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Modelování efektů přelévání volatility
Modelling Volatility Spillover Effects

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3. Methodology
4. Data Sample Description
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6. Conclusion

Bibliography
List of Abbreviations
Declaration of Utilisation of Results from the Diploma Thesis
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The declaration

“I hereby declare that I have elaborated the entire thesis including annexes myself. I have supplemented the provided annexes No. 1-3 myself.”

Ostrava dated ..27/4/2018........

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CONTENTS

1 Introduction

In contemporary society, almost all transactions in financial markets are recorded, which lead to a vast amount of data available on internet or other approaches. Therefore, a great deal of analysis and a host of predictions are existing in financial markets. The financial time series is one of the most significant tools for analysis and predictions. financial time series, hence, is playing a significant role in quantitative analysis in financial market. Besides, the volatility is an essential element for financial time series, which is considered when making decision. Moreover, there are different measures to estimate the volatility with the different financial situation.

It is generally arguable that the stock market is a critical segment of financial market to represent the current situation of finance. Hence, exploring the regularity of the stock market is consistently popular in this day and age. the fundamental and technical methods are the basic methods for analyzing the stock markets. Except that, the financial time series is using to exhibit the volatility of the indexes during a specialized period of time to analyze and predict the tendency of the stocks.

The main goal of this thesis is to investigate, compute and interpret volatility spillover effect in selected European developed stock markets using extended autoregressive conditional volatility models. In particular, there will be modelled an impact of volatility coming from US and Eurozone stock markets. For the purpose of this thesis, we utilize daily returns of US, Eurozone, German, French, British and Swiss stock markets covering the period from January 2003 to August 2017. All the stock markets will be approximated by main stock indexes.

The main goal of this thesis is supported by two sub-goals: the first sub-goal is to model and measure also the price spillover effect using VAR models; the second sub-goal is to investigate an impact of global financial crisis on volatility spillover effects.

Including the introduction and conclusion, the whole thesis is divided by six chapters.

The financial market and financial time series are the fundamental knowledge of this thesis, therefore, in the chapter 2, it will start with a brief account of the basic information of financial markets. Then, the financial crises – the stock market crash of 1987, the dot-com bubble and the global financial crisis of 2007-2009 - in stock market will be described which would influent the trend of stock indexes. Moreover, the basic features of financial time series – volatility clustering, leptokurtic distribution and leverage effect – will be indicated.

For chapter 3, cause the price and volatility spillover effects are the essential results of the volatility, the methodologies to estimate them will be described in this chapter. Therefore, the VAR model will be introduced from basic interpretation, stationarity, and pros and cons. Besides, the four main sorts of the ARCH models – ARCH model, GARCH model, EGARCH model and AR/GARCH model – will be illustrated.

For chapter 4, firstly, the basic characteristics of investigated stock markets will be illustrated, and the most important stock indexes in investigated stock markets will also be introduced, in which the values and return of indexes will be analyzed. Moreover, the reasons and descriptive statistics of used time series will be explained and analyzed.

For chapter 5, according to the chapter 3, firstly, the non-linear models – EGARCH (1,1) models - will be established as well as the conditional variances will be analyzed in each stock markets in each period. Furthermore, the VAR models will estimate the price spillover effects for investigated stock market in given periods. Moreover, AR/EGARCH models will estimate and test the price and volatility spillover effects and variance ratios will be computed. Lastly, comparing the results of models above, getting the summary of estimation.

For chapter 6, it will summarize the whole thesis, evaluating if the purpose of this thesis is fulfilled.

Taking a panoramic view of the thesis, the figures in the chapter 2 and 3 are mainly from the reference of the books, while the figures and tables in the chapter 4 and 5 are from the statistical software Eviews 7.2.

