitted among markets.

The empirical application of our model has focused on the transmission of volatility in the case where markets have overlapping trading hours. We focused on one specific setting, i.e. the volatility spillover between the US and UK equity markets. Of course this approach can easily be adapted to broader set of markets and different asset classes.

Chapter 4

Time-varying Contemporaneous Return Spillovers During the European Debt Crisis

4.1 Introduction

The sovereign debt crisis has been one of the toughest challenges for the Euro Area (Kosmidou et al., 2015; Bhanot et al., 2014). Although the Euro Area (EA) is a single currency market with a common monetary policy, it consists of diverse countries in terms of economic growth, and their financial markets are different with regard to depth and development (Louzis, 2015). The European Debt Crisis (EDC) highlighted these differences among the EA countries, as shown by the various challenges that each country faced in meeting their obligations from the Stability and Growth Pact and the Maastricht Treaty, such as government deficits of less than 3% of GDP and public debt levels limited to 60% of GDP. While the crisis originated in Greece, it rapidly spread to several Eurozone countries, such as Italy, Portugal and Spain. Unable to fund their deficits, these countries sought financial assistance to avoid default or a return to pre-Euro national currencies. The responses to the crisis, namely, the European governments' willingness to rescue Greece from the sovereign default by providing financial support in May 2010, the establishment of the European Financial Stability Facility program in June 2010 and the European Central Bank's (ECB) policies[1], aimed to

[1]The European Financial Stability Facility program was created as a temporary solution to the EDC. Starting from October 2012, the European Stability Mechanism is the permanent rescue mech-

avoid the transmission of shocks across the European countries and markets (Ehrmann and Fratzscher, 2015). To gauge the success of the programmes and future ones, it is therefore important to investigate the relations and spillovers among European financial markets.

While a few studies address the relations and spillovers among the EA sovereign debt markets (Ludwig, 2014; Gomez-Puig and Rivero, 2013; De Santis, 2014; Alter and Bayer, 2014), the EDC also affected European equity markets (Gentile and Giordano, 2013; Stracca, 2015; Louzis, 2015). These equity-related studies show that news in the sovereign debt market for a given country has significant impacts on another country's stock markets, and there are spillover effects among these markets. For instance, Bhanot et al. (2014) find that news regarding Greece's downgrades negatively affected European equity markets, whereas Kosmidou et al. (2015) show that the approval of financial support programs positively affected the Greek capital market. Furthermore, Louzis (2015) identifies the stock markets, rather than bond markets, as the key transmitters of shocks across the EA markets. The above findings suggest that further investigation of spillover effects among European equity markets is important.

Given that European equity markets trade simultaneously, transmission of shocks among these markets can occur instantaneously. Therefore, taking into consideration these contemporaneous spillover effects is essential. Currently, a clear understanding of how the contemporaneous effects change over time, especially during financial crises, together with what drives their dynamics, is limited in European equity markets. For instance, it is yet to be documented whether there is asymmetry and time-variation in contemporaneous spillover effects, and whether financial crises, financial assistance programs and credit rating downgrades influence their dynamics. To address these issues, identifying the shocks to individual equity markets is fundamental. Existing studies on spillover

anism that safeguards financial stability in Europe by providing financial assistance to the European countries. The ECB's policies refer to its decision to purchase the government debt of the troubled EA countries under its Securities Markets Program, adopted in May 2010 and replaced by the Outright Monetary Transactions program in October 2012.

effects in financial markets usually either apply standard VAR models which focus on lead-lag relations or typically assume a priori that transmission of shocks occurs in one or another direction. However, such an assumption may not be reasonable and attempts should be made to detect the direction of causality, i.e., whether shocks occurring in one market affect another market or vice versa. Moreover, lead-lag relations may not entirely capture the contemporaneous spillover effects given the high level of integration among the EA markets.

As an alternative solution to identify the direction of causality among financial markets, Rigobon (2003) proposes the "identification through heteroskedasticity" approach, and more recently, Lütkepohl (2012) proposes a similar approach through shifts in the volatility of the residuals. The former approach has been implemented by several studies (Andersen et al., 2007; Ehrmann et al., 2011; Ehrmann and Fratzscher, 2015) which show the existence of contemporaneous spillover effects among financial markets.

In this chapter, we examine the instantaneous transmission of return shocks, namely, contemporaneous spillover effects. Using a structural VAR and Lütkepohl's (2012) approach through shifts in the residual volatility, we investigate these effects that occur between the German equity market and the peripheral Greek, Italian, Portuguese and Spanish (GIPS) equity markets.[2] By investigating the contemporaneous spillovers, we make the following contributions. First, we analyze the instantaneous transmission of shocks across the German and GIPS equity markets taking into consideration the EDC,

[2]There are several reasons for the choice of the German equity market and GIPS equity markets. First, these markets are integrated and related through trade, banking system and debt holdings which facilitate the transmission of shocks among them, especially during the European crisis (Stracca, 2015). For instance, German banks have invested heavily in Greek bonds. As such, it is important to investigate whether or not the magnitude of the spillover effects has changed with the ongoing EDC. Second, Germany is an important member of the European Union which has been less affected by the EDC and has highly contributed to the European Financial Stability Facility program (now European Stability Mechanism). This has led to an increase in its influence with regard to the implementation of different policies across the Euro Area. These policies (e.g., the financial support programs, OMT program) have affected and have mainly focused on the GIPS countries, the origin of the debt crisis. In addition, the GIPS's credit ratings have been downgraded several times between 2010 and 2012. These credit rating downgrades might negatively affect their stock markets as well as the German stock market. As such, it is essential to explore the relations between the German and GIPS returns and also to what extent the EDC has influenced them. Specifically, it is relevant to examine to what extent the GIPS markets moved away from Germany and the other way around.

as well as the Global Financial Crisis (GFC). Specifically, we split our sample into four periods: the period prior to the GFC, the GFC period, the first phase of the EDC and the second phase of the EDC. We then estimate contemporaneous relations for each of these periods. In addition, we investigate the time-variation in contemporaneous spillover effects using a rolling windows estimation. Second, we assess how the financial assistance programs and credit rating downgrades contribute to spillover effects. In doing so, our approach differs from the works of Bhanot et al. (2014) and of Kosmidou et al. (2015), who investigate the impacts of similar events on equity markets rather than spillover effects. Our paper also differs from Ehrmann and Fratzscher (2015) who examine contemporaneous spillover effects between the EA bond markets. Third, from an empirical perspective, we use Lütkepohl's (2012) approach which allows us to address the simultaneity issue without imposing restrictions on the direction of spillover effects. By using this method, our paper differs from the existing studies on spillover effects across the European equity and bond markets, such as Gentile and Giordano (2013) and Louzis (2015), who analyze spillover effects by either imposing a priori assumptions on what country the shocks originate from or concentrating on the lead-lag dynamics.[3]

Our investigation leads to several important findings. First, we show that there are asymmetric contemporaneous spillover effects, where the contemporaneous return spillover from the German to the GIPS equity markets is higher than the other way around. This implies that return shocks originating from Germany have stronger effects on each of the GIPS returns than the other way around. Given that Germany is leading member in Europe and its equity market can be seen as a benchmark of the equity markets in the Euro Area, these findings are not surprising. Second, we find that while the GFC led to an increase in the magnitude of the contemporaneous spillovers, the first phase of

[3]Another study related to the EDC which is important to mention is the study of Stracca (2015). This study investigates the effects of EDC on 40 non-Euro Area countries together with what drives the transmission of shocks among their equity, bond and foreign exchange markets. Our study differs from this study by assessing the impacts of EDC inside the Euro Area, where the crisis started. Moreover, while Stracca (2015) applies an event study approach, our study takes into account the asymmetries in contemporaneous effects and assesses their variation over time. These effects allow us to investigate how integrated are the GIPS equity markets with the German equity market and how integrated is the German with GIPS equity markets, especially during the European Debt Crisis.

the EDC caused a decrease in their magnitude. During the second phase of the EDC, we observe an increase in the return spillover from Germany to GIPS stock markets, and respectively, a similar magnitude as in the first phase of EDC of the return spillover effects the other way around. These findings are in line with Ehrmann and Fratzscher (2015), Caporin et al. (2013) and Claeys and Vasicek (2014) who examine the transmission of shocks among European bond markets. Third, we highlight the impact that financial assistance programs and credit rating downgrades have on the contemporaneous spillover effects. We find that financial support programs have reduced the spillover effects from GIPS equity markets to the German equity market and in most cases increased their magnitude the other way around. Credit rating downgrades, e.g., of Portugal and Italy, decreased contemporaneous spillover effects. This finding indicates that financial markets have expected them to occur. De Santis (2014) provides similar evidence regarding the impacts of these events on European bond markets.

Our results have several implications. First, for financial markets, our findings highlight the influential role of the German stock market for the GIPS stock markets since shocks to German returns have greater impacts on GIPS markets than the other way around. Second, our model provides a useful tool that can be used to monitor the contemporaneous spillover effects which are of considerable importance to investors, as well as policy makers. Knowledge of these spillover effects is relevant for policies aiming to strengthen the stability of the EA markets and improve their ability to reduce the transmission of shocks among financial markets. As such, our findings provide insights for a country's financial stability and implementation of adequate policy actions (Louzis, 2015). For instance, our findings show that EDC has led to a reduction in contemporaneous spillover effects rather than an increase in their magnitude, which occurs during the GFC. While on the one hand, this reduction was preferable since it hampered a more systemic crisis in the Euro Area, on the other hand, it has posed challenges for policy makers given that it has led to unequal transmission of policies across Euro Area.

The rest of the paper is organized as follows. Section 2 discusses the studies on spillover effects among financial markets and how our work contributes to existing studies. Section 3 presents the empirical setting. Section 4 discusses the data and Section 5 presents the results. We conclude in Section 6.

4.2 Literature Review

This chapter investigates the contemporaneous spillovers among European equity markets and the impact of financial assistance programs, credit rating downgrades and financial crises to these spillovers. Hence, our study connects two strands of literature; namely, the spillover effects among financial markets and the impact of these events on financial markets. While each of these concepts have been studied independently in the literature, to our knowledge there are no studies which explore the relation between spillovers among equity markets and the announcement of financial assistance programs and credit rating downgrades. Moreover, despite significant research on bond markets, there are only few studies which focus on the European equity markets. Using vector autoregressive (VAR) models, Granger Causality tests and vector error correction (VEC) models, these studies concentrate on the lead-lag dynamics, and the impact of financial support programs and credit rating downgrades on equity markets. As such, there is limited evidence with regard to the instantaneous transmission of shocks among European equity markets. We start this section by discussing the papers which focus on bond markets and the impact of financial assistance programs and credit rating downgrades on these markets. We then show that there are spillover effects between the bond and equity markets within and outside the EA. Finally, we discuss the few studies that assess the impact of financial assistance programs and credit rating downgrades on equity markets rather than on the spillovers among markets.

There is a large body of literature that explores the relations among the European bond markets (e.g., Ehrmann and Fratzscher, 2015; Gorea and Radev, 2014; Ludwig, 2014; Arghyrou and Kontonikas, 2012; Giordano et al., 2013; Alter and Bayer, 2014; Gomez-Puig and Rivero, 2013). The majority of these studies concentrate on the drivers that facilitate the transmission of shocks across bond markets, with the banking system, trade and debt holdings playing an important role. Other studies consider the role of news announcements, namely, bailout programs and credit rating downgrades, in the transmission of shocks across EA bond markets. For instance, Mink and De Haan (2013) examine the impact of general news about Greece and the Greek bailout program on European bank stock prices and bond markets in 2010. They find that news about Greece's bailout program had a significant impact even on stock prices of banks without exposure to Greece, Ireland, Portugal and Spain. However, general news about Greece does not affect bank stock prices but has an impact on the sovereign bond prices of Portugal, Spain, Ireland. Similarly, De Santis (2014) investigates the impact of Troika's (European Commission/ECB/International Monetary Fund) bailout programs and credit rating downgrades on bond markets in several EA countries.[4] He finds that while Greece's and Portugal's credit rating downgrades led to an increase in the sovereign spreads of EA countries, news announcements associated with Greece's, Portugal's and Ireland's bailout packages have triggered a decline in bond prices. These studies suggest that news announcements have significant impacts on the European bond markets.

The closest paper to our study in terms of methodology and issues addressed by previous studies on bond markets, is that of Ehrmann and Fratzscher (2015). Using the "identification through heteroskedasticity" approach of Rigobon (2003) they examine the contemporaneous spillover effects across several EA countries, which are interpreted as integration, fragmentation and contagion.[5] Their findings show that the EDC actually led to a reduction in the return spillover effects from German bond market to other bond markets compared to the GFC. Their observation suggests that while before the EDC bond markets were integrated, since the start of the EDC bond markets experienced fragmentation. The exceptions were Italian and Spanish yields, which experienced an

[4]Belgium, Netherlands, Finland, Austria, France, Ireland and GIPS.

[5]Their analysis includes three core countries (Germany, France and the Netherlands) and five peripheral countries of the EA (GIPS and Ireland).

increase in their bi-directional spillovers and were less affected by the German shocks. Consistent with this view, the studies of Battistini et al. (2014), Caporin et al. (2013) and Claeys and Vasicek (2014) also provide evidence of fragmentation in the bond markets.

Given that European countries are related to each other by the joint monetary policy transmission mechanism and the shared default risk via the European Financial Stability Facility and European Stability Mechanism programs (Alter and Bayer, 2014), one would expect shocks to be transmitted from bond to equity markets. Indeed, several papers have investigated the relations between these markets and show that the EDC has affected not only European bond markets, but also equity markets in EA and even non-EA countries. For example, Louzis (2015) applies the generalized forecast error variance decomposition framework in investigating the return (price) and volatility (uncertainty) spillovers among the equity, bond, foreign exchange and the money markets in Europe.[6] He shows that Greek bond market volatility spills over to the other European markets. Moreover, he finds that during the EDC the periphery EA stock markets have the highest degree of spillover to the other markets. In addition, Stracca (2015) examines the global implications of the EDC on the equity, bond and foreign exchange markets outside Europe. Considering 40 non-EA countries of which 19 belong to the OECD the author documents that the EDC led to an increase in the global risk aversion, as shown by the movements of the VIX, respectively, a decrease in financial stocks which dropped by half a percentage point. The main drivers of the EDC's international transmissions are found to be the trade exposure to the EA, countries' financial integration with the EA and financial development.

It has further been documented that the GFC and EDC had different effects on both European bond and equity markets. For instance, Gentile and Giordano (2013) ex-

[6]See also, the studies of Antonakakis and Vergos (2013) and of Claeys and Vasicek (2014) who use this method of a VAR model proposed by Diebold and Yilmaz (2012). The study of Louzis (2015) considers the EONIA rate, EUR/USD exchange rate, Ireland and GIPS bond markets and the equity markets in GIPS countries, Ireland, France, Belgium, Austria, Netherland, US and Germany.

amine the number of short- and long-run connections, and their direction in European sovereign bond spreads and stock returns applying Granger causality tests and a VEC model.[7] They show that during the GFC and EDC there was an increase in the transmission of shocks and the direction of causality was different in bond and equity markets. Specifically, in the case of stock markets (bond markets), during the GFC, Germany and France (Germany, Ireland and Portugal) influenced the other EA markets, whereas during the EDC, Greece, Italy and Portugal (Germany and Spain) affected the EA markets. Similarly, Samitas and Tsakalos (2013) provide evidence of increased correlations between the equity markets in Greece and several EA countries during both the GFC and the Greek debt crisis.[8] However, they argue that the Greek debt crisis had a lower than expected impact on the correlation between the Greek stock market and European stock markets. These findings are contrary to those of other studies (Ehrmann and Fratzscher, 2015; Caporin et al., 2013; Claeys and Vasicek, 2014) which showed that the EDC in fact led to either a decrease or no change in the transmission of shocks among European equity markets.

Besides studies that assess the impacts of financial crises on the transmission of shocks, several studies investigate the impact of financial support programs and credit rating downgrades on European equity markets. Kosmidou et al. (2015), for example, show the impact of credit rating downgrades and rescue programs on the banking, financial and real sectors of the Greek capital market. They indicate that the credit rating announcements had negative impacts on the returns of Greek banking sector firms. In contrast, Troika's bailout programs had positive impacts on both the financial and real economy sectors of the Greek capital market. The importance of these events is also documented in Bhanot et al. (2014) who analyze the relation between the GIPS stock markets and Greek sovereign yield spreads around these events and during the Greek debt crisis. They conclude that an increase in the yield spread of Greek bonds led to a decline in stock market returns, which was driven by the Greek rating downgrades,

[7] Their investigation includes GIPS, Ireland, France, UK and Germany.

[8] Countries included Germany, France, UK and peripheral counties, i.e., GIPS and Ireland.

whereas news about bailout possibilities had positive effects on the stock markets.