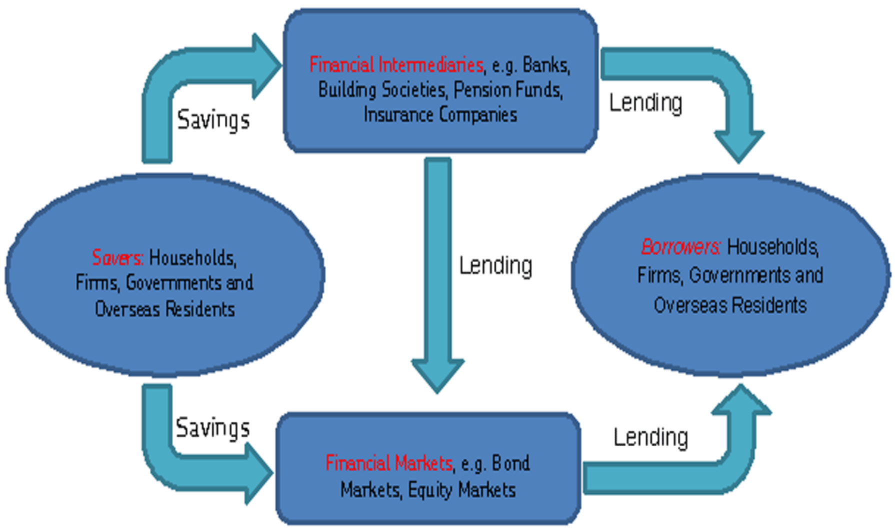
2 Financial Markets and Financial Time Series

In this chapter, the basic characteristics of financial markets and financial time series will be descripted. In the first place, there is a brief description of the fundamental information on financial markets, and why the financial market is important in the economy will be indicated. Furthermore, the three stock crises, which influenced the European financial markets, will be described. More importantly, the last subchapter will illustrate volatility clustering, leptokurtic distribution and leverage effect which are the basic features of financial time series. There are a vast number of textbooks available. The basic concepts of financial markets can be got from Mishkin (2004) and Jurgen, F. and Christian, M. (2012), moreover explanations of financial time series will be introduced briefly by Campbell, Lo and MacKinlay (1997), Mandelbrot (1963).

2.1 Basic Characteristics of Financial Markets

Financial markets are markets, in which funds are transferred from people who have extra funds to people who want more funds to invest. "Without financial markets and the institutional structure that supports them, selling the assets we own would be extremely difficult." (Cecchetti and Schoenholtz, 2015).

Figure 2.1 Flows of funds through the financial system



Source: Mishkin, F. (2004)

As can be shown from the Figure 2.1, there are massive financial flows between economies while it is the fundamental purpose of financial markets, transferring the funds. Hence, this subchapter will describe the basic information of financial markets.

2.1.1 Fundamental Information on Financial Markets

A financial market is a market where the financial instruments are traded and exchanged. As a financial market, there are two basic elements which are essential.

2.1.1.1 Basic Element to Form and Develop a Financial Market

a) First of all, the suppliers of funds and demanders of funds are requisite, including government, financial instruments, residents, foreign businesses and so on. The suppliers provide extra funds and the demanders raise funds from financial markets, both are indispensable. It is the basic element to form and develop a financial market.

b) Moreover, financial instruments are also important. A financial instrument is a monetary contract between two parties, writing a legal obligation of one party to transfer something of value to another party at a certain future date. Bonds, stocks, bills, insurance are examples of financial instruments.

c) Lastly, it is about financial intermediaries. A financial intermediary is an institution or individual between who wants to purchase financial instruments and who wants to issue them. Banks, investment companies, insurance companies, brokers are all financial intermediaries.

2.1.1.2 Functions of the Financial Markets

With a financial market, a further comprehension is necessary – functions of the financial markets. There are three main functions served as financial markets, which include market liquidity, information and risk sharing.

Financial markets offer the market liquidity to lenders and borrowers, to ensure the lenders or borrowers can sell or buy the instruments easily and cheaply. If a market has so many buyers and sellers, it can be said that the market has high market liquidity. Normally, the traders are willing to invest in liquidity financial instruments, such as stock, bond and so on, to instead of investing in non-current financial instruments, such as real estate.

Moreover, Financial markets pool and communicate information about the financial instruments. In financial markets lenders and borrowers are easier to get a mass of information with low costs, comparing with the information which they got, they can invest some financial instruments with low risk and high return, and they even allow have a portfolio with their funds. Furthermore, Financial markets are the place where you can transfer risk. Investors can buy or sell risks while sharing them with others in financial markets. Investors would allow holding ones if they think is low risk, and they also can get rid of ones if it is high risk. And investors can choose different financial instruments together as a portfolio to reduce risk. Anyway, it just can be in financial markets that sharing risk.

2.1.2 The Classifications of Financial Markets

In the world, there are a lot of financial markets, hence, it is necessary to categorize them with different ways to make people get it easier.

a) Firstly, we can categorize the markets by maturity of claim – Money market and capital market. Money market is a market where financial instruments are traded with high liquidity and very short maturities. Lenders and borrowers can sell or buy in the short term with maturities up to one year. The financial instruments in money market have small yield. And the main money markets securities are treasury-bills, commercial papers, negotiable certificates of deposit and so on. Capital market is a market where buys and sells equity and debt instruments. It is the market for long-term loans and equity capital. In this market, the maturity of it is more than one year, hence, it has lower liquidity compared with money markets. Furthermore, the financial instruments in capital market have various risk.

b) Secondly, we can distinguish between debt market and equity market which classification by nature of claim. Debt market also can be called bond market, it means that bonds are issued and traded in this market. Bondholders will have a fixed payment, usually with interest, and bonds have maturity date. Equity can be named as stock market, it is a market where stocks are issued and traded. The return to stockholders are less assured because the dividends can be easy changed. Moreover, stocks do not have maturity date while the stockholder is one of the owners of the business.

c) Thirdly, we can group them based on the type of seasoning – primary market and secondary market. The primary market is a market which issues new securities on a stock exchange for business to obtain financing. After financial instruments are issued in the primary market, they are trading in the secondary market. The secondary market offers issues information and liquidity.

For the purpose of this thesis, the equity market, classified by nature of claim, will be used as the background information.

2.1.3 Importance of Financial Markets for Economics

In the present age, business firms need large amounts of capital to finance their operations. In the financial market, they can raise funds from investors by selling stock or bonds. Additionally, the government also needs funds to provide goods and services. With the financial markets, government can borrow funds by selling bonds. Whatever bonds, stocks or other financial instruments, which used in our life, is trading in financial markets, hence, the financial markets are essential. Totally, this subchapter will discuss why the financial markets are important for economics clearly.

Firstly, the readers need comprehend the main subjects of the financial market, which include banks, investment banking firms, savings and loan associations, pension funds, insurance companies etc. Hence, some main subjects will be described.

Starting from commercial banks, they provide banking and other financial services and they represent the most important financial intermediary. As a bank, the banking license is necessary, which are granted by financial supervision authorities and provide rights to conduct the most fundamental banking services, the most common services are accepting deposits and making loans. Furthermore, pension fund is setting up by a corporation, labor union, governmental entity or other organization to pay the pension benefits of retired workers. Lastly, insurance companies are the business of providing protection against financial aspects of risk. Those financial instruments are everywhere in this day and age; therefore, financial markets are important to economics.

Moreover, this subchapter will show the benefit of the financial markets for economics.

a) Possibility of obtaining funds. The units who are deficit can obtain funds in the financial markets, and it means they can borrow the money in the financial markets and not only from banks;

b) Motivation factor. As a rational investor, low risk and high return are best. And the financial markets satisfy what investors want. Hence, it can motivate investors to invest their money through financial markets;

c) Information of price. Periodic trading of a security reveals the consentaneous price which an assets commands on the market. Hence, if an issuer wants to invest new securities, the investor would know what the price level must be set for new bonds or stocks;

d) Liquidity in financial markets. Liquidity provides investors an opportunity to reverse the trade. It means that investors can sell or purchase securities if they want;

e) Reduced search and transaction costs. The financial markets provide a place for buyers and sellers to trade, which place is called secondary markets, and it will reduce search costs because of the brokers and dealers. Transaction costs would be kept low with large trading quantities and continuous trading;

f) Reduce risk. Investors can invest a lot of different financial instruments simultaneously, they can make the portfolios what they want.