The extant literature investigates the impacts of financial crises on the spillover effects among European financial markets, and announcement of financial assistance programs and credit rating downgrades on these markets. These studies show that the GFC and EDC affected the transmission of shocks from one market to other markets differently. While some studies show that these crises increased the spillover effects, other studies demonstrate that there was a decrease in spillovers. One important aspect, however, which is not taken into consideration and may be one of the reasons for this disagreement is that European markets are highly integrated and trade simultaneously. Thus, the transmission of shocks may occur instantaneously in addition to having a delayed effect. Our study extends the above studies and contributes to the literature in that we explore the contemporaneous spillover effects in equity markets. Moreover, we assess the contribution of financial assistance programs and credit rating downgrades on the return spillovers from Germany to GIPS and the other way around, rather than only on equity markets. From an empirical perspective, we use the structural VAR (SVAR) and Lütkepohl's (2012) approach which allows us to estimate the direction of causality among the German and GIPS equity markets. In addition, the use of a rolling window estimation provides us with a better understanding of the transmission of return shocks across European equity markets over time, and especially during the GFC and EDC.

4.3 Model

In this study, we examine the spillover effects between Germany (GE) and Greece (G), Italy (I), Portugal (P) and Spain (S).[9] We apply a structural VAR (SVAR) model that is well suited to investigate the transmission of shocks, especially during the GFC and EDC, among these stock markets. The main challenge in the estimation of the SVAR

[9] In line with Cappiello et al. (2006) the German equity market can be seen as the benchmark of the EA equity markets. Moreover, Germany is one of the major European contributors to the financial assistance programs. Additionally, Germany is a leading member of EA with an influential role regarding the European politics (e.g., the implementation of austerity measures), especially during the EDC.

model is the identification of the contemporaneous relations among equity markets without imposing restrictions on the direction of these relations. To achieve identification, we employ the approach of Lütkepohl (2012) which relies on the heterogeneity of the volatility in equity returns.

We compute weekly returns for all markets, i.e., $R_t^i = log(P_t^i) - log(P_{t-1}^i)$, where P_t^i is the weekly price for country i. We model the returns using a SVAR process:

$$\mathbf{A}R_t = c + \mathbf{\Phi}(\mathbf{L})R_t + \varepsilon_t \tag{4.1}$$

where R_t is a (2×1) vector representing the weekly returns, i.e.,

$$R_t = \begin{pmatrix} {R_t}^{GE} & {R_t}^{j} \end{pmatrix}' \tag{4.2}$$

where ${R_t}^{GE}$ consists of the German equity returns and j represents either the Greek, Italian, Portuguese or Spanish stock market. The coefficient c is a (2×1) vector of constants and $\mathbf{\Phi}(\mathbf{L})$ is a (2×2) matrix capturing lagged effects. The (2×2) matrix $\mathbf{A}$ captures the contemporaneous relations among returns, i.e.,

$$\mathbf{A} = \begin{pmatrix} \alpha_{11} & \alpha_{12} \\ \alpha_{21} & \alpha_{22} \end{pmatrix}, \tag{4.3}$$

where α_{12} captures the spillover effect from market j to the German stock market, and α_{21} captures the spillover effect from the German stock market to each of the GIPS stock markets j. The other parameters are defined likewise.

The starting point for the identification of $\mathbf{A}$ is to estimate the reduced-form VAR between Germany and each of the GIPS countries separately by premultiplying Equation (4.1) by $\mathbf{A^{-1}}$:

$$R_t = c^* + \mathbf{\Phi}(\mathbf{L})^* R_t + u_t \tag{4.4}$$

The coefficients of Equation (4.4) can be estimated by OLS and are related to the structural coefficients by: $c^* = \mathbf{A^{-1}}c, \mathbf{\Phi}(\mathbf{L})^* = \mathbf{A^{-1}\Phi}(\mathbf{L}), u_t = \mathbf{A^{-1}}\varepsilon_t$ and $u_t \sim N(0, \mathbf{\Omega_t})$ where $\mathbf{\Omega_t} = \mathbf{A^{-1}\Sigma_t\ A^{-1}}'$, where Σ_t is the covariance matrix of the residuals ε_t.

When analyzing these contemporaneous relations among markets, we face an endogeneity problem. That is, the transmission of return shocks between Germany and GIPS equity markets could occur instantaneously. Some studies (Ehrmann et al., 2011; Andersen et al., 2007) address the endogeneity problem by using the "identification through heteroscedasticity" approach of Rigobon (2003). Others (Alter and Bayer, 2014; Louzis, 2015; Antonakakis and Vergos, 2013) either use sign restrictions for the identification of the matrix $\mathbf{A}$ or argue that changes in one variable can affect the other variable immediately, but not vice versa.[10]

To solve the simultaneity problem, Lütkepohl (2012) proposes an approach based on changes in variances of the reduced form VAR.[11] If there are non-proportional changes in variances over time, we can make use of them for the identification of contemporaneous relations. The basic idea is to have at least two regimes where the variance of one of the variables is changing and is presented in more detail in Chapter 2. In particular, to identify $\mathbf{A}$, we impose two restrictions. First, we assume that structural shocks, ε_t from Equation (4.1) are uncorrelated, i.e., the variance of ε_t, $\mathbf{\Sigma_t}$ is a diagonal matrix. Moreover, given that $\mathbf{A}$ is chosen such that its diagonal elements are unrestricted, we normalize the structural variances in the first regime. Second, all the parameters from Equation (4.4) are time-invariant. If these assumptions hold, then we can decompose $\mathbf{\Omega_t}$ such that matrix $\mathbf{A}$ is uniquely identified,

$$\begin{aligned} \mathbf{\Omega_1} &= \mathbf{A^{-1}A^{-1}}' \\ \mathbf{\Omega_2} &= \mathbf{A^{-1}\Psi A^{-1}}' \end{aligned} \tag{4.5}$$

where $\mathbf{\Psi}$ is a (2×2) diagonal matrix with distinct elements showing the change in variance from the $\mathbf{\Omega_1}$ to the $\mathbf{\Omega_2}$.

We estimate the model using Quasi-Maximum Likelihood (QML), where the log-likelihood

[10] This is the lower triangular matrix approach, or the Cholesky factorization.

[11] Although both Lütkepohl's (2012) and Rigobon's (2003) approaches allows us to solve the simultaneity issue, given the fact that we use a rolling window estimation to capture the time-variation in contemporaneous relations, we choose Lütkepohl's (2012) approach. This approach is more appropriate than the one of Rigobon (2003) when estimating the time-varying contemporaneous spillovers, which relies on the computation of rolling window variance from the reduced-form residual, u_t to achieve the identification of matrix $\mathbf{A}$. Given the fact that Chapter 3 focuses on the contemporaneous relations over the full sample period, Rigobon's (2003) approach is as appropriate as Lütkepohl's (2012) approach.

function is given as,

$$
\begin{aligned}
l_T(\gamma, \Psi, \mathbf{A}) = \sum_{t=1}^{T} log(\gamma\, det(\mathbf{\Omega_1})^{-\mathbf{1/2}} exp\{-\frac{1}{2}\ \mathbf{u_t^{'}\Omega_1^{-1}u_t}\} \\
+(1-\gamma) det(\mathbf{\Omega_2})^{-\mathbf{1/2}} exp\{-\frac{1}{2}\ \mathbf{u_t^{'}\Omega_2^{-1}u_t}\})
\end{aligned}
\tag{4.6}
$$

where γ is the mixture probability, $0 < \gamma < 1$. Given the fact that the elements of matrix $\mathbf{A}$ vary freely, we normalize the estimated matrix $\mathbf{A}$ such that its diagonal elements are one. In this case, its off diagonal elements can be written as:

$$
\begin{aligned}
\widehat{\alpha_{12}} &= \frac{\alpha_{12}}{\alpha_{11}} \\
\widehat{\alpha_{21}} &= \frac{\alpha_{21}}{\alpha_{22}}
\end{aligned}
\tag{4.7}
$$

The t-statistics for the $\widehat{\alpha_{12}}$ and $\widehat{\alpha_{21}}$ are computed using the Bollerslev-Wooldrige standard errors.

The estimation procedure through which we obtain the contemporaneous spillover effects, matrix $\mathbf{A}$ is the following:

1. We estimate the reduced-form VAR between German returns and each of the GIPS returns as can be seen from Equation (4.4) by OLS. We then recover the reduced-form residuals which capture the contemporaneous relations. Using Akaike Information Criterion to select the optimal lag, we find a lag length of five days to be optimal. This optimal lag length remains the same for the estimation of contemporaneous spillovers over the four sub-sample periods (i.e., pre-GFC, GFC and, first and second phase of the EDC) as well as for the estimation of time-varying contemporaneous spillovers presented in Section 4.5.2.

2. To achieve the identification of contemporaneous relations the Lutkepohl's (2012) approach relies on the decomposition of the variance covariance matrix of the reduced-form residuals as shown in Equation (4.5). These covariance matrices are defined using the inverse of matrix $\mathbf{A}$ and $\mathbf{\Psi}$ which can be seen as the change in the volatility from $\mathbf{\Omega_1}$ to $\mathbf{\Omega_2}$. Specifically, this decomposition indicates that we have two volatility regimes with distinct covariance matrices, namely, $\mathbf{\Omega_1}$ and $\mathbf{\Omega_2}$.

The γ is the mixture of probability between zero and one and can be interpreted as the probability that a first regime will have covariance matrix $\mathbf{\Omega_1}$ while (1-γ) can be seen as the probability that the second regime will have the covariance matrix $\mathbf{\Omega_2}$. Given this specific distribution for the reduced-form error term, we use quasi-maximum likelihood to estimate the model.

4.4 Data

In line with the extant literature (Savva and Aslanidis, 2010; Guidi and Ugur, 2014; Baele and Inghelbrecht, 2010; Baele et al., 2007; Caporale and Spagnolo, 2011) we employ weekly data covering the period from January 2003 to December 2014.[12] The data are obtained from Thomson Reuters DataStream and consist of the Morgan Stanley Capital International (MSCI) equity return indices for Greece, Italy, Portugal, Spain and Germany.

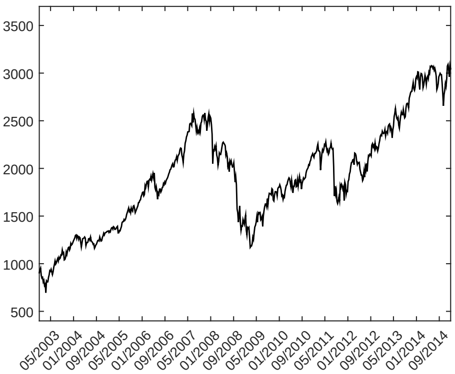
In Figure 4.1, we provide time series plots of the equity indices. We notice a sharp decline in the equity markets due to the GFC in September 2008 and smaller declines over the period January 2010 to December 2012 related to the EDC. The figure clearly highlights that the EDC affected equity markets to varying degrees.

Table 4.1 presents summary statistics for equity returns in Germany and each of the GIPS countries. As can be seen, the highest variability of the returns based on minimum and maximum is in Germany and Italy, while the highest volatility is in Greece. The negative skewness on returns suggests that negative shifts in the German and GIPS stock markets occur more often than positive shifts. The presence of excess kurtosis in all countries implies that large shifts occur more often than is the case of normally distributed series. The ADF tests confirm the stationarity of equity returns at 1% level.

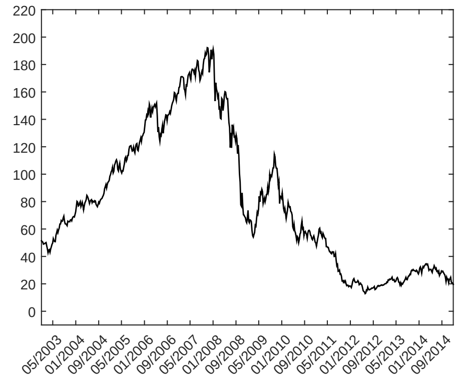
[12]This frequency minimizes the effects of non-synchronous data which may arise when a market is closed in one country, while another market is open in another country. Moreover, the weekly frequency is characterized by less noise and is able to better analyze the transmission of return shocks over time and during financial crises.

Figure 4.1: European Stock Market Indices

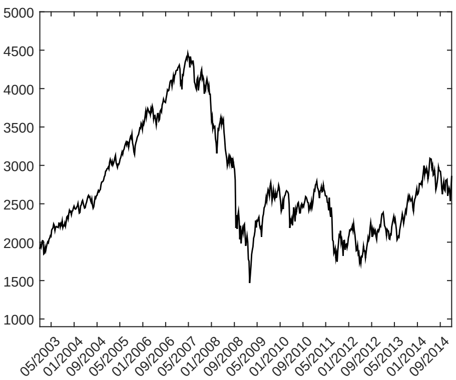
(a) Germany



(b) Greece

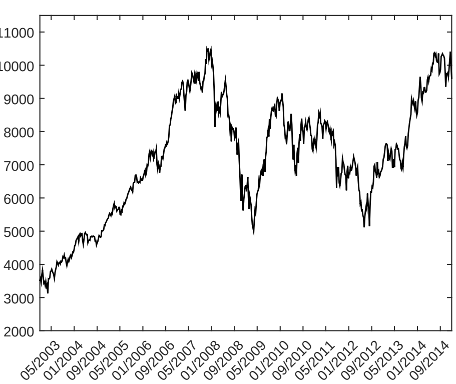


(c) Italy



(d) Portugal

(e) Spain



Note: This Figure shows the MSCI indices for Germany, Greece, Italy, Portugal and Spain. We cover the period from January, 2003 to December, 2014.

Table 4.1: Summary Statistics

	${R_t}^{GE}$	${R_t}^{G}$	${R_t}^{I}$	${R_t}^{P}$	${R_t}^{S}$
Mean	0.0019	−0.0016	0.0004	0.0002	0.0016
Max	0.16	0.15	0.10	0.08	0.13
Min	−0.17	−0.19	−0.25	−0.19	−0.12
Std.Dev.	0.0303	0.0468	0.0325	0.0285	0.0318
Skew.	−0.83	−0.51	−1.47	−0.95	−0.15
Kurt.	8.11	4.55	10.90	7.64	5.03
ADF	-9.63^{***}	-8.53^{***}	-9.97^{***}	-8.72^{***}	-9.39^{***}

Note: This table reports summary statistics for the returns in Germany, Greece, Italy, Portugal and Spain, i.e., ${R_t}^{GE}$, ${R_t}^{G}$, ${R_t}^{I}$, ${R_t}^{P}$, and ${R_t}^{S}$. We cover the period from January 2003 to December 2014. ADF is the t-statistics for the Augmented Dickey-Fuller test. *** denotes significance at the 1% level.

Table 4.2 reports the event dates regarding financial assistance programs and both credit rating downgrades to and close to non-investment grade. The main reason for taking into account the bailout packages is that financial markets might consider these events as a signal of European governments' willingness to use public funds to protect private investors (Mink and De Haan, 2013). At the same time, financial support could also be understood as evidence that other countries might receive financial support. Further, there are two reasons for taking into consideration the credit rating downgrades. First, credit rating downgrades provide information about a country's ability to meet its debt obligations. Therefore, these downgrades are important for investors who might take them into consideration when estimating the discount rate and expected flow of dividend from stocks, affecting stock valuations. Second, a credit rating downgrade might affect a country's ability to borrow in international markets, and thus contribute to a credit crunch, which negatively impacts the stock market (Ferreira and Gama, 2007). We present the credit rating downgrades as reported by Standard and Poor's (S&P), Moody's Investors Service (Moody's) and Fitch's agencies. Particularly, we take into consideration the announcement for Greece's, Portugal's and Spain's

Table 4.2: Financial Assistance Programs and Credit Rating Downgrades Event Dates

	Credit rating agency	Event date
Financial assistance program		
Greece		2^{nd} May 2010
		21^{st} February 2012
Portugal		17^{th} May 2011
Spain		5^{th} June 2012
Downgrades to non-investment grade		
Greece	Standard & Poor's	27^{th} April 2010
	Moody	14^{th} June 2010
	Fitch	14^{th} January 2011
Portugal	Moody	5^{th} July 2011
	Fitch	24^{th} November 2011
	Standard & Poor's	14^{th} January 2012
Spain	Moody	22^{nd} October 2012
Downgrades close to non-investment grade		
Italy	Standard & Poor's	19^{th} September 2011
Spain	Standard & Poor's	10^{th} October 2012

Note: This table reports the event dates for Greece's, Portugal's and Spain's financial assistance programs and Greece's, Italy's, Portugal's and Spain's credit rating downgrades. We focus on the main credit rating agencies, i.e., Standard & Poor's, Moody and Fitch.

downgrades to non-investment grade and rescue programs. Given that Moody's downgrade of Spain refers to the downgrade to junk status of it's five biggest regions, i.e., Catalonia, Andalucia, Castilla-La Mancha, Extremadura and Muricia, we also consider Spain's downgrade close to non-investment grade by Standard & Poor's. We include Italy's downgrade close to non-investment grade as it has been the first Italian revision since 2006 by Standard & Poor's.

4.5 Results

In this section, we begin by presenting the evidence on the contemporaneous relations over the full sample period. We then show the impacts of GFC and EDC on these relations by estimating the model presented in Section 3 for each of the four periods, i.e., pre-GFC, GFC and, first and second phase of the EDC. Further, we estimate the time-varying contemporaneous relations. Finally, we assess whether the financial assistance programs and credit ratings downgrades affected the dynamics of contemporaneous spillover effects between the German and GIPS equity markets.