All of them would promote the development of economics and improve the importance of economics in the world. Therefore, financial markets are important to economics.

2.2 Crises in Stock Markets

Stock market is one of the biggest financial markets in the contemporary world economy. Thus, the development process of the stock market could influence the developing direction of the financial markets. Moreover, the development process of the stock market could not be always successful, it always moves in zigzags and by roundabout ways. That is why there have crises in stock markets, and it is characterized as huge fluctuation of financial assets in the secondary market, such as the market prices of stock markets, bond markets, fund markets and derivatives markets change to depreciate rapidly.

This subchapter will indicate three typical crises in stock markets, which have deepest influence on Euro area, to comprehend, including the Stock Market Crash of 1987, the Dot-com Bubble from 1997 to 2001 and the global financial crisis of 2007.

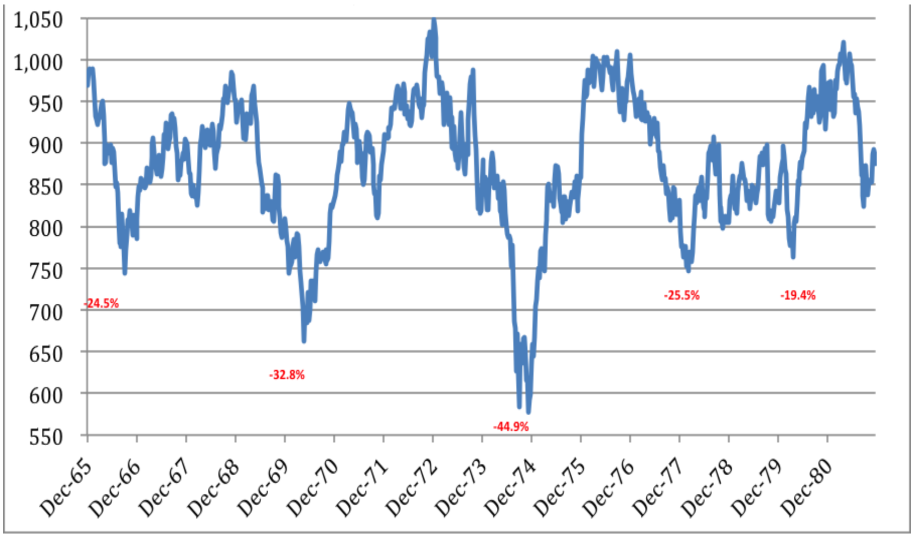
Before talking that, there is a briefly account of types of financial crises. There have three categories of financial crises – banking crises, currency crises, and sovereign debt crises.

It is a banking crisis if the significant signs of financial distress were in the banking system, and if the significant banking policy intervention measures in response to significant losses in the banking system; if it was a currency crisis, the currency would be in depreciation; a sovereign debt crisis is when a country is unable to pay its bills.

2.2.1 The Stock Market Crash of 1987

After the WWII, with the greatly enhanced of the economic strength of the United States, all kinds of investment activities were very active, and the stock market turned into a prosperous stage. The index of stock was a very substantial increase in the 1950s, and there was a peak in 1966, and the Dow Jones Industrial Average (DJIA) Index was closed to 1000 points (Figure 2,2). As showing in the Figure 2.2, during the 1966 to 1981, the price of stock had been in a state of volatility. In the early 1980s, the price of stock started to rise, reaching to 1036 points on October 21, 1982, which broken the highest point in past ten years. In the same year, the DJIA raised to 1065 on November 3, which was the highest points after the WWII. Since then, the DJIA was increasing in the next five years. The DJIA reached to 1896 points, increasing by 78% compared with 1982. In the start of the 1987, the price of stock raised rapidly, and the DJIA reached to 2722 on August.