4.5.1 Contemporaneous Relations

We start our analysis with the estimation of the reduced form VAR model using Equation (5.5) over the full sample period and all four sub-periods as defined below. The first sub-period is from January 2005 to August 2008. The second sub-period uses Lehman Brothers' collapse as the starting date of GFC and lasts from September 2008 until September 2009.[13] The third sub-period covers the $\text{EDC}^{\text{first phase}}$, when most of the austerity measures started to be implemented and lasts from October 2009 until September 2012. The start date for the $\text{EDC}^{\text{first phase}}$ coincides with investors' concerns regarding the quality of Greek sovereign debt, which were followed shortly after, on November, by the Greek government announcement of a budget deficit twice of the previous estimates (Bhanot et al., 2014). The fourth sub-period, the $\text{EDC}^{\text{second phase}}$, covers October 2012 to December 2014. The starting date of this sub-period coincides with the ECB's announcement of the Outright Monetary Transactions program and is in line with Ehrmann and Fratzscher (2015). We then use the residuals from the reduced form VAR and Lütkepohl's (2012) approach, which allows us to identify the

[13]The start date for the GFC is in line with the studies of Ait-Sahalia et al. (2012), De Santis (2014), Gjika and Horváth (2013), Mierau and Mink (2013) and Syllignakis and Kouretas (2011).

responses of the German stock market to changes in the returns of each peripheral European stock markets, i.e., Greece, Italy, Portugal and Spain and vice versa, the return spillover effects from Greece, Italy, Portugal and Spain to Germany.

Table 4.3 presents contemporaneous relations for the entire sample period, the period before the GFC, the period during the GFC and the periods during the first and second stage of the EDC. These relations have initially negative signs as they are captured by matrix **A** which is on the left-hand side of Equation (4.1). When taken to the right-hand side, the signs of the contemporaneous relations become positive. As such, an increase in the German stock market returns leads to an increase in the Greek, Italian, Portuguese and Spanish stock market returns and the other way around.[14]

Analyzing the contemporaneous relations for the entire sample period (reported in Panel A), we find high and positive contemporaneous spillovers with values ranging between 0.51 and 0.70 from the German returns to GIPS returns. The coefficients suggest that a 1% increase in the German returns leads to a contemporaneous increase between 0.51% and 0.70% in GIPS returns. Vice versa, a 1% increase in GIPS returns causes a smaller increase in German returns than the other way around, varying from approximately 0.17% to 0.27%. These results highlight the important role of Germany in transmitting shocks to the GIPS countries.

Panel B, which documents the contemporaneous relations prior to GFC, shows that shocks to German stock returns are transmitted to GIPS stock returns, with spillover coefficients ranging between around 0.40 and 0.70. In particular, a 1% increase in German returns leads to an increase in Greek, Italian, Portuguese and Spanish returns of 0.72%, 0.39%, 0.55% and 0.73%, respectively. These findings suggest that GIPS equity markets are moving together in response to German stock market shocks. Vice versa,

[14]In addition, we assess the stability and statistical significance of contemporaneous relations using the Chow breakpoint test. Appendix A1 reports the F-statistics of Chow's breakpoint test. We show that the null hypotheses of constant contemporaneous spillover effects can be rejected at the 1% confidence level for the structural breaks due to both GFC and EDC. In sum, Chow's breakpoint test emphasizes the relevance of considering contemporaneous relations over the pre-GFC, GFC, $EDC^{\text{first phase}}$ and $EDC^{\text{second phase}}$ periods.

GIPS returns have smaller impacts on the German returns, ranging from approximately 0.12 to 0.40. These findings indicate that the German returns are less sensitive to GIPS return shocks than the other way around.

When we consider Panel C, the spillover effects during the GFC, we notice that the magnitude of return spillover effects between Germany and GIPS is higher than in the pre-GFC period. Specifically, we find that shocks to the German returns lead to higher comovement across GIPS returns than in the opposite direction. For instance, while a 1% increase in the German returns leads to an increase ranging from 0.57% in Portuguese returns to 0.80% in Greek returns, the responses of German returns to shocks in GIPS stock market returns are much smaller, with the spillover coefficients varying between 0.30 and 0.40. These findings also indicate that a one standard deviation increase in German market leads to an increase from 1.7% in Portuguese returns to 2.4% in Greek returns. Thus, the mean of Portuguese and Greek returns is 0.05% and 0.22% and is economically significant, since their actual mean is 0.002% and -0.16%. Interestingly, one of the highest return spillovers is from Germany to Italy. A possible explanation may be related to the political tensions, namely, during this period Prodi's government has collapsed and Berlusconi and the right regain power in Italy. An Italian peculiarity since 1999 is that while the left has always supported financial stability and reduction in the public debt, the right has been in favour of increasing the public debt to support spending. These evidences provide information about the direction of causality between German and GIPS returns which explain the increases during the GFC in their correlations from Appendix A2. In sum, we conclude that the GFC has led to an intensification in the transmission of shocks between the German stock market and GIPS stock markets. This finding is somewhat in line with Claeys and Vasicek (2014) and Louzis (2015) who show that the GFC also increased the spillover effects among European bond and equity markets.

When investigating the contemporaneous relations during $EDC^{\text{first phase}}$ in Panel D, we find that shocks to German stock market lead to less comovement across GIPS stock markets than during the GFC. In particular, a 1% increase in German returns causes an increase in GIPS returns equal to 0.66%, 0.52%, 0.55% and 0.68%, respectively. Since German returns have the standard deviation of 0.03, these findings also imply that during the $EDC^{\text{first phase}}$ there is an increase in GIPS returns of 1.98%, 1.56%, 0.65% and 2.04%. Thus, one standard deviation increase in German returns leads to a mean of 0.15%, 0.10%, 0.03% and 0.48%. This increase is economically important given that the GIPS actual mean is -0.16%, 0.04%, 0.02% and 0.16%, respectively. Vice versa, we find that spillover effects from GIPS returns to German returns are mostly insignificant and smaller in magnitude compared with the GFC period, with values around 0.10. The exception is the return spillover from Spain to Germany which is 0.24. These results are in line with Ehrmann and Fratzscher (2015), who interpret this decrease in the magnitude of the return spillover effects from Germany to GIPS compared to the GFC as evidence that GIPS markets are less integrated with the German market. In addition, when considering the correlations between German returns and GIPS returns in Appendix A2, we observe that during $EDC^{\text{first phase}}$ there is a higher decrease in correlations than during the GFC.

When we analyze Panel E, the contemporaneous effects during the $EDC^{\text{second phase}}$, we observe that German return shocks have become more important for GIPS equity market returns. For example, a 1% increase in the German returns induces an increase in Italian and Portuguese returns equal to 0.76% and 0.63%, respectively. The return spillover effects from Germany to Greece and Spain are higher than during both GFC and $EDC^{\text{first phase}}$ with the values around 0.90. This increased transmission of German return shocks to Greek and Spanish returns indicates that the Greek and Spanish stock markets are more sensitive to German shocks than the other peripheral markets. When exploring the spillover effects from GIPS returns to German returns, we notice that their magnitude is, most of the time, statistically insignificant, once again, this finding is in line with Ehrmann and Fratzscher (2015).

On the whole, our analysis so far shows that the magnitude of contemporaneous spillover

Table 4.3: Contemporaneous Relation between Returns

	$\left(R_t{}^{GE} \quad R_t{}^{G}\right)'$	$\left(R_t{}^{GE} \quad R_t{}^{I}\right)'$	$\left(R_t{}^{GE} \quad R_t{}^{P}\right)'$	$\left(R_t{}^{GE} \quad R_t{}^{S}\right)'$
Panel A: Full sample				
Spillover from GIPS to GE	0.17***	0.18***	0.19***	0.27***
	(3.39)	(2.72)	(2.97)	(3.92)
Spillover from GE to GIPS	0.56***	0.52***	0.54***	0.70***
	(18.58)	(18.28)	(15.80)	(18.11)
Panel B: Pre-GFC				
Spillover from GIPS to GE	0.26***	0.12*	0.18**	0.38***
	(2.55)	(1.89)	(1.99)	(13.48)
Spillover from GE to GIPS	0.72***	0.39***	0.55***	0.73***
	(8.25)	(14.68)	(13.79)	(48.37)
Panel C: GFC				
Spillover from GIPS to GE	0.32*	0.30***	−0.48	0.42***
	(1.92)	(3.69)	(−0.67)	(4.69)
Spillover from GE to GIPS	0.80***	0.70*	0.57***	0.73***
	(7.67)	(1.82)	(10.08)	(21.04)
Panel D: $\text{EDC}^{\text{first phase}}$				
Spillover from GIPS to GE	0.04	0.06	0.12	0.24**
	(0.46)	(0.66)	(0.46)	(2.24)
Spillover from GE to GIPS	0.66***	0.52***	0.55***	0.68***
	(14.62)	(14.24)	(3.21)	(10.18)
Panel E: $\text{EDC}^{\text{second phase}}$				
Spillover from GIPS to GE	0.07	−0.08	0.15***	0.02
	(0.68)	(−0.77)	(4.08)	(0.22)
Spillover from GE to GIPS	0.90***	0.76***	0.63***	0.91***
	(15.68)	(15.38)	(9.87)	(11.87)

Note: This table reports the contemporaneous relations between German and GIPS returns. The coefficients have opposite signs to the coefficients of matrix **A** as matrix **A** is on the left-hand side of Equation (4.1). When taken to the right-hand side the signs of the contemporaneous spillover effects become positive. We estimate our model between $R_t{}^{GE}$ and each of the GIPS equity market returns, $R_t{}^{G}$, $R_t{}^{I}$, $R_t{}^{P}$, $R_t{}^{S}$ for the full sample period and each of the four different periods. The first period (Pre-GFC) is from January 2003 to August 2008. The second period (GFC) is from September 2008 to September 2009. The third period ($\text{EDC}^{\text{first phase}}$) is from October 2009 to September 2012 and the last period ($\text{EDC}^{\text{second phase}}$) is from October 2012 to December 2014. The vector of variables is $R_t = \left(R_t{}^{GE} \quad R_t{}^{j}\right)'$, where j= Greece, Italy, Portugal and Spain. The coefficient α_{12} indicates the return spillover from each of GIPS stock markets to the German stock market. Vice versa, the coefficient α_{21} shows the return spillover from German stock market to each of the GIPS stock markets. Numbers in parentheses are the t-statistics based on the Bollerslev-Wooldrige standard errors. ***, ** and * denote significance at 1%, 5% and 10% levels.

effects among the German and GIPS equity markets has changed considerably during the GFC and EDC. Moreover, we provide evidence of asymmetry in these relations, where contemporaneous return spillover from German stock market to GIPS stock markets is higher than the other way around. Particularly, we find that while the GFC has led to an increase in the contemporaneous spillover effects between these markets; the first phase of the EDC has actually led to a decrease in their magnitude. During the second phase of the EDC we notice an increase in the return spillover effects from Germany to GIPS. Vice versa, the return spillover effects from GIPS to Germany are similar with those during the first phase of EDC. The results are in line with those from Appendix A2 who documents that while there is an increase in the correlations during the GFC, there is a large decrease in correlations during the $EDC^{\text{first phase}}$ which further continue to decrease during the $EDC^{\text{second phase}}$. In sum, our findings reveal the existence of asymmetry and time-variation in contemporaneous relations.

4.5.2 Contemporaneous Relations Over Time

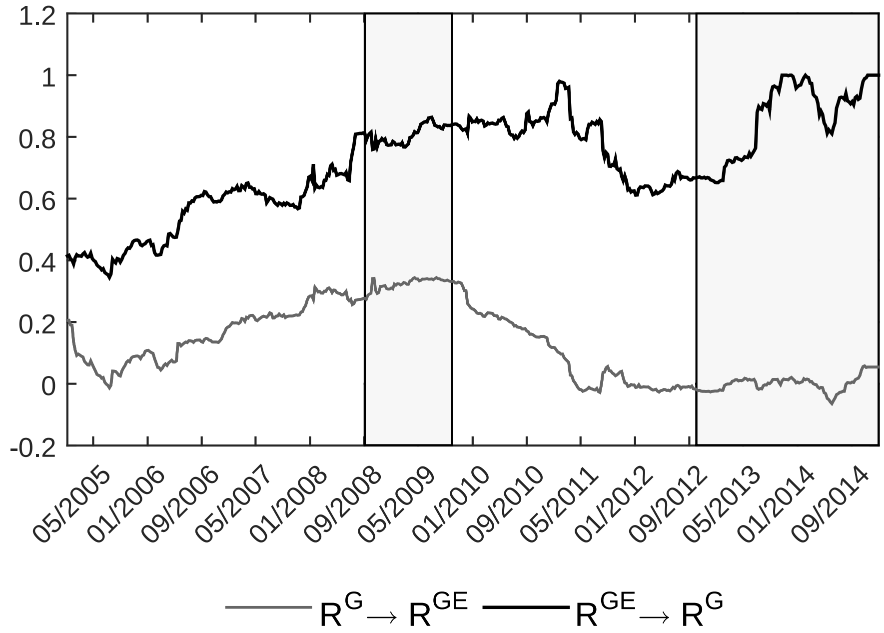
To gain further insights into the contemporaneous relations, we apply a rolling window estimation. Specifically, we estimate our model for a two year window or 104 observations and roll this window forward one week at a time.[15]

Figure 4.2 presents the time-varying contemporaneous relations between the German and GIPS equity markets covering the period from January, 2005 to December, 2014. The patterns in Figure 4.2 are in line with those in Table 4.3. Specifically, during the GFC, we document the existance of a considerable increase in the return spillover effects between Germany and GIPS equity markets. The high magnitude of the spillover effects is persistent in the early stage of the EDC and well into 2011. In response to the German return shocks, the Greek and Italian returns start to decrease in the summer of 2011, soon followed by those of Portugal and Spain. These results emphasize the fact that during the first phase of the EDC, GIPS equity markets are less affected by

[15] As a robustness check, we also use a window of 78 observations (a period of one and a half year). We find that the results are very similar to those presented in this paper.

Figure 4.2: Contemporaneous Relation between Returns

(a) The relations between R_t^G and R_t^{GE}



(b) The relations between R_t^I and R_t^{GE}

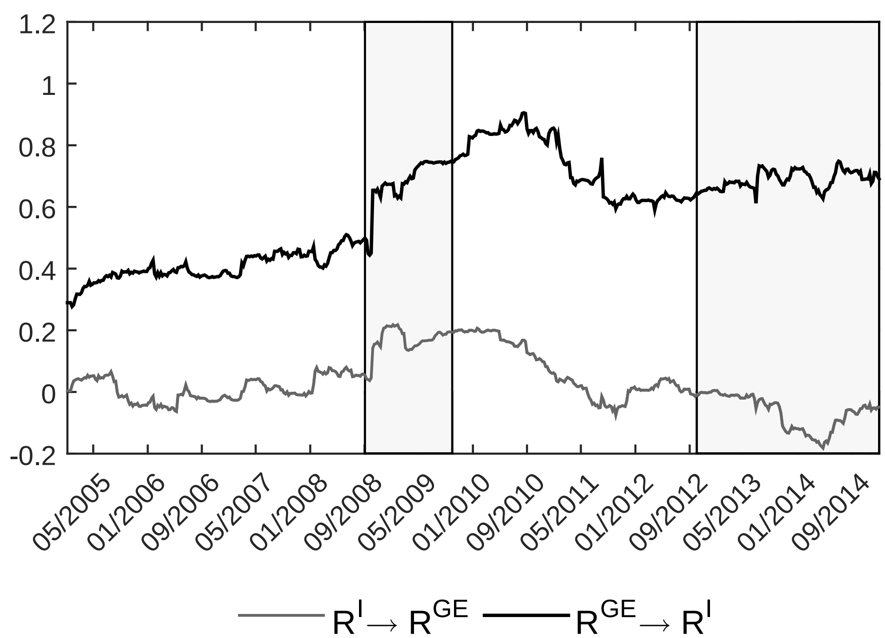
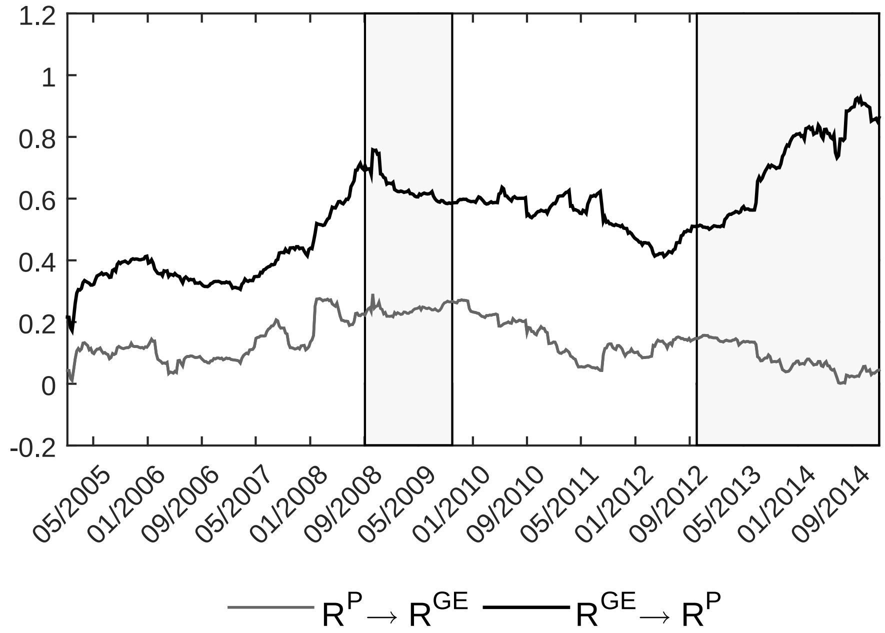
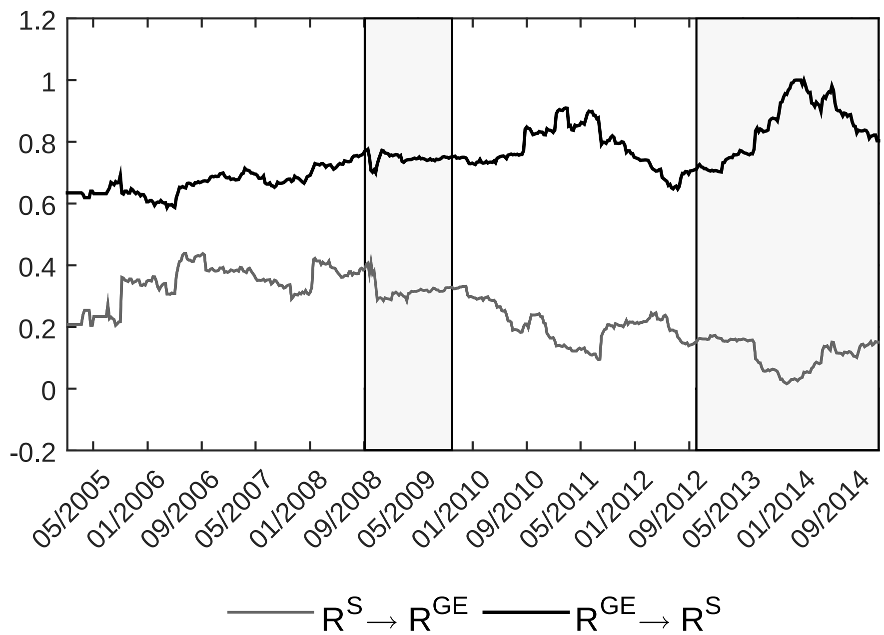