Figure 2.2 The Dow Jones Industrial Average from 1966 to 1981

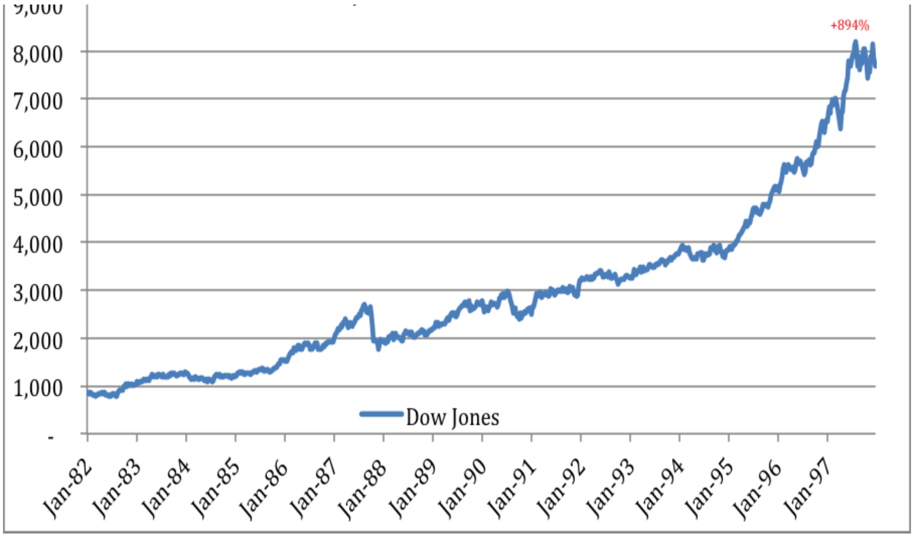


Source: by author

However, looking at the Figure 2.3, on Monday, October 19, 1987, a wave of stock plummeting started from the New York stock market on Wall Street, triggering the largest crash in the history. The DJIA tumbled 508.32 points in that day, dropping 22.6%, the highest one-day decline since 1941. Within 6.5 hours, the stock market in the New York lost 500 billion U.S. dollars, which equivalent to one-eighth of the annual GDP of the United States. The plunge in the New York stock market shocked the entire financial market, and it created a domino effect in the stock markets around world, especially, the stock markets in the London, Frankfurt, Tokyo, Sydney, Hong Kong, and Singapore were suffered very strong shock, the shares declining more than 10%.

The plummeting stock market caused a great panic among the shareholders, many millionaires became the poor overnight nervous breakdowns. This day was called "the Black Monday" in the financial market, and the New York Times said it was "Well Street's blackest hours".

Figure 2.3 The Dow Jones Industrial Average from 1982 to 1997

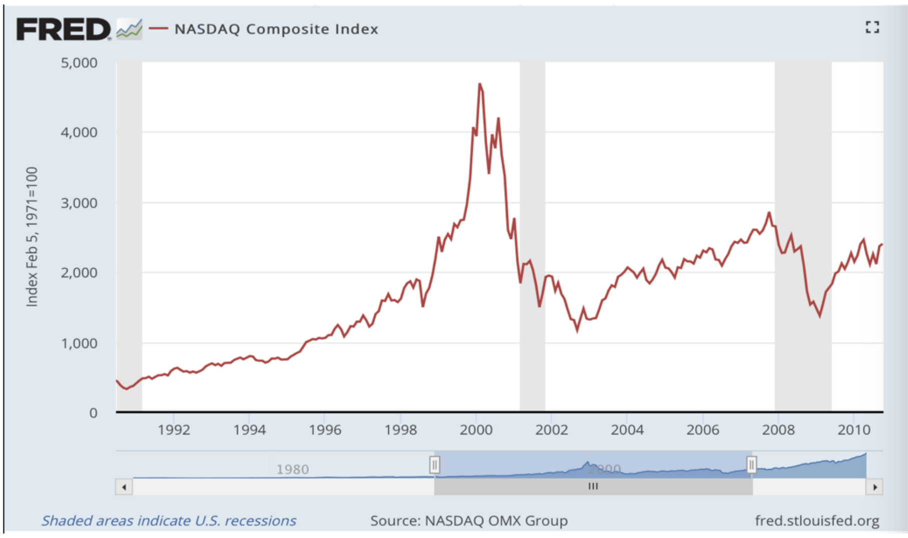


Source: by author

2.2.2 The Dot-Com Bubble

In the 1990s, the U.S. economy recovered and was growing around 110 months with the rapid economic growth, low inflation, low unemployment and low deficits working together.

Figure 2.4 The Nasdaq Composite Index from 1990 to 2010



Source: https://fred.stlouisfed.org/series/NASDAQCOM

During this period, the software development industry became the significant investments, people started to buy the high-tech stocks that as the representative of the new economy, so more and more software development companies would like issue the IPO in the stock exchanges to finance capital. Hence, the Nasdaq, based on high-tech stock, became the main investing place at the end of the last century. The Nasdaq Composite Index raised from 338.01 in October 1990 to 4,802.99 in March 2000, which was the historical peak.

Nevertheless, the IPOs of internet companies emerged with ferocity and frequency, more and more companies could not growth as quick as the increasing of stocks, so they had to go out of business. As these cases multiplied, the dotcom bubble burst, then it turned into the dotcom crash. Therefore, the Nasdaq Composite Index was persisting decline from March 12, 2000. On the April 4, 2001, the Nasdaq Composite Index fell to 1638.80, it removed two-thirds compared with the highest level in 2000. The total market value declined from 6.7 trillion U.S. dollars to 3.16 trillion U.S. dollars, 3.5 trillion U.S. dollars, equivalent to 35% of the U.S. GDP, disappeared as a bubble as showing in Figure 2.4.

The bubble of dotcom was because the market prices of the software companies were significant higher than the intrinsic value, so it was inevitable that the market price went back.

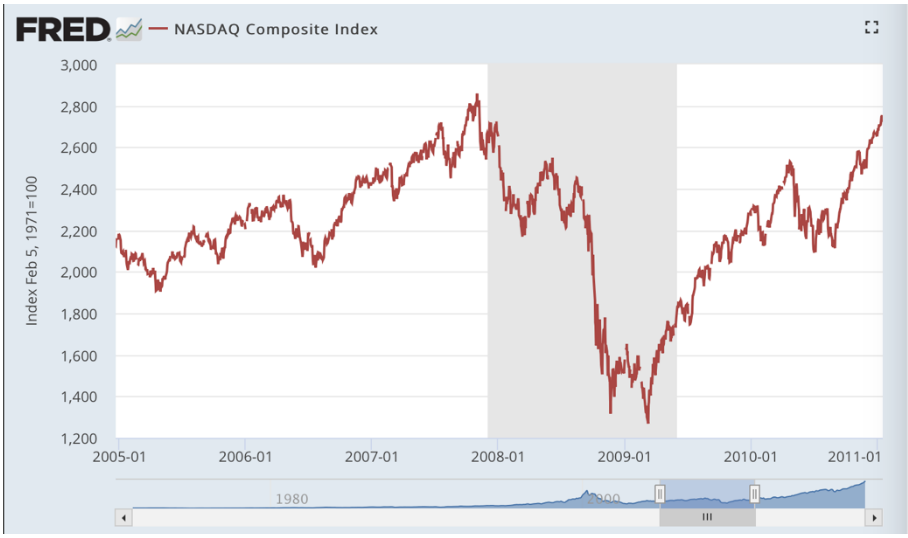
2.2.3 Global Financial Crisis of 2007-2009

The global financial crisis of 2007 was the worst of its kind since the Great Depression while it cast its huge shadow on the economy of many countries. Moreover, it began with failures of the sub-prime segment of the US housing market, so it was also called sub-prime mortgage crisis. Due to the U.S. economy had a deeply effect of economy in the world, the European Union and Japan went collectively into recession from the 2008. Accordingly, the world was in financial crisis od 2009, a catastrophic turn around on the boom years of 2003 to 2007.

As we can see from the Figure 2.5, the index of the Nasdaq composite fluctuated from 2005 to 2011. More specifically, at firstly, the basic trend of the index had been going up before November 2007, meanwhile, the index reached the peak at 2,780.42 in October 2007. After that, the index started to fall down, and it plunged to 1,432.23 in March 2009, which was the bottom of the index during the global financial crisis. Therefore, the global financial crisis of 2007 had a huge influence on financial markets.