Figure 4.2 (continued): Contemporaneous Relation between Returns

(c) The relations between R_t^P and R_t^{GE}



(d) The relations between R_t^S and R_t^{GE}



Note: This figure shows the rolling window estimates for the contemporaneous relations of the equity markets. As our data start January 2003 and we choose the window for the rolling estimation to be two years, we present the spillover effects from January, 2005 to December, 2014.

the German equity market. Claeys and Vasicek (2014) and Caporin et al. (2013) also find a similar pattern when investigating transmission of shocks among the European bond markets. Contrary to the findings in Table 4.3, Figure 4.2 shows that during both phases of the EDC there are periods when shocks to German returns have high impacts on GIPS returns, and the GIPS return shocks cause a decrease in German returns. For instance, in response to German return shocks, we observe an increase in Greek returns around the beginning of 2011 and an increase in Greek, Portuguese and Spanish returns in the summer of 2013. Further, we find that an increase in the Greek returns in the summer of 2011 and 2014, and Italian returns in the summer of 2011 and summer of 2013 until the end of our sample period leads to a decrease in German stock market returns. According to Ehrmann and Fratzscher (2015) these findings indicate the existence of a "flight-to-safety" effects towards Germany. These effects from Figure 4.2 are not evident in Table 4.3, which reflects the overall picture of the contemporaneous effects over the entire sample and each of the four periods.

In sum, Figure 4.2 highlights the impacts of the GFC and EDC on the contemporaneous spillover effects and the importance of taking into consideration their time-variation. The next section further investigates the drivers of these dynamics in the contemporaneous relations context.

4.5.3 Explaining the Contemporaneous Relations

In previous sections, we emphasized the relevance of taking into account the time-variation in contemporaneous spillovers and the differences in their magnitudes that are observed over time and especially during the GFC and EDC. In this section, we focus on explaining the impact of financial support programs and credit rating downgrades on the time-varying contemporaneous spillover effects shown in Figure 4.2. In particular, we first calculate the mean of contemporaneous spillover effects six weeks before and after each of these events. We then use these findings and compute the absolute change in contemporaneous relations as the difference between the mean of contemporaneous spillover effects after and before each of the financial support programs and credit rating downgrades. Finally, we provide the *t*-statistics which are computed by dividing the absolute change in contemporaneous relations by their sum of standard deviations six weeks before and after the events. Table 4.4 shows the absolute change in contemporaneous relations after each of the GIPS's credit rating downgrade and financial assistance program as given in Table 4.2.

Examining the impact of financial support programs on these contemporaneous effects, we observe that Greece's first financial assistance program has led to a significant decrease in the spillover effects from GIPS returns to German returns, respectively, and increases in the spillover effects from German returns to Italian, Portuguese and Spanish returns. This is in line with the patterns of spillover effects in Figure 4.2 and indicates that in the early stage of the EDC, the Greek financial support program affected the transmission of return shocks to peripheral EA countries since these countries were confronted with similar circumstances. We find that Greece's second financial support program significantly decreased the return spillover from Greece to Germany with -0.006 and the spillovers from German returns to Portuguese and Spanish returns with -0.019 and -0.017, respectively. Portugal's and Spain's financial assistance programs have caused a decrease in the transmission of return shocks from GIPS equity markets to German equity market. Vice versa, the spillover effects from German returns to GIPS returns experienced a significant increase after both Portugal's and Spain's financial support programs. The exceptions are the return spillovers from Germany to Italy and Spain, which have decreased by -0.007 and -0.027, respectively, after Spain's bailout and which also correspond with the implementation of Outright Monetary Transactions program. These results are in line with Ehrmann and Fratzscher (2015) who show that under this program there is a reduction in the return spillovers from the German bond market to the Italian and Spanish bond markets. Additionally, Altavilla et al. (2014) find that Italian and Spanish yields declined under the Outright Monetary Transactions program. Overall, our results suggest that while the transmission of GIPS return shocks to Germany's returns decrease after the rescue programs, the transmission other way around increases. These findings are in line with De Santis (2014) who, focusing on Greece's and Portugal's financial assistance programs, shows that these events led to a decline in the EA sovereign yields.

We further investigate the impact of credit rating downgrades on the transmission of return shocks between German and GIPS equity markets. We find a significant decrease in the transmission of GIPS return shocks to German returns and respectively, increase in transmission the other way around, after Greece's downgrades. These results are consistent with those from Panel D of Table 4.3, which show that during the $EDC^{\text{first phase}}$ shocks occurring in GIPS equity market returns have smaller impacts on German equity market returns than those shocks originating during the GFC. Moreover, Greece's downgrades explain the high magnitude of return spillovers from Germany to GIPS during the early stage of the EDC, as shown in Figure 4.2. On the contrary, while contemporaneous spillover effects did not change significantly after Portugal's first downgrade, these spillovers significantly declined after the following two downgrades and Italy's downgrade. This indicates that investors already anticipated Portugal's and Italy's downgrades leading to a decrease in the magnitude of contemporaneous spillover effects. Instead, Spain's credit rating downgrades, which occurred at the end of 2012 led to an increase in contemporaneous spillover effects between German and GIPS equity market returns. These findings are consistent with those from Panel E of Table 4.3, which indicate that during the $EDC^{\text{second phase}}$ there is an increase in the transmission of return shocks between Germany and GIPS, compared to the transmission during $EDC^{\text{first phase}}$.

Overall, we find that although European governments' willingness to provide support to Greece, Spain and Portugal has decreased the transmission of return shocks from peripheral countries to Germany, it (most of the time) has increased the transmission of German return shocks to GIPS equity markets. We show that Greece's credit rating downgrades led to an increase in spillover effects from Germany to GIPS returns and

Table 4.4: Change in Contemporaneous Relation Surrounding Events

		Panel A: The spillovers from GIPS to Germany(α_{12})				Panel B: The spillovers from Germany to GIPS (α_{21})			
		G-GE	I-GE	P-GE	S-GE	GE-G	GE-I	GE-P	GE-S
Financial assistance program									
Greece^{first}	Pre	0.22	0.20	0.22	0.28	0.84	0.84	0.59	0.74
	Post	0.21	0.16	0.20	0.24	0.84	0.85	0.61	0.75
	Diff	−0.012***	−0.033***	−0.022***	−0.039***	−0.003	0.014***	0.022***	0.014***
		(−3.45)	(−25.21)	(−3.47)	(−4.90)	(−0.36)	(4.54)	(2.75)	(4.02)
Greece^{second}	Pre	−0.01	0.01	0.09	0.22	0.63	0.62	0.46	0.74
	Post	−0.02	0.01	0.10	0.23	0.63	0.62	0.44	0.73
	Diff	−0.006***	0.003	0.009	0.018***	−0.004	−0.004	−0.019***	−0.017***
		(−2.60)	(1.37)	(1.11)	(4.12)	(−0.56)	(−0.68)	(−2.49)	(−2.93)
Portugal	Pre	−0.01	0.02	0.06	0.13	0.80	0.68	0.56	0.86
	Post	−0.02	−0.01	0.06	0.12	0.82	0.68	0.58	0.89
	Diff	−0.004	−0.030***	−0.005	−0.009***	0.021*	−0.002	0.025***	0.031***
		(−0.96)	(−3.33)	(1.17)	(−2.48)	(1.94)	(−0.52)	(2.57)	(4.23)
Spain	Pre	−0.02	0.04	0.13	0.23	0.63	0.64	0.42	0.68
	Post	−0.01	0.03	0.14	0.19	0.66	0.63	0.44	0.65
	Diff	0.007***	−0.014***	0.011**	−0.040***	0.030***	−0.007**	0.019***	−0.027***
		(2.59)	(−4.48)	(2.09)	(−6.55)	(3.50)	(−2.18)	(2.96)	(−3.65)
Credit rating Downgrade									
Greece^{first}	Pre	0.22	0.20	0.22	0.28	0.84	0.84	0.59	0.74
	Post	0.21	0.17	0.19	0.26	0.85	0.85	0.62	0.75
	Diff	−0.013***	−0.027***	−0.032***	−0.027***	0.009**	0.013***	0.033***	0.015***
		(−6.26)	(−5.33)	(−16.10)	(−4.94)	(2.29)	(3.29)	(6.71)	(5.71)
Greece^{second}	Pre	0.21	0.17	0.19	0.25	0.85	0.85	0.62	0.75
	Post	0.19	0.15	0.20	0.20	0.80	0.87	0.60	0.76
	Diff	−0.018***	−0.013***	0.008***	−0.048***	−0.046***	0.021***	−0.017***	0.007***
		(−5.61)	(−4.45)	(2.58)	(−5.57)	(−8.00)	(2.65)	(−2.91)	(4.23)
Greece^{third}	Pre	0.12	0.06	0.13	0.16	0.90	0.84	0.58	0.84
	Post	0.09	0.04	0.10	0.14	0.97	0.77	0.61	0.90
	Diff	−0.024***	−0.021***	−0.028***	−0.021***	0.071***	−0.074***	0.032***	0.059***
		(−5.62)	(−4.15)	(−11.71)	(−4.37)	(10.45)	(−4.45)	(6.99)	(6.38)

(continued)

Table 3.4 (continued): Change in Contemporaneous Relation Surrounding Events

		Panel A: The spillovers from GIPS to Germany(α_{12})				Panel B: The spillovers from Germany to GIPS (α_{21})			
		G-GE	I-GE	P-GE	S-GE	GE-G	GE-I	GE-P	GE-S
Credit ratings Downgrade									
Italy	Pre	0.04	−0.04	0.12	0.20	0.73	0.62	0.53	0.80
	Post	0.03	−0.06	0.12	0.21	0.71	0.61	0.51	0.80
	Diff	−0.012***	−0.013***	-0.000	0.007	−0.027***	−0.016***	−0.012***	0.000
		(−3.37)	(−2.34)	(−0.06)	(1.61)	(−2.52)	(−3.59)	(−3.81)	(0.00)
Portugal^{first}	Pre	−0.02	−0.02	0.06	0.11	0.83	0.68	0.59	0.89
	Post	−0.01	−0.04	0.06	0.13	0.83	0.70	0.60	0.84
	Diff	0.008	−0.019*	−0.000	0.012	0.001	0.017	0.002	−0.048***
		(0.79)	(−1.90)	(−0.04)	(0.72)	(0.07)	(1.03)	(0.14)	(−2.71)
Portugal^{second}	Pre	0.02	−0.04	0.11	0.21	0.68	0.62	0.51	0.79
	Post	−0.01	0.01	0.10	0.21	0.62	0.63	0.48	0.76
	Diff	−0.029***	0.053***	-0.004	0.006*	−0.051***	0.010***	−0.027***	−0.030***
		(−3.97)	(14.81)	(−0.66)	(1.82)	(−7.05)	(1.97)	(−6.39)	(−4.57)
Portugal^{third}	Pre	−0.01	0.01	0.10	0.21	0.62	0.63	0.48	0.76
	Post	−0.01	0.01	0.09	0.22	0.64	0.62	0.46	0.74
	Diff	−0.003	−0.003	−0.017***	0.001	0.016***	−0.010**	−0.021***	−0.015***
		(−1.28)	(−1.43)	(−7.47)	(0.73)	(4.45)	(−2.26)	(−4.73)	(−3.78)
Spain^{first}	Pre	−0.01	−0.01	0.14	0.14	0.66	0.63	0.51	0.71
	Post	−0.02	−0.002	0.15	0.16	0.67	0.65	0.51	0.72
	Diff	−0.011***	0.004	0.011***	0.017***	0.004***	0.021***	0.004	0.011***
		(−5.78)	(1.20)	(5.74)	(8.85)	(2.41)	(5.09)	(1.07)	(3.17)
Spain^{second}	Pre	−0.02	−0.01	0.15	0.15	0.67	0.64	0.51	0.71
	Post	−0.02	−0.001	0.16	0.16	0.67	0.66	0.51	0.71
	Diff	−0.007***	0.007***	0.009***	0.009***	0.000	0.017***	−0.004***	−0.001
		(−3.38)	(4.33)	(5.40)	(2.77)	(0.28)	(4.33)	(−2.59)	(−0.13)

Note: This table provides the change in α_{12}, the spillover effects from GIPS to Germany, and α_{21}, the spillover effects from Germany to GIPS obtained from a rolling window estimation. The figures reported show the absolute change in spillover effects which is measured as the difference 6 weeks pre and post GIPS's downgrades and Greece's, Portugal's and Spain's financial support programs. The results are robust also to 2 and 10 weeks before and after the previous events. The superscript of GIPS's credit rating downgrades, i.e, first, second and third, refers to the chronological order of these events as reported in Table 4.2. Numbers in parentheses are t-statistics. ***, ** and * denote significance at 1%, 5% and 10% levels.

a decrease in return spillovers the other way around. Finally, we document that while Portugal's and Italy's downgrades led to a decrease in contemporaneous spillover effects, Spain's downgrades caused an increase in contemporaneous spillovers. In sum, based on the statistics in Table 4.4, it is evident that financial support programs and credit rating downgrades affected the contemporaneous spillovers between German and GIPS stock markets.

4.6 Conclusion

In this chapter, we examine the contemporaneous spillover effects between the German and GIPS equity markets. Using Lütkepohl's (2012) approach and a rolling window estimation, we explain the extent to which these relations vary over time, especially during financial crises. Moreover, we investigate the impact of financial assistance programs and credit rating downgrades on the time-varying contemporaneous spillover effects at the return level.

Our analyses yield several interesting findings. First, we document the existence of asymmetric contemporaneous spillover effects. We notice that an increase in German returns had a greater impact on GIPS returns than the other way around. Second, we observe that while during the GFC there was an increase in the magnitude of contemporaneous spillover effects, during the first phase of the EDC there was a decrease in their magnitude. Importantly, however, during the second phase of the EDC, we notice an increase in the return spillover effects from Germany to GIPS equity markets. Third, we show the impacts that financial support programs and credit rating downgrades had on the direction of return spillover effects among our stock markets.

Our findings have several important implications. First, for regulatory authorities, central banks and governments, our findings provide a better understanding of the transmission of shocks and thus, useful information on a country's financial stability. Second, our methodology can be used as a useful tool for monitoring the spillovers among markets. This can assist policy makers to implement and coordinate their policy actions that aim at controlling through early warning indicators transmission of shocks (Louzis, 2015). Finally, the fact that financial support packages have reduced the transmission of return shocks from peripheral countries to Germany indicates that these programs have, to some degree, restored market participants' confidence in the EA. On the whole, our analyses highlight the relevance of taking into consideration the asymmetry and time-variation in contemporaneous spillover effects.

4.A Appendix A1: Chow's Breakpoint Test

	Panel A: The spillovers from GIPS to Germany(α_{12})				Panel B: The spillovers from Germany to GIPS (α_{21})			
	G-GE	I-GE	P-GE	S-GE	GE-G	GE-I	GE-P	GE-S
GFC	24.75***	15.45***	98.07***	25.01***	48.68***	13.19***	49.13***	44.82***
EDC$^{\text{first phase}}$	19.19***	7.91***	60.91***	15.50***	24.77***	2.82***	29.07***	22.99***
EDC$^{\text{second phase}}$	155.17***	164.45***	126.09***	134.88***	65.61***	99.16***	83.34***	89.00***

Note: This table reports the Chow breakpoint test on contemporaneous relations, matrix **A**. The Chow test is estimated considering each of the GFC (September 2008 to September 2009), EDC$^{\text{first phase}}$ (October 2009 to September 2012) and EDC$^{\text{second phase}}$ (October 2012 to December 2014) periods as the breakpoint. We report the F-statistics which is defined as $F = \frac{(\bar{\varepsilon}'\varepsilon - \varepsilon_1'\varepsilon_1 - \varepsilon_2'\varepsilon_2)/k}{(\varepsilon_1'\varepsilon_1 + \varepsilon_2'\varepsilon_2)/(T-2k)}$, where T is the total number of observations, k is the number of parameters, $\bar{\varepsilon}'\varepsilon$ is the residual sum of squares over the full sample, $\varepsilon_1'\varepsilon_1$ and $\varepsilon_2'\varepsilon_2$ is the residual sum of squares before and after each of the break points considered, i.e., GFC, EDC$^{\text{first phase}}$ and EDC$^{\text{second phase}}$. The null hypothesis of no structural change can be rejected. *** denotes significance at 1% level judged through the p-values, which are zero for all the estimates.

4.A Appendix A2: Correlation Matrix between Returns

		${R_t}^G$	${R_t}^I$	${R_t}^P$	${R_t}^S$
Panel A: Full Sample	${R_t}^{GE}$	0.55	0.47	0.63	0.80
Panel B: Pre-GFC	${R_t}^{GE}$	0.66	0.47	0.66	0.87
Panel C: GFC	${R_t}^{GE}$	0.83	0.69	0.79	0.85
Panel D: $EDC^{\text{first phase}}$	${R_t}^{GE}$	0.45	0.42	0.67	0.79
Panel E: $EDC^{\text{second phase}}$	${R_t}^{GE}$	0.47	0.37	0.62	0.67

Note: This table reports the correlation matrix between German and GIPS returns for the full sample period and each of the four different periods. The first period (Pre-GFC) is from January 2003 to August 2008. The second period (GFC) is from September 2008 to September 2009. The third period ($EDC^{\text{first phase}}$) is from October 2009 to September 2012 and the last period ($EDC^{\text{second phase}}$) is from October 2012 to December 2014.

Chapter 5

Volatility Spillovers Among Oil and Stock Markets in the US and Saudi Arabia

5.1 Introduction

Oil prices are of great importance for stock markets (Driesprong et al., 2008). The economic rationale behind the investigation of relations between oil and stock prices is that based on the equity valuation theory, stock prices are equal to their discounted future cash flows (Wang and Liu, 2016; Creti et al., 2014; Jouini, 2013). As fluctuations in oil prices influence the various determinants of expected future cash flows, such as economic growth, inflation rate, corporate performance and earnings, these fluctuations affect stock prices (Salisu and Oloko, 2015; Demirer et al., 2015; Park and Ratti, 2008; Apergis and Miller, 2009). Several studies further show that oil prices can serve as a predictor of stock markets'performance and economic recessions (Narayan and Gupta, 2015; Kang et al., 2015; Balcilar and Ozdemir, 2013; Fayyad and Daly, 2011; Engemann et al., 2011). Increases in oil prices generally depress economic activity, put pressure on credit markets, and negatively affect stock prices (Nazlioglu et al., 2015). Ramos and Veiga (2013), instead, show that oil prices have negative effects on the stock markets of oil-importing countries, while the effects are positive on the stock markets of oil-exporting countries. Financialization of oil-related products[1] and intensive oil trading

[1] Financialization means that oil prices are not only determined by the supply-demand structure of the oil market, but are also importantly affected by changes in financial market conditions (Wan

can increase bi-directional transmission of oil shocks between oil and financial markets (Creti et al., 2013).

Knowledge of these spillover effects between oil and stock markets is relevant especially during financial crises given that markets have experienced a decline in their prices and an increase in their volatility. Moreover, Hamilton (2008) points out that nine of the last ten US recessions were preceded by rises in oil prices. The increase in oil's volatility is usually seen as representing greater uncertainty in stock markets (Malik and Ewing, 2009; Yang et al., 2002). Vo (2011), for example, finds evidence of bi-directional volatility dependence between oil and stock markets, showing that past volatility of oil market has predictive power for the future volatility of the stock market and vice versa. As such, the assessment of volatility spillover effects can provide better forecasts of volatility in oil and stock markets. Additionally, this investigation provides useful information for international asset hedging strategies. Oil plays a crucial role in these strategies for a variety of economic agents, such as investors holding stocks of oil and oil-related industries, oil producers and consumers (Arouri et al., 2011).

While most studies investigate the relations between oil and stock markets in developed economies, the investigation of these relations in the US and emerging economies, such as the Gulf Cooperation Council (GCC) countries is limited.[2] Over the last decade these countries have experienced an unprecedented economic growth triggered by high oil prices. On the one hand, the economic expansion has provided greater access for foreign investors to their stock markets, while, on the other hand, has led to extraordinary speculative activity in their stock markets and made them more susceptible to shocks in international markets and thus, more volatile (Awartani and Maghyereh, 2013). An interesting characteristic of the GCC stock markets, which makes them unique and different from those of the developed countries and from other emerging markets, is

and Kao, 2015). This is due to the increased participation in oil and commodity markets of financial investors, who are looking to achieve greater portfolio benefits, rather than commercial traders, who use derivatives market to hedge against price fluctuations (Basak and Pavlova, 2015).

[2] The GCC consists of the following countries: Saudi Arabia, United Arab Emirates, Kuwait, Qatar, Oman and Bahrain.

that their economies are heavily dependent on oil revenues. In fact, the GCC countries are the world's major oil-exporters. As such, their economic performance is driven by oil prices which are determined at the global rather than the domestic level. Additionally, GCC investors have placed large amounts of petrodollars in the US stock market either for safety reasons or cross-market hedging (Malik and Hammoudeh, 2007). To understand the impact that these shocks to oil and US stock market volatility have on the GCC stock markets, it is important to investigate the interactions among them.

Given that oil is trading continuously, its shocks can be instantaneously transmitted to the US and GCC stock markets when these markets are trading. Thus, there may exist contemporaneous spillover effects among these markets. In addition, oil shocks can affect the GCC stock markets indirectly via its contemporaneous spillover with the US stock market. At the moment, a clear understanding of these issues is lacking in the literature focusing on the GCC countries. For instance, it is yet to be explored whether there are any contemporaneous spillovers, if yes, whether they are asymmetric and whether there is an indirect transmission of shocks among oil and stock markets. The few studies examining the spillover effects have applied traditional VAR and GARCH models which solely focus on the lead-lag dynamics (Alotaibi and Mishra, 2015; Jouini, 2013; Jouini and Harrathi, 2014; Khalifa et al., 2014). These dynamic relations might not fully capture the instantaneous and indirect transmission of shocks. There are, however, alternative solutions which allow us to identify these shock transmissions by making use of the non-proportional shifts in volatility (Rigobon, 2003; Lütkepohl, 2012).

In this paper, we investigate the instantaneous transmission of volatility between oil and the US and Saudi Arabia (SA) stock markets.[3] We analyze these contemporaneous spillover effects using a structural VAR and Lütkepohl's (2012) approach via changes

[3] There are several reasons for the choice of the Saudia Arabia stock market from the GCC countries. First, SA is the largest capital market, oldest, most liquid and the market with the highest turnover ratio (Awartani et al., 2013). Although, SA market has been open to foreign direct investment from GCC countries, only since August 2008 has been open to foreign investors indirectly through swaps and exchange-traded funds. Recently, in June 2015 SA has been opened to foreign direct investment. Second, SA is the world's largest producer and exporter of oil. Moreover, SA is the second largest petroleum exporter to the US, after Canada.

in volatility focusing on the period when oil and stock markets trade simultaneously.

Our study makes several contributions to the existing literature. First, our study is the first to examine volatility transmission between the oil and the US and SA stock markets taking into consideration the continuous trading hours of oil prices. In particular, using high frequency data, we split the continuous trading period of oil into four: the overlapping period when the US stock market is open, the non-overlapping period after the US stock market closes, the overlapping period when the SA stock market is open and the non-overlapping period after the SA stock market closes. For each of these periods and the periods of the US and SA stock markets during the normal trading hours, we calculate the realized volatility which allows us to explore the contemporaneous volatility spillover effects, namely, the direct effects among these markets. Second, we assess the indirect transmission of volatility between oil and SA stock market. For instance, during the time when oil's trading hours overlap with the US stock market, a change in oil's volatility could not only directly affect the SA stock market volatility but this might also indirectly influence its volatility via the volatility of the US stock market and oil during overlapping trading hours with the SA stock market. Third, from an empirical point of view, using Lütkepohl's (2012) approach enables us to address the simultaneity issue without imposing any restrictions to identify the structural shocks between oil and stock markets. By addressing these issues, our study differs from the existing studies (e.g., Arouri et al., 2011; Awartani and Maghyereh, 2013; Malik and Hammoudeh, 2007) who only consider the spot oil prices when analyzing the lead-lag relations between oil and stock markets.

Our analysis yields several important results. First, we show that volatility of oil during the overlapping trading hours with the US stock market has a small direct impact on SA stock market volatility. Instead, when taking into consideration the indirect effects there is a significant volatility spillover. This finding indicates that shocks to oil's volatility during the period when trading hours overlap with the US stock market indirectly (namely, via their impact on the volatility of the US stock market and oil during the period when trading hours overlap with the SA stock market) affect the volatility of the SA stock market. The existence of these indirect effects could be the explanation for the mixed results in literature about the relations between oil and the SA stock market (Jouini and Harrathi, 2014; Arouri et al., 2011). Second, we find asymmetry in the contemporaneous volatility spillovers. Specifically, we document that shocks occurring during the overlapping trading periods of oil with the US and SA stock markets have higher impacts on the US and SA stock market volatilities than the other way around. Third, we emphasize the relevance of volatility transmission across trading venues by computing the impulse responses and variance decomposition using our structural VAR and a traditional VAR. On the whole, our results clearly underline that contemporaneous effects are necessary to be taken into account since the indirect transmission of volatility occurs through them.

Our findings have several important implications. First, for market participants, we show that the overlapping trading period of oil with the US and SA stock markets have an influential role on other volatilities given that increases in oil's volatility leads increases in other volatilities. Second, understanding the direct and indirect volatility transmission is necessary for high frequency traders. Our findings clearly reveal that when oil and stock markets trade simultaneously the volatility shocks are transmitted instantaneously. We emphasize that oil's volatility shocks which occur during the simultaneous trading with the US stock market indirectly influence the SA stock market volatility. Moreover, volatility shocks to the US stock market directly affect the SA stock market volatility. Saudi Arabia's monetary authorities and policy-makers might consider these volatility transmissions as a signal to introduce financial instruments such as, futures and options, to reduce volatility impact on its stock market or at least allow market participants to hedge against such shocks (Malik and Hammoudeh, 2007; Hammoudeh and Choi, 2007).

The remainder of the paper is structured as follows. Section 2 briefly reviews the literature which explores the relations between the oil and stock markets with emphasis on the GCC countries. Section 3 presents the empirical setting. Section 4 discusses the data and Section 5 outlines the empirical findings. We conclude in Section 6.

5.2 Literature Review

This paper examines the contemporaneous volatility spillovers between oil and stock markets in the US and Saudi Arabia. We start this section by briefly presenting the relevance of assessing the relations between oil and stock markets. We then discuss the spillovers between the oil and GCC stock markets, and between the stock markets in the US and GCC. Finally, we address the few studies that investigate the spillovers among oil and the US and GCC stock markets.

There is a considerable amount of literature that analyzes the interactions between oil and stock markets (Park and Ratti, 2008; Miller and Ratti, 2009; Filis et al., 2011; Creti et al., 2014; Wang and Liu, 2016; Ramos and Veiga, 2013). Most of these studies indicate that oil price shocks have negative impacts on the stock markets of oil importing countries and positive effects on the stock markets of oil exporting countries. The main economic reason for existence of these links, for oil importing countries, is based on the fact that higher oil prices lead to higher inflation rates, lower real consumption, higher production costs and lower expected cash flows, all of which ultimately affect stock prices (Reboredo and Ugolini, 2016; Chkili et al., 2014). For oil exporting countries, instead, higher oil prices generate more income and wealth, thereby stimulating economic activity which may be beneficial for stock markets (Awartani and Maghyereh, 2013). Other studies consider the role of oil prices for future stock markets' performance. For instance, Liu et al. (2015), Driesprong et al. (2008) and Bacilar and Ozdemir (2013) show that changes in oil prices predict stock market returns. Likewise, Christoffersen and Pan (2014), Wang and Liu (2015) and Vo (2011) find that oil volatility provides useful information about stock market volatilities. Furthermore, Salisu and Oloko (2015), Khalfaoui et al. (2015) and Belgacem et al. (2015) document the existence of significant bi-directional volatility spillovers between oil and stock markets. These studies, therefore, emphasize that shocks occurring in oil martket have significant impacts on the stock markets.

Despite the substantial research on the relations between oil and stock markets in developed countries, the literature on these relations in the GCC countries is limited. Awartani and Maghyereh (2013) applying a VAR model find asymmetric return and volatility spillover effects between oil and GCC stock markets, where the spillover from oil to GCC stock markets is stronger than the spillovers in the opposite direction. Moreover, the authors conclude that the magnitude of these spillover effects has increased in the aftermath of the Global Financial Crisis (GFC). In contrast, Arouri et al. (2011) show that while there are return and volatility spillover effects from oil to several GCC stock markets (Bahrain, Oman, Qatar and UAE), the spillovers from GCC stock markets to oil are nearly absent. Contrary to previous studies, Jouini (2013) documents bi-directional spillovers at the volatility level, where spillovers from the SA stock market sectors to oil are higher than the other way around. At the return level, authors observe unidirectional spillovers from oil to the SA stock market sectors. Similarly, Jouini and Harrathi (2014) argue that volatility transmission is from the GCC stock markets to oil. With regards to the spillover effects between the US and GCC stock markets, employing VAR and GARCH models, Awartani et al. (2013) and Alotaibi and Mishra (2015) provide evidence of asymmetric volatility and return spillovers. Specifically, the authors show that following the GFC, spillover effects from both US and SA stock markets to other GCC stock markets have increased and are higher than the other way around.

A possible explanation for this disagreement is that the above studies separately examine the relations either between the oil and GCC stock markets or the US and GCC stock markets. As such, these studies are unable to capture the indirect transmission of shocks via the US stock market or respectively, oil prices. Moreover, as oil futures are heavily and continuously traded, using low frequency data may fail to capture the information contained in intraday price movements (Phan et al., 2015) and thus, the instantaneous transmission of shocks.

Besides the majority of studies that individually investigate the spillovers between oil and either US or GCC stock markets, Malik and Hammoudeh (2007) and Fayyad and Daly (2011) address these spillovers considering oil and stock markets in the US and GCC. Malik and Hammoudeh (2007), for instance, investigate volatility transmission between the oil and stock markets of the US, SA, Kuwait and Bahrain using a multivariate GARCH model for the period February 1994 to December 2001. Their findings reveal the existence of volatility spillover effects from oil and the US stock market to all three stock markets. Moreover, the authors show that the SA stock market is more sensitive to oil volatility than the US stock market, and is the only market from the GCC stock markets which transmits volatility to the oil market. This finding emphasizes the major role that SA plays in the global oil market as the largest oil supplier. Fayyad and Daly (2011) examine the return spillover effects between oil and the US, UK and GCC stock markets, with exception of the SA stock market. Applying a VAR model, the authors find that during the GFC, i.e., October 2008 to February 2010, the predictive power of oil prices on stock prices increases, except those in Kuwait and Bahrain. Although there are studies that examine the relations among oil and stock markets, these studies assess the lead-lag relations, namely, the transmission of volatility shocks that occurs the next trading day. As such, these studies do not take into consideration the fact that oil is continuously trading. Our work contributes to this literature by focusing on the continuous trading of oil in exploring the relations among oil and the stock markets in the US and Saudi Arabia. In addition to the lead-lag relations, the high frequency data of oil allow the investigation of the instantaneous and indirect transmission of volatility among these markets.

It has further been documented that the examination of spillover effects between oil and the stock markets is relevant for implementation of hedging strategies and portfolio diversification. Khalifa et al. (2014), for example, analyze volatility transmission using a VAR model and show that is better to hedge between the GCC markets and each of oil and US stock market than between the paired individual GCC markets. Mensi et al. (2015) provide evidence of average correlations between the SA stock market and cereal (wheat, corn, rice), gold and oil, and indicate that these commodity markets are useful for diversification benefits and can serve as hedge in both normal and stress market periods. As such, a better understanding of the shock transmissions among oil and stock markets could provide useful information for market participants.

The above studies share a few common characteristics. For instance, these studies explain the spillover effects using VAR and GARCH models, which are able to only capture the lead-lag relations between oil and stock markets. Moreover, they use low frequency data, e.g., either daily or weekly, and spot oil prices. However, since oil futures contracts are traded continuously, their shocks can be instantaneously transmitted to the stock markets and the other way around. Thus, the effects of these shocks might not be reflected in the dynamic relations using VAR or GARCH analysis. Moreover, oil shocks can also indirectly influence the SA stock market via a third market, e.g., the US stock market. The current paper fills this gap in the literature by being the first, to the best of our knowledge, to consider these contemporaneous and indirect effects. In particular, our study uses Lütkepohl's (2012) approach via changes in volatility together with the high frequency data and the West Texas Intermediate crude oil futures which allows us to shed light on the interactions between the oil, and both US and SA stock markets.

5.3 Model

We focus on contemporaneous spillover effects between oil and stock markets in the US and SA. To examine these effects, we use a structural VAR (SVAR) model and Lütkepohl's (2012) approach which allows us to achieve the identification of shocks to our realized variances.

We define the total trading day by splitting each day of the oil-trading into two overlapping (O) and non-overlapping (NO) trading periods when the US and SA stock markets are open and respectively, after they close. Specifically, $\text{Oil}^{\text{O,US}}$ refers to the overlapping trading period of oil with the US stock market, $\text{Oil}^{\text{O,SA}}$ is the overlapping trading period of oil with the SA stock market, $\text{Oil}^{\text{NO,US}}$ is the non-overlapping trading period of oil after the US stock market closes and $\text{Oil}^{\text{NO,SA}}$ is the the non-overlapping trading period of oil after the SA stock market closes.[4] Regarding the US and SA stock (S) markets, we consider their normal trading hours. In particular, $\text{S}^{\text{O,US}}$ refers to the US stock market during the overlapping trading hours with oil and $\text{S}^{\text{O,SA}}$ is the SA stock market during the overlapping trading hours with oil. All times are taken to be Greenwich Mean Time as follows:

$$\overbrace{2:30pm \ldots 9pm}^{\text{Oil}^{\text{O,US}}} \quad \overbrace{9pm \ldots 8am}^{\text{Oil}^{\text{NO,US}}} \quad \overbrace{8am \ldots 12:30pm}^{\text{Oil}^{\text{O,SA}}} \quad \overbrace{12:30pm \ldots 2:30pm}^{\text{Oil}^{\text{NO,SA}}}$$

$$\underbrace{2:30pm \ldots 9pm}_{\text{S}^{\text{O,US}}} \qquad \underbrace{8am \ldots 12:30pm}_{\text{S}^{\text{O,SA}}}$$

$$t-1| \underbrace{\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad}_{\text{Total Trading Day (t)}} |t+1$$

Using the intraday returns, $\Delta P_i = log(P_i) - log(P_{i-1})$, where the P_i is the price at time i, we compute the realized variances for oil and stock markets as $RV_t^j = log(\sum_{i=1}^{N}(\Delta P_i)^2 \frac{T}{t_j})$, with $j = \{Oil^{O,US}, S^{O,US}, Oil^{NO,US}, Oil^{O,SA}, S^{O,SA}, Oil^{NO,SA}\}$, $T = 24$ and t_j is the number of trading hours in the j^{th} trading period. We implement the scaling by T/t_j to have all volatility measures expressed on the same time interval, namely, 24 hour basis.

To assess the interactions among our realized variances, we implement the following SVAR:

$$\mathbf{A}RV_t = c + \mathbf{\Phi}(\mathbf{L})RV_t + \varepsilon_t \tag{5.1}$$

where RV_t is a (6×1) vector representing the realized variances of oil and stock markets,

[4] See also Kao and Fung (2012) who defines the trading day considering the 24-hour GLOBEX trading in examining the volume-volatility relations for the Japanese yen futures, euro FX futures and E-mini S&P 500 futures.

i.e.,

$$RV_t = \left(RV_t^{Oil^{O,US}} \quad RV_t^{S^{O,US}} \quad RV_t^{Oil^{NO,US}} \quad RV_t^{Oil^{O,SA}} \quad RV_t^{S^{O,SA}} \quad RV_t^{Oil^{NO,SA}} \right)', \tag{5.2}$$

where $RV_t^{Oil^{O,US}}$ is the oil volatility during the overlapping trading period with the US stock market volatility, $RV_t^{S^{O,US}}$ is the US stock market volatility, $RV_t^{Oil^{NO,US}}$ is the oil volatility during the non-overlapping trading period with the US stock market volatility (i.e., the oil volatility after the US stock market closes), $RV_t^{Oil^{O,SA}}$ is the oil volatility during the overlapping trading period with the SA stock market volatility, $RV_t^{S^{O,SA}}$ is the SA stock market volatility and $RV_t^{Oil^{NO,SA}}$ is the oil volatility during the non-overlapping trading period with the SA stock market volatility (i.e., the oil volatility after the SA stock market closes). The coefficient c is a (6×1) vector of constants and $\mathbf{\Phi}(\mathbf{L})$ is a (6×6) matrix polynomial in the lag operator. The (6×6) matrix $\mathbf{A}$ captures the contemporaneous spillover effects among the realized variances and has the following structure,

$$\mathbf{A} = \begin{pmatrix} \alpha_{11} & \alpha_{12} & 0 & 0 & 0 & 0 \\ \alpha_{21} & \alpha_{22} & 0 & 0 & 0 & 0 \\ \alpha_{31} & \alpha_{32} & \alpha_{33} & 0 & 0 & 0 \\ \alpha_{41} & \alpha_{42} & \alpha_{43} & \alpha_{44} & \alpha_{45} & 0 \\ \alpha_{51} & \alpha_{52} & \alpha_{53} & \alpha_{54} & \alpha_{55} & 0 \\ \alpha_{61} & \alpha_{62} & \alpha_{63} & \alpha_{64} & \alpha_{65} & \alpha_{66} \end{pmatrix} \tag{5.3}$$

where α_{12} captures the volatility spillover effect from the US stock market, $RV_t^{S^{O,US}}$ to the oil during the overlapping with the US stock market, $RV_t^{Oil^{O,US}}$ and α_{21} captures the volatility spillover effect from $RV_t^{Oil^{O,US}}$ to $RV_t^{S^{O,US}}$. The other parameters are similarly defined. We set restrictions on matrix $\mathbf{A}$ such that we allow for spillover effects only in one direction, that is forward.

To identify the matrix $\mathbf{A}$, we first estimate the reduced-form VAR model below:

$$\begin{aligned} RV_t &= \mathbf{A^{-1}}c + \mathbf{A^{-1}}\mathbf{\Phi}(\mathbf{L})RV_t + \mathbf{A^{-1}}\varepsilon_t \\ RV_t &= c^* + \mathbf{\Phi}(\mathbf{L})^* RV_t + u_t \end{aligned} \tag{5.4}$$

where the coefficients of Equation (5.4) can be estimated by OLS and are related to the structural coefficients of Equation (5.1) through matrix $\mathbf{A}$. As such, the reduced-form residuals $u_t \sim N(0, \mathbf{\Omega_t})$ where $\mathbf{\Omega_t} = \mathbf{A^{-1}}\mathbf{\Sigma_t}\ \mathbf{A^{-1}}^{'}$.

Given the fact that volatility transmission between oil and stock markets occurs instantaneously, we face an endogeneity problem. That is, we are unable to identify the matrix $\mathbf{A}$ from Equation (5.1) through estimation of Equation (5.4). As such, many studies (Khalifa et al., 2014; Fayyad and Daly, 2011; Malik and Hammoudeh, 2007) solely concentrate on the reduced-form dynamic effects, matrix $\mathbf{\Phi}(\mathbf{L})^*$ from Equation (5.4) in examining the spillover effects between oil and stock markets. To address this issue several studies (Ehrmann and Fratzscher, 2015; Ehrmann et al., 2011; Andersen et al., 2007) use the "identification through heteroskedasticity" approach of Rigobon (2003).

To overcome the endogeneity problem, Lütkepohl (2012) introduces an approach via changes in volatility. The idea behind this approach is to use non-proportional changes in the reduced-form variances, $\mathbf{\Omega_t}$ to identify the contemporaneous relations, namely, matrix $\mathbf{A}$. A more intuitive explanation of how these changes in volatility allow the identification of contemporaneous effects is provided in Chapter 1. Specifically, we assume that the structural shocks, ε_t from Equation (5.1) are uncorrelated and the parameters from Equation (5.4) are time-invariant. In doing so, we can decompose $\mathbf{\Omega_t}$ as follows,

$$\begin{aligned} \mathbf{\Omega_1} &= \mathbf{A^{-1}}\mathbf{A^{-1}}^{'} \\ \mathbf{\Omega_2} &= \mathbf{A^{-1}}\mathbf{\Psi}\mathbf{A^{-1}}^{'} \end{aligned} \tag{5.5}$$

where $\mathbf{\Psi}$ is a (6×6) diagonal matrix with distinct elements capturing the change in variance from $\mathbf{\Omega_1}$ to $\mathbf{\Omega_2}$.

The model is estimated using the Quasi-Maximum Likelihood (QML) and the log-likelihood function is written as follows,

$$\begin{aligned} l_T(\gamma, \Psi, \mathbf{A}) = \sum_{t=1}^{T} log(\gamma\, det(\mathbf{\Omega_1})^{-\mathbf{1/2}} exp\{-\frac{1}{2}\ \mathbf{u_t^{'}\Omega_1^{-1}u_t}\} \\ +(1-\gamma) det(\mathbf{\Omega_2})^{-\mathbf{1/2}} exp\{-\frac{1}{2}\ \mathbf{u_t^{'}\Omega_2^{-1}u_t}\}) \end{aligned} \tag{5.6}$$

where γ is the mixture probability, $0 < \gamma < 1$. As the elements of matrix $\mathbf{A}$ vary freely, we normalize the estimated matrix $\mathbf{A}$ such that its diagonal elements are one as in Equation (4.7) from Chapter 2. We the compute the t-statistics for the normalized matrix $\mathbf{A}$ using the Bollerslev and Wooldrige (1992) standard errors.

5.4 Data

We employ high frequency data sampled at a 5-minute frequency for the oil and both US and SA stock markets. Due to limited availability of high frequency data for the SA stock market, we cover the period from 7th April 2008 to 31st December 2015. The data source is Thomson Reuters Tick History. We include Mondays, Tuesdays, Wednesdays and Thursdays, during which time the US and SA stock markets are open for trading. Days where one market is closed (i.e., the Sundays and Fridays), as well as the US and SA public holidays are eliminated from the sample. For our investigation, we use the WTI crude oil futures traded on New York Mercantile Exchange and the S&P 500/Tadawul All Share Index indices for the US/SA stocks traded on New York Stock Exchange, and the Saudi Stock Exchange, respectively.

Table 5.1 provides summary statistics for equity volatilities in the US and SA, and oil volatility during both overlapping and non-overlapping trading periods with the equity markets.[5] As shown, the highest volatility is during the non-overlapping trading periods of oil with the US and SA stock markets, followed by the overlapping trading period of oil with the US stock market, and then the US stock market and the overlapping

[5]We report the realized volatilities in Table 5.1, as volatilities are more commonly reported than variances.

Table 5.1: Summary Statistics

	$V_t^{Oil^{O,US}}$	$V_t^{S^{O,US}}$	$V_t^{Oil^{NO,US}}$	$V_t^{Oil^{O,SA}}$	$V_t^{S^{O,SA}}$	$V_t^{Oil^{NO,SA}}$
Mean	0.0283	0.0143	0.0249	0.0178	0.0142	0.0340
Max	0.1448	0.0963	0.1966	0.0723	0.0828	0.1134
Min	0.0056	0.0021	0.0029	0.0041	0.0048	0.0061
Std. Dev.	0.0172	0.0103	0.0212	0.0101	0.0095	0.0188
Skew.	2.03	2.91	2.64	1.68	2.87	1.24
Kurt.	8.60	15.00	13.99	6.67	13.97	4.83
ADF	-3.47^{***}	-4.20^{***}	-6.75^{***}	-4.00^{***}	-5.61^{***}	-4.33^{***}

Note: This Table reports summary statistics for the equity volatilities defined as $V_t = \sqrt{\sum_{i=1}^{N}(\Delta P_i)^2 \frac{T}{t_j}}$, i.e., $V_t^{Oil^{O,US}}$, $V_t^{S^{O,US}}$, $V_t^{Oil^{NO,US}}$, $V_t^{Oil^{O,SA}}$, $V_t^{S^{O,SA}}$ and $V_t^{Oil^{NO,SA}}$ in all six trading periods. ADF is the t-statistics for the Augmented Dickey-Fuller test. *** denotes significance at the 1% level. The total trading day is defined as follows:

$$\overbrace{2:30pm \dots 9pm}^{\text{Oil}^{\text{O,US}}} \;\; \overbrace{9pm \dots 8am}^{\text{Oil}^{\text{NO,US}}} \;\; \overbrace{8am \dots 12:30pm}^{\text{Oil}^{\text{O,SA}}} \;\; \overbrace{12:30pm \dots 2:30pm}^{\text{Oil}^{\text{NO,SA}}}$$

$$\underbrace{2:30pm \dots 9pm}_{\text{S}^{\text{O,US}}} \qquad\qquad \underbrace{8am \dots 12:30pm}_{\text{S}^{\text{O,SA}}}$$

$$t-1| \underbrace{\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad}_{\text{Total Trading Day (t)}} |t+1$$

trading period of oil with the SA stock market. These first three trading periods also exhibit the highest mean volatility and variability of volatility based on minimum and maximum. All of the oil and stock market volatilities show the typical characteristics of skewness and excess kurtosis. Augmented Dickey-Fuller tests confirm the stationarity of oil and equity volatilities at the 1% level.

In Table 5.2, we present the correlations among the realized variances of oil in all four trading periods and stock markets in the US and SA. We observe a positive relation between the volatilities of oil and both, US and SA stock market trading periods. In particular, we find that the highest correlation is between the volatility of the overlapping trading period of oil with the US stock market and, the volatilities of stock

Table 5.2: Correlation Matrix between Realized Variances

	${RV_t}^{Oil^{O,US}}$	${RV_t}^{S^{O,US}}$	${RV_t}^{Oil^{NO,US}}$	${RV_t}^{Oil^{O,SA}}$	${RV_t}^{S^{O,SA}}$	${RV_t}^{Oil^{NO,SA}}$
${RV_t}^{Oil^{O,US}}$						
${RV_t}^{S^{O,US}}$	0.6567					
${RV_t}^{Oil^{NO,US}}$	0.6597	0.4407				
${RV_t}^{Oil^{O,SA}}$	0.8167	0.6269	0.6231			
${RV_t}^{S^{O,SA}}$	0.6201	0.5471	0.4583	0.6178		
${RV_t}^{Oil^{NO,SA}}$	0.7385	0.6171	0.5796	0.9509	0.5891	

Note: This Table reports the correlation matrix among the realized variances, ${RV_t}^{Oil^{O,US}}$, ${RV_t}^{S^{O,US}}$, ${RV_t}^{Oil^{NO,US}}$, ${RV_t}^{Oil^{O,SA}}$, ${RV_t}^{S^{O,SA}}$ and ${RV_t}^{Oil^{NO,SA}}$. The total trading day is defined as follows:

$$t-1|\underbrace{\overbrace{\underbrace{2:30pm \ldots 9pm}_{\text{S}^{\text{O,US}}}}^{\text{Oil}^{\text{O,US}}}\;\overbrace{9pm \ldots 8am}^{\text{Oil}^{\text{NO,US}}}\;\overbrace{\underbrace{8am \ldots 12:30pm}_{\text{S}^{\text{O,SA}}}}^{\text{Oil}^{\text{O,SA}}}\;\overbrace{12:30pm \ldots 2:30pm}^{\text{Oil}^{\text{NO,SA}}}}_{\text{Total Trading Day (t)}}|t+1$$

markets and both overlapping and non-overlapping trading periods of oil with the SA stock market. These results imply that there are volatility spillover effects between the overlapping trading period of oil with the US stock market and the other oil and stock market trading periods. The next section explains these relations.

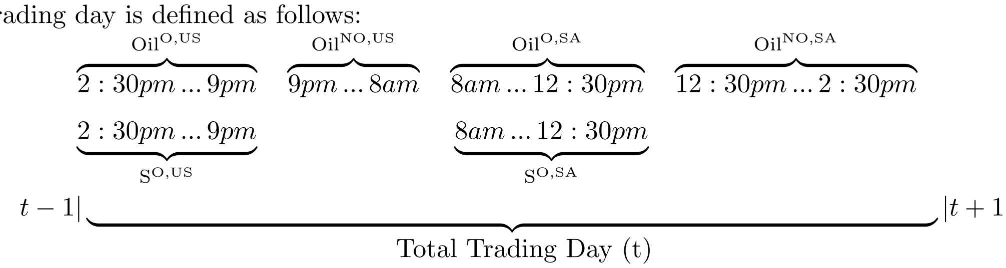
5.5 Empirical Findings

In this section, we present the results for the model shown in Section 3. We start by discussing the Granger causality tests and continue with the evidence on the contemporaneous spillover effects among realized variances of oil and stock markets. We then highlight the importance of the indirect transmission of volatility by presenting the total spillover effects. Finally, we emphasize the relevance of structural shocks in forecasting the impulse responses and variance decomposition by comparing these results with those obtained when using the reduced form shocks.

Table 5.3: Granger Causality for Realized Variances

To\From	$RV_t^{Oil^{O,US}}$	$RV_t^{S^{O,US}}$	$RV_t^{Oil^{NO,US}}$	$RV_t^{Oil^{O,SA}}$	$RV_t^{S^{O,SA}}$	$RV_t^{Oil^{NO,SA}}$
$RV_t^{Oil^{O,US}}$		5.22***	6.00***	12.09***	5.65***	8.38***
$RV_t^{S^{O,US}}$	1.36		1.47	2.91***	3.43***	3.21***
$RV_t^{Oil^{NO,US}}$	25.49***	9.01***		25.81***	9.14***	14.87***
$RV_t^{Oil^{O,SA}}$	20.65***	6.70***	8.96***		4.32***	0.40
$RV_t^{S^{O,SA}}$	5.70***	2.17**	3.15***	7.18***		5.91***
$RV_t^{Oil^{NO,SA}}$	11.30***	5.71***	6.25***	2.96***	3.35***	

Note: This Table reports the results for the Granger causality tests on the reduced-form VAR which is estimated using 5 lags. The columns represent the volatilities from which causality is running, whereas the rows represent the volatilities towards which causality is running. *** and ** denote significance at the 1% and 5% levels, respectively. The total trading day is defined as follows:



5.5.1 Granger Causality

We initiate our analysis by estimating the reduced form VAR model as given Equation (5.4). Using the Akaike Information Criterion, we obtain a lag length of 5 days to be optimal. We then compute the Granger causality tests for our realized variances which are shown in Table 5.3.

The Granger causality tests show the existence of strong and significant bi-directional causality among oil and stock market volatilities in most of the trading periods. Specifically, we find that the $\mathrm{Oil}^{\mathrm{O,US}}$ volatility Granger causes the $\mathrm{Oil}^{\mathrm{NO,US}}$, $\mathrm{Oil}^{\mathrm{O,SA}}$ and $\mathrm{Oil}^{\mathrm{NO,SA}}$ volatilities stronger than the other way around. Interestingly, while there is no significant causality running from the $\mathrm{Oil}^{\mathrm{O,US}}$ volatility to the $\mathrm{S}^{\mathrm{O,US}}$ volatility, the other way around the causality is highly significant. Instead, the $\mathrm{Oil}^{\mathrm{O,SA}}$ volatility has a significantly higher causal effect on the $S^{O,SA}$ volatility than the other way around. Moreover, this causal effect is higher than the bi-directional causal effects between $Oil^{O,US}$ and $S^{O,SA}$ volatilities. This significant causality highlights the important role of the $Oil^{O,SA}$ volatility for the SA stock market volatility. Considering the causal effects of the $S^{O,US}$ volatility on the $Oil^{NO,US}$, $Oil^{O,SA}$, $S^{O,SA}$ and $Oil^{NO,SA}$ volatilities, we notice the highest impact on the $Oil^{NO,US}$ volatility. All these causal effects are bi-directional with the exception of causality running from the $Oil^{NO,US}$ volatility to the $S^{O,US}$ volatility.

In sum, our findings indicate that the volatilities of oil during the overlapping trading hours with the US stock market ($Oil^{O,US}$) and US stock market ($S^{O,US}$) significantly Granger cause the other volatilities. However, it is important to point out that these causality tests capture the lead-lag relations, and thus may not capture the entire causal effects between oil and stock market realized variances. For instance, Table 5.3 shows no significant causality running from the $Oil^{O,US}$ volatility to the $S^{O,US}$ volatility, whereas Table 5.2 documents high correlation between the $Oil^{O,US}$ and $S^{O,US}$ volatilities which is similar with the correlation between the $Oil^{O,US}$ and $Oil^{NO,US}$ volatilities. These results imply that Granger causality tests might not capture the contemporaneous spillover effects, which are addressed in the next section.

5.5.2 Contemporaneous Relations

Table 5.4 provides the contemporaneous spillovers, namely, the direct effects, together with their t-statistics.[6] These relations have negative signs as they are captured by matrix **A** which is on the left-hand side of Equation (5.1). Therefore, when taken to the right-hand side the contemporaneous relations become positive. We find a high and significant contemporaneous spillover of 0.24 from the volatility of the overlapping

[6]Additionally, we assess the statistical significance of equality regarding the contemporaneous spillovers between the $Oil^{O,US}$ volatility and $S^{O,US}$ volatility and between the $Oil^{O,SA}$ volatility and $S^{O,SA}$ volatility. Using a Wald test, we find that these contemporaneous spillovers are significantly different from each other at the 1% level.

trading period of oil with the US stock market to the volatility of the US stock market. This coefficient implies that a 1% increase in the $Oil^{O,US}$ volatility causes a contemporaneous increase of 0.24% in the $S^{O,US}$ volatility. Vice versa, a 1% increase in the $S^{O,US}$ volatility leads to a smaller increase of 0.16% in the $Oil^{O,US}$ volatility than the other way around. Note that these spillover effects are not evident from the Granger causality tests reported in Table 5.3, which showed the opposite, namely, that the $S^{O,US}$ volatility has a significant and higher effect on the $Oil^{O,US}$ volatility than the other way around. These findings demonstrate that the reduced form VAR model is unable to capture the contemporaneous spillover effects.

When we analyze the direct spillover effects from the $Oil^{O,US}$ volatility to the $Oil^{NO,US}$, $Oil^{O,SA}$, $S^{O,SA}$ and $Oil^{NO,SA}$ volatilities, we notice the highest spillovers to the $Oil^{NO,US}$ and $Oil^{O,SA}$ volatilities, with the coefficients of approximately 0.76 and 0.16, respectively. These coefficients suggest that a 1% increase in the $Oil^{O,US}$ volatility causes an increase of 0.76% in the $Oil^{NO,US}$ volatility and respectively, 0.16% in the $Oil^{O,SA}$ volatility. Instead, the volatility of $Oil^{O,US}$ has a small impact on the volatilities of the $S^{O,SA}$ and $Oil^{NO,SA}$, around -0.01 and respectively, -0.02 suggesting that the $S^{O,SA}$ and $Oil^{NO,SA}$ volatilities are less sensitive to the $Oil^{O,US}$ volatility shocks.

The above findings also indicate that volatility transmission from oil during the overlapping trading hours with the US stock market ($Oil^{O,US}$) to the SA stock market might indirectly occur via the high impacts that $Oil^{O,US}$ shocks has on the volatilities of $S^{O,US}$, $Oil^{NO,US}$ and $Oil^{O,SA}$. Additionally, the $S^{O,SA}$ volatility may be instantaneously affected by shocks occurring in the $Oil^{O,SA}$ volatility. Indeed, we document that there is a significant contemporaneous spillover from the volatility of the overlapping trading period of oil with the SA stock market to the volatility of the SA stock market that is higher than the other way around. Specifically, while a 1% increase in the $Oil^{O,SA}$ volatility leads to an increase of 0.07% in the $S^{O,SA}$, the response of $Oil^{O,SA}$ volatility to shocks in $S^{O,SA}$ volatility is smaller, with the spillover coefficient of 0.02. This finding emphasizes the important role of oil when the SA stock market is opened in transmitting volatility

Table 5.4: Contemporaneous Relation between Realized Variances

To\From	$RV_t^{Oil^{O,US}}$	$RV_t^{S^{O,US}}$	$RV_t^{Oil^{NO,US}}$	$RV_t^{Oil^{O,SA}}$	$RV_t^{S^{O,SA}}$	$RV_t^{Oil^{NO,SA}}$
$RV_t^{Oil^{O,US}}$	1	0.16***	0	0	0	0
		(0.0139)				
$RV_t^{S^{O,US}}$	0.24***	1	0	0	0	0
	(0.0325)					
$RV_t^{Oil^{NO,US}}$	0.76***	0.01***	1	0	0	0
	(0.0132)	(0.0001)				
$RV_t^{Oil^{O,SA}}$	0.16***	0.10***	0.07***	1	0.02	0
	(0.0035)	(0.0021)	(0.0017)		(0.0261)	
$RV_t^{S^{O,SA}}$	−0.01***	0.16***	0.03***	0.07***	1	0
	(0.0002)	(0.0049)	(0.0009)	(0.0281)		
$RV_t^{Oil^{NO,SA}}$	−0.02***	0.01***	0.003***	0.98***	0.01***	1
	(0.0019)	(0.0005)	(0.0002)	(0.0951)	(0.0013)	

Note: This Table reports the contemporaneous relations between oil, US and SA stock market volatilities. These coefficients have opposite signs to those of matrix **A** as this matrix is on the left-hand side of Equation (5.1). When taken to the right-hand side these contemporaneous relations become positive. Subsequently, the column and row variables are the dependent and respectively, the explanatory variables. Numbers in parentheses are the Bollerslev and Wooldrige (1992) standard errors. ***, ** and * denote significance at 1%, 5% and 10% levels. The total trading day is defined as follows:

$$\overbrace{2:30pm \ldots 9pm}^{\text{Oil}^{\text{O,US}}} \quad \overbrace{9pm \ldots 8am}^{\text{Oil}^{\text{NO,US}}} \quad \overbrace{8am \ldots 12:30pm}^{\text{Oil}^{\text{O,SA}}} \quad \overbrace{12:30pm \ldots 2:30pm}^{\text{Oil}^{\text{NO,SA}}}$$

$$\underbrace{2:30pm \ldots 9pm}_{\text{S}^{\text{O,US}}} \qquad \underbrace{8am \ldots 12:30pm}_{\text{S}^{\text{O,SA}}}$$

$$t-1| \underbrace{\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad}_{\text{Total Trading Day (t)}} |t+1$$

shocks to the SA stock market.

With regards to the spillover effects from the $S^{O,US}$ volatility to the $Oil^{NO,US}$, $Oil^{O,SA}$, $S^{O,SA}$ and $Oil^{NO,SA}$ volatilities, we observe a strong spillover to the $Oil^{O,SA}$ and $S^{O,SA}$ volatilities. In particular, we find that the $S^{O,US}$ volatility shocks lead to higher volatility in $Oil^{O,SA}$ and $S^{O,SA}$ with spillover coefficients equal to 0.10 and respectively, 0.16, than in $Oil^{NO,US}$ and $Oil^{NO,SA}$, where the spillover coefficients equal around 0.01. These findings are again inconsistent with Granger causality results presented in Table 5.3, which document that the causality running from the $S^{O,US}$ volatility to the $Oil^{NO,US}$ volatility is stronger than to the SA stock market volatility and other oil volatilities. As such, our results reveal that the assessment of lead-lag dynamics fails to capture the spillover effects transmitted on the same trading day.

Our investigations so far, documents the existence of contemporaneous spillover effects that are not captured by the reduced-form VAR model. In particular, we show that when oil trades simultaneously with the US and SA stock markets, shocks occurring in either the markets are transmitted instantaneously among the volatilities of oil and stock markets. Further, we highlight that whereas oil volatility during the overlapping trading period with the US stock market has a small impact on the SA stock market volatility, volatility shocks occurring in US stock market have a high impact on SA stock market.

5.5.3 Total Spillovers

In the previous section, we emphasized the importance of investigating the contemporaneous spillover effects and thus, the direct transmission of volatility. This section aims to shed light on the indirect transmission of volatility by discussing the total volatility spillovers defined according to Ehrmann and Fratzscher (2015) and Ehrmann et al. (2011) by matrix $\mathbf{A^{-1}}$ as given in Equation (5.4). To capture the overall effect of a shock to one market on another market that is transmitted on the same trading day defined in Section 5.3, is necessary to take into consideration the instantaneous spillover effects. This also indicates that the overall spillover effects capture the effects of shocks which are indirectly transmitted through the contemporaneous spillovers, i.e., direct effects. As such, the total spillover effects are a combination of contemporaneous spillover effects, and the indirect spillover effects, which are transmitted on the same trading day. Given the reduced-form VAR model in Equation (5.4), these overall spillovers correspond to the estimated parameters in the inverse of matrix **A**. In other words, from this equation it can clearly be seen that $\mathbf{A^{-1}}$ captures the overall spillover effects of the initial structural shocks. That is, the cumulative effect of the different direct transmission shocks. For instance, a shock in the $\text{Oil}^{\text{O,US}}$ volatility could directly affect the $\text{S}^{\text{O,SA}}$ volatility but this may also indirectly occur on the same trading day via the US stock volatility and other oil volatilities (i.e., volatility of oil before opening of SA stock market and when the SA market is opened). Essentially, an increase in the $\text{Oil}^{\text{O,US}}$ volatility could affect the US stock volatility and oil volatilities, which then in turn might affect the $\text{S}^{\text{O,SA}}$ volatility. Thus, the indirect effects can be computed as the difference between the total and direct spillover effects. Table 5.5 report the findings of the total spillover effects which are compared with the direct effects, matrix **A** presented in Table 5.4.

When comparing the total effects in Table 5.5, with the direct effects in Table 5.4, we notice that the indirect transmission of volatility leads to an increase in the magnitude of spillover effects. For example, we find high and positive spillover effects of 0.79, 0.25 and 0.23 from the $\text{Oil}^{\text{O,US}}$ volatility to the $\text{Oil}^{\text{NO,US}}$, $\text{Oil}^{\text{O,SA}}$ and $\text{Oil}^{\text{NO,SA}}$ volatilities, versus the direct spillover effects of 0.76, 0.16 and -0.02. The magnitude of total effects indicates that around 0.03, 0.09 and respectively, 0.21 from these spillovers are indirectly transmitted. Therefore, it is essential to take into consideration the indirect volatility transmission in addition to the direct transmission of volatility reported in the previous section.

We further observe the existence of a volatility spillover from $\text{Oil}^{\text{O,US}}$ to $\text{S}^{\text{O,SA}}$. For instance, a 1% increase in the $\text{Oil}^{\text{O,US}}$ volatility leads to an increase of 0.07% in the $\text{S}^{\text{O,SA}}$ volatility. Notice that the magnitude of this total spillover is higher than the magnitude of the direct spillover reported in Table 5.4. This finding clearly demonstrates that volatility shocks to the overlapping trading period of oil with the US stock market are indirectly transmitted to the SA stock market, namely, approximately 0.06. As such, the existence of indirect volatility transmission may be the main reason for observed mixed empirical results in literature regarding the interactions between volatilities of oil and SA stock market (Jouini and Harrathi, 2014; Awartani and Maghyereh, 2013; Malik

Table 5.5: Total Spillovers among Realized Variances

To\From	$RV_t^{Oil^{O,US}}$	$RV_t^{S^{O,US}}$	$RV_t^{Oil^{NO,US}}$	$RV_t^{Oil^{O,SA}}$	$RV_t^{S^{O,SA}}$	$RV_t^{Oil^{NO,SA}}$
$RV_t^{Oil^{O,US}}$	1	0.16***	0	0	0	0
		(0.0297)				
$RV_t^{S^{O,US}}$	0.24***	1	0	0	0	0
	(0.0231)					
$RV_t^{Oil^{NO,US}}$	0.79***	0.13***	1	0	0	0
	(0.0058)	(0.0011)				
$RV_t^{Oil^{O,SA}}$	0.25***	0.14***	0.07***	1	0.02	0
	(0.0055)	(0.0037)	(0.0024)		(0.0217)	
$RV_t^{S^{O,SA}}$	0.07***	0.17***	0.03***	0.07***	1	0
	(0.0018)	(0.0055)	(0.0020)	(0.0120)		
$RV_t^{Oil^{NO,SA}}$	0.23***	0.14***	0.08***	0.98***	0.03***	1
	(0.0408)	(0.0306)	(0.0321)	(0.1760)	(0.0062)	

Note: This Table reports the total spillovers among oil, US and SA stock market volatilities as given by $\mathbf{A^{-1}}$ which is normalized as matrix $\mathbf{A}$ such that its diagonal elements are one. The matrix $\mathbf{A^{-1}}$ is a combination of the direct spillover effects as presented in Table 5.4 and the indirect spillover effects via other other markets. The column and row variables are the dependent and respectively, the explanatory variables. The total trading day is defined as follows:

$$\overbrace{2:30pm \ldots 9pm}^{\mathrm{Oil^{O,US}}} \quad \overbrace{9pm \ldots 8am}^{\mathrm{Oil^{NO,US}}} \quad \overbrace{8am \ldots 12:30pm}^{\mathrm{Oil^{O,SA}}} \quad \overbrace{12:30pm \ldots 2:30pm}^{\mathrm{Oil^{NO,SA}}}$$

$$\underbrace{2:30pm \ldots 9pm}_{\mathrm{S^{O,US}}} \quad \underbrace{8am \ldots 12:30pm}_{\mathrm{S^{O,SA}}}$$

$$t-1| \underbrace{\qquad\qquad\qquad\qquad\qquad\qquad}_{\text{Total Trading Day (t)}} |t+1$$

and Hammoudeh, 2007). The extant literature focuses on transmission of volatility the next trading day without taking into account the possible interactions among volatilities of oil and stock markets in the US and SA.

Furthermore, we show that the responses of $\mathrm{Oil^{NO,US}}$ and $\mathrm{Oil^{NO,SA}}$ volatilities to shocks in $\mathrm{S^{O,US}}$ volatility are strong, with the spillover coefficients of around 0.13 and 0.14, respectively. These spillover effects are again stronger than the direct spillover effects presented in Table 5.4, implying that around 0.12 and 0.13 of the $\mathrm{S^{O,US}}$ volatility is indirectly transmitted to $\mathrm{Oil^{O,SA}}$ and respectively, $\mathrm{Oil^{NO,SA}}$. Contrary to the high indirect impact of the $\mathrm{Oil^{O,US}}$ volatility on the $\mathrm{S^{O,SA}}$ volatility, we find that US stock market volatility has a small indirect impact on the SA stock market volatility. Particularly, only 0.01 of the $S^{O,US}$ volatility is indirectly transmitted suggesting that most of the volatility shocks occurring in the US stock market directly impact the SA stock market volatility.

In sum, our analysis reveals that when we allow for the indirect spillover effects there is an increase in transmission of volatility. In particular, while volatilities of the Saudi Arabia stock market and the non-overlapping trading period of oil after the SA stock market closes are less directly affected by the oil volatility during the overlapping trading hours with the US stock market, their volatilities greatly increase when accounting for the indirect volatility transmission. We also show that while majority of the US stock market volatility shocks are indirectly transmitted to the volatility of non-overlapping trading periods of oil, the SA stock market is more directly affected by these shocks. These results underline the relevance of taking into consideration the contemporaneous effects and the continuous trading hours of oil as these allow us to better explain the indirect volatility transmission, which is unrecoverable when applying a reduced form VAR model.

5.5.4 Reduced-form versus Structural Impulse Response Functions

In the previous sections, we explained the direct and indirect volatility spillover effects. In this section, we examine the impacts of these effects in forecasting the impulse response functions. Specifically, we assess the contemporaneous reactions of structural shocks to ε_t given by the total spillover effects, matrix $\mathbf{A^{-1}}$. In addition, we compare these structural impulse responses with the reduced-form generalized impulse responses of Pesaran and Shin (1998) which are not affected by the ordering of the volatilities in the reduced form VAR model. This comparison aims to highlight the importance of identifying the contemporaneous and indirect relations which are not captured by the reduced-form impulse responses. Table 5.6 reports the results of the reduced-form and structural impulses responses.

We document that the impulse responses of oil and stock volatilities to a unit shock in the $\text{Oil}^{\text{O,US}}$ volatility are higher than to shocks occurring in other market volatilities. For example, a unit shock in the $\text{Oil}^{\text{O,US}}$ volatility causes an increase in the $\text{S}^{\text{O,US}}$, $\text{Oil}^{\text{NO,US}}$, $\text{Oil}^{\text{O,SA}}$, $\text{S}^{\text{O,SA}}$ and $\text{Oil}^{\text{NO,SA}}$ volatilities of 9.25, 14.24, 13.76, 9.31 and respectively, 12.48 units in the reduced-form VAR, versus 8.27, 14.48, 13.54, 9.00 and 12.42 units in the SVAR model. These findings suggest the existence of strong spillover effects from the $\text{Oil}^{\text{O,US}}$ volatility to the other market volatilities which are overestimated in the reduced-from VAR. In addition, if we compare the responses of our market volatilities to a unit shock in the $\text{Oil}^{\text{O,SA}}$ and $\text{S}^{\text{O,SA}}$ volatilities with a unit shock in other oil and US stock market volatilities, we notice that the former shocks have greater impacts than the latter shocks. This implies that there are spillovers among these volatilities. The reduced-form VAR once again overestimates the responses of oil and stock market volatilities to these shocks. At the same time, we notice that their magnitude is higher than the other way around since we capture the indirect spillover effects. For instance, the $\text{Oil}^{\text{O,SA}}$ volatility affects the $\text{S}^{\text{O,US}}$ volatility over the next trading days indirectly through the spillover with $\text{Oil}^{\text{NO,SA}}$ volatility that is transmitted on the same trading day.

On the whole, our findings show that responses to volatility shocks occurring in the overlapping trading periods of oil when the US and SA stock markets are open and SA stock market are higher than shocks to other volatilities and are overestimated in the reduced-form VAR. Additionally, the results once again highlight the relevance of properly incorporating the simultaneous trading periods and the indirect transmission of volatility.

Table 5.6: Long-Run Impact Matrix

		$RV_t^{Oil^{O,US}}$	$RV_t^{S^{O,US}}$	$RV_t^{Oil^{NO,US}}$	$RV_t^{Oil^{O,SA}}$	$RV_t^{S^{O,SA}}$	$RV_t^{Oil^{NO,SA}}$
		Panel A: Reduced Form shock					
Response	$RV_t^{Oil^{O,US}}$	15.30	8.87	7.09	12.20	9.23	12.00
	$RV_t^{S^{O,US}}$	9.25	10.91	4.31	8.03	7.53	8.72
	$RV_t^{Oil^{NO,US}}$	14.24	8.23	7.63	12.27	9.11	12.27
	$RV_t^{Oil^{O,SA}}$	13.76	8.51	6.78	12.89	8.91	13.25
	$RV_t^{S^{O,SA}}$	9.31	6.20	4.55	7.91	10.00	8.01
	$RV_t^{Oil^{NO,SA}}$	12.48	7.96	6.37	12.05	8.66	13.64
		Panel B: Structural shock					
Response	$RV_t^{Oil^{O,US}}$	15.04	5.59	1.26	8.34	7.02	3.40
	$RV_t^{S^{O,US}}$	8.27	9.51	0.78	5.19	5.22	13.89
	$RV_t^{Oil^{NO,US}}$	14.48	5.24	2.24	8.63	6.94	6.82
	$RV_t^{Oil^{O,SA}}$	13.54	5.61	1.40	9.63	6.67	12.44
	$RV_t^{S^{O,SA}}$	9.00	4.25	0.85	5.45	8.65	4.85
	$RV_t^{Oil^{NO,SA}}$	12.42	5.46	1.54	9.34	6.45	30.02

Note: This Table reports the long-run impact matrix of the reduced-form and structural VAR model. The impacts are computed at the 250-day ahead response to a unit structural shock. The total trading day is defined as follows:

$$\overbrace{2:30pm \ldots 9pm}^{\mathrm{Oil^{O,US}}} \; \overbrace{9pm \ldots 8am}^{\mathrm{Oil^{NO,US}}} \; \overbrace{8am \ldots 12:30pm}^{\mathrm{Oil^{O,SA}}} \; \overbrace{12:30pm \ldots 2:30pm}^{\mathrm{Oil^{NO,SA}}}$$

$$\underbrace{2:30pm \ldots 9pm}_{\mathrm{S^{O,US}}} \qquad \underbrace{8am \ldots 12:30pm}_{\mathrm{S^{O,SA}}}$$

$$t-1| \underbrace{\qquad\qquad\qquad\qquad\qquad\qquad}_{\text{Total Trading Day (t)}} |t+1$$

5.5.5 Reduced-form versus Structural Variance Decomposition

In this section, we focus on the differences that the reduced-form and structural shocks have on forecasting the variance decomposition. Specifically, we assess the percentage contribution of shocks occurring in each of the market volatilities in explaining the share of the total variance of the $\text{Oil}^{\text{O,US}}$, $\text{S}^{\text{O,US}}$, $\text{Oil}^{\text{NO,US}}$, $\text{Oil}^{\text{O,SA}}$, $\text{S}^{\text{O,SA}}$ and $\text{Oil}^{\text{NO,SA}}$ volatilities. Table 5.7 presents the findings of the reduced-form and structural variance decomposition.

We notice that the largest share of our oil and stock market volatilities is due to their own shocks varying between around 18% and 49% in the reduced-form VAR, versus 18% and 78% in SVAR. The exception is the $\text{Oil}^{\text{NO,US}}$ volatility that is more affected by the $\text{Oil}^{\text{O,US}}$ shocks than its idiosyncratic shocks. In line with the impulse responses findings presented in Table 5.6, we observe that besides the own shocks, a large share of the variability in $\text{Oil}^{\text{O,SA}}$ and $\text{S}^{\text{O,SA}}$ volatilities is explained by shocks originating in the $\text{Oil}^{\text{O,US}}$ volatility, approximately 21% and 16% in the reduced-form VAR, versus 30% and 20% in the SVAR. The reduced-form shocks to the $\text{Oil}^{\text{O,SA}}$ and $\text{S}^{\text{O,SA}}$ volatilities also explain a large amount of the oil and stock market volatilities ranging between around 8% and 27%, whereas structural shocks explain between about 2% and 15%, respectively. These findings imply that volatility spillovers from the overlapping trading period of oil with the US and SA stock markets and SA stock market to the non-overlapping trading periods of oil and US stock market volatilities are higher in the reduced-form VAR than the SVAR. The exceptions are the spillovers from the $\text{Oil}^{\text{O,US}}$ to the $\text{Oil}^{\text{NO,US}}$, $\text{Oil}^{\text{O,SA}}$ and $\text{S}^{\text{O,SA}}$ volatilities which are smaller in the reduced-form VAR than the SVAR.

Overall, our results clearly show the dominant role of oil shocks occurring during overlapping trading hours with the US stock market in explaining the other volatilities and the different inferences that the reduced-form and structural VAR models have on the magnitude of spillover effects. We also emphasize the high contribution of shocks occurring during the simultaneous trading of oil with the SA stock market in explaining the variability of volatility of oil and US stock market.

Table 5.7: Variance Decomposition

		$RV_t^{Oil^{O,US}}$	$RV_t^{S^{O,US}}$	$RV_t^{Oil^{NO,US}}$	$RV_t^{Oil^{O,SA}}$	$RV_t^{S^{O,SA}}$	$RV_t^{Oil^{NO,SA}}$
				Panel A: Reduced Form shock			
Variance	$RV_t^{Oil^{O,US}}$	37.76	10.89	6.93	18.04	9.43	16.95
	$RV_t^{S^{O,US}}$	14.60	49.36	2.89	10.40	10.37	12.38
	$RV_t^{Oil^{NO,US}}$	25.45	8.89	18.19	19.19	9.40	18.88
	$RV_t^{Oil^{O,SA}}$	21.20	8.65	5.57	28.14	8.06	28.38
	$RV_t^{S^{O,SA}}$	15.98	8.39	3.91	11.63	48.19	11.90
	$RV_t^{Oil^{NO,SA}}$	18.26	8.17	5.29	26.69	8.33	33.26
				Panel B: Structural shock			
Variance	$RV_t^{Oil^{O,US}}$	64.87	7.27	0.40	14.62	9.54	3.30
	$RV_t^{S^{O,US}}$	10.02	46.36	0.09	4.05	4.36	35.12
	$RV_t^{Oil^{NO,US}}$	43.40	5.73	17.95	13.36	7.56	12.00
	$RV_t^{Oil^{O,SA}}$	30.15	5.77	0.44	30.10	6.47	27.07
	$RV_t^{S^{O,SA}}$	20.41	6.26	0.21	7.58	60.26	5.28
	$RV_t^{Oil^{NO,SA}}$	8.47	1.92	0.19	9.68	2.08	77.66

Note: This Table reports the share of the variance of each realized variances, $RV_t^{Oil^{O,US}}$, $RV_t^{S^{O,US}}$, $RV_t^{Oil^{NO,US}}$, $RV_t^{Oil^{O,SA}}$, $RV_t^{S^{O,SA}}$ and $RV_t^{Oil^{NO,SA}}$, that is explained by the reduced form and structural shocks. The variance decomposition are computed at the 250-day ahead response to a unit structural shock. The total trading day is defined as follows:

$$\overbrace{2:30pm \ldots 9pm}^{\text{Oil}^{\text{O,US}}} \quad \overbrace{9pm \ldots 8am}^{\text{Oil}^{\text{NO,US}}} \quad \overbrace{8am \ldots 12:30pm}^{\text{Oil}^{\text{O,SA}}} \quad \overbrace{12:30pm \ldots 2:30pm}^{\text{Oil}^{\text{NO,SA}}}$$

$$\underbrace{2:30pm \ldots 9pm}_{\text{S}^{\text{O,US}}} \qquad \underbrace{8am \ldots 12:30pm}_{\text{S}^{\text{O,SA}}}$$

$$t-1| \underbrace{\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad}_{\text{Total Trading Day (t)}} |t+1$$

5.6 Conclusion

In this paper, we investigate the contemporaneous spillover effects between oil and stock markets in the US and Saudi Arabia. Using the continuous high frequency data of oil futures split in overlapping and non-overlapping trading periods together with the Lütkepohl's (2012) approach, we explain volatility transmission among these markets.

Our analyses lead to several interesting findings. First, we find that US stock market volatility has a strong impact on the SA stock market, whereas the volatility of oil during overlapping hours with the US stock market has a small impact on the SA stock market. Instead, when exploring the indirect effects, there is significant volatility spillover from oil to the SA stock market. These findings suggest that while volatility shocks occurring in the US stock market are directly affecting the SA stock market, shocks to oil volatility are transmitted to other volatilities (i.e., the volatility of US stock market and of oil before opening of SA stock market and when the SA market is opened) which then influence the SA stock market. The evidence of these indirect volatility spillovers might constitute a possible explanation for the various conclusions in the literature regarding the shock transmissions between oil and the Saudi Arabia stock market. Second, we document that there is asymmetry in contemporaneous spillovers between oil and stock markets. Specifically, when oil trades simultaneously with the US and SA stock markets an increase in oil's volatility has a higher impact on the volatilities of stock markets than the other way around. Third, we highlight the importance of contemporaneous and indirect volatility spillover effects in forecasting as shown by the impulse responses and variance decompositions. Particularly, we observe that that contemporaneous effects are necessary to be taken into account since the indirect transmission of volatility occurs through them.

Our findings have several important implications. First, we highlight the instantaneous transmission of volatility when oil trades simultaneously with both US and SA stock markets. This transmission provides relevant information for prediction of volatility and high frequency trading, which can contribute to better hedging strategies and Value at Risk calculations. Second, we find that oil volatility is influencing the SA stock market not only directly but also indirectly through other volatility channels. To better evaluate the transmission of volatility, investors and risk managers should take into account both direct and indirect spillover effects. The impulse responses and variance decomposition show that absence of these effects in traditional models leads to inadequate inferences about volatility transmission. These findings might be of importance for the monetary authorities in Saudi Arabia who could consider introducing futures and options to reduce the effect of volatility shocks on its stock market. All in all, our analyses emphasize the importance of volatility transmission between oil and stock markets focusing on the continuous trading of oil futures.

Chapter 6

Concluding Remarks

This thesis aims to shed light on the spillover effects among financial markets at the volatility and return level. The spillover effects, which address transmission of information across different markets and assets, are of considerable importance given that over the last decade, globalization and expansion of financial markets have led to an increase into their magnitude. This fast transmission of shocks has emphasized the need to better understand especially during financial crises, how one market responds to shocks to another market and vice versa. Such an understanding is crucial for monetary and regulatory authorities, which aimed at controlling through early warning indicators the transmission of shocks and helps them on implementing adequate policy actions. In that respect, the findings presented here are of interest to policy makers, investors as well as risk managers.

The empirical chapters of this thesis provide evidence about several aspects of the information transmission among financial markets. Firstly, paying attention to partial overlapping trading hours, we find that transmission of volatility occurs instantaneously and is asymmetric, namely, increases in the US stock market volatility leads increases in the UK stock market volatility. Secondly, we document the existence of time-variation and asymmetry in instantaneous transmission of return shocks among European stock markets. Particularly, contemporaneous spillovers from the German returns to each of peripheral returns are higher than the other way around and are decreasing during the European Debt Crisis. Thirdly, taking into consideration the overlapping trading hours of oil with the US and Saudi Arabia stock markets, we show that there is an instantaneous, asymmetric and stronger transmission of volatility from oil to the both stock markets than the other way around. Moreover, shocks to oil volatility during trading hours overlap with the US stock market, indirectly affect the Saudi Arabia volatility. On the whole, the analyses and results in this thesis clearly shed light on volatility and return transmission among financial markets.

As regards the future research, there are several promising and stimulating opportunities which could enrich our current understanding on the relations among different markets and assets. For instance, analysis from Chapter 3 could be extended by considering the dual listed stocks. As such, we could capture the cross-sectional dependence between stocks, in addition to time-series dependence. Thus, we can document financial versus non-financial transmission of shocks across markets. Another interesting idea is considering different industries and assessing their contribution to information transmission. A further issue that could be addressed is related to the contemporaneous spillovers in foreign exchange markets. Given that our findings from Chapter 4 show the existence of time-variation in transmission of shocks, the high and low yielding currencies might also differently interact during the financial crises. The uniqueness of the exchange rates examination is that both positive and negative returns could increase volatility, because a positive return for one side of the foreign exchange pair is a negative return for the other side. Further research could also focus on proposing a new approach to capture the time-variation in structural VAR models. Although, the rolling windows estimation has been successful in explaining the time-varying contemporaneous spillover effects, a different estimation technique might provide an improvement of the information transmission over time.

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