There are three main causes, which gave rise to the global financial crisis of 2007. The first point with respect to this is that easy credit conditions were existing in the financial markets. More specifically, the lower interest rates encourage borrowing while banks borrowed funds to investment firms, caused that the potential returns from investment rose and then the banks were overleveraged to create a higher risk of bankruptcy. Moreover, the deregulation indicates that the insufficient regulation to guard against excessive risk-taking in the financial system. Additionally, sub-prime lending refers to the credit quality of particular borrowers, and the sub-prime borrowers have weakened credit histories and a greater risk of loan default than prime borrowers. Overall, all of causes worked to give rise to higher demand and price of house, and then the real estate pricing bubbles generated, therefore, the financial crisis broken out.

Figure 2.5 The Nasdaq Composite Index from 2005 to 2011 (1971=100)



Source: https://fred.stlouisfed.org/series/NASDAQCOM

To summary, the financial crisis, producing in one financial market, would also influent other financial markets.

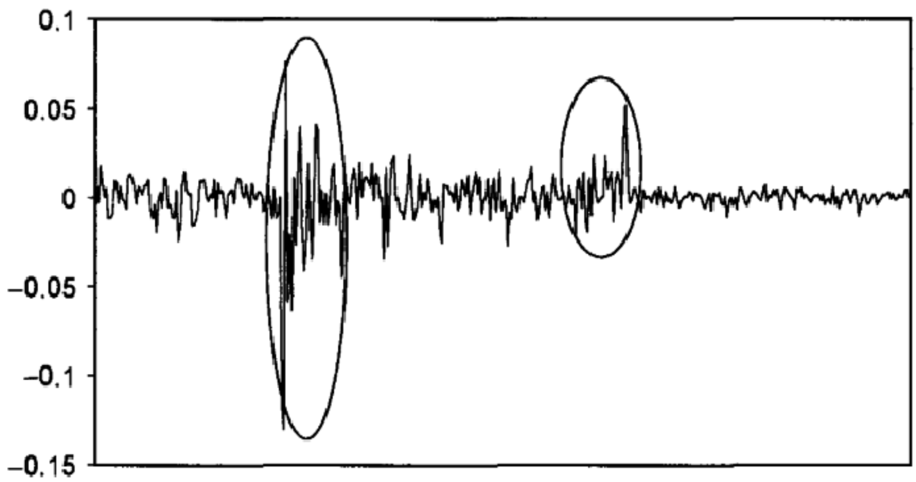
2.3 Characteristics of Financial Time Series

Frequent volatility is a characteristic of financial time series in the stock market. In one ward, the volatility describes the account of risk or uncertainly about the changes' size in a value of security. Generally, the higher the volatility exists, the risker the security is. Therefore, analyzing the volatility is useful to comprehend the stock market. This subchapter will show you the features of the volatility, which include volatility clustering, leptokurtic distribution and leverage effect, from these three characteristics, it will be clearly why volatility is important (Franke and Hafner, 2011).

2.3.1 Volatility Clustering

Volatility of price in the stock market usually relates to time series. Sometimes the price is fairly stable, sometimes the volatility of price is fierce, so that the return keeps persistently high or low during a certain period. In sum, this phenomenon was general called "volatility clustering". Benoit Mandelbrot (1963) had described the volatility clustering that "large changes tend to be followed by large changes, of either sign, and small changes tend to be followed by small changes." And here has a quantitative expression of this fact that an autocorrelation function, which is significant and slowly decaying, showing as $corr(|r_t|, |r_{t+\tau}|) > 0$, where the $|r_t|$ is an absolute return, and the τ is a time lag.

Figure 2.6 Volatility clustering phenomenon of financial time series



Source: by Alexander, C. (2001)

As illustrated in the Figure 2.6, the circles are indicating the low and high volatility which denote the spread autocorrelation. It is clearly to obverse that there has the trend of sustained periods of high or low volatility.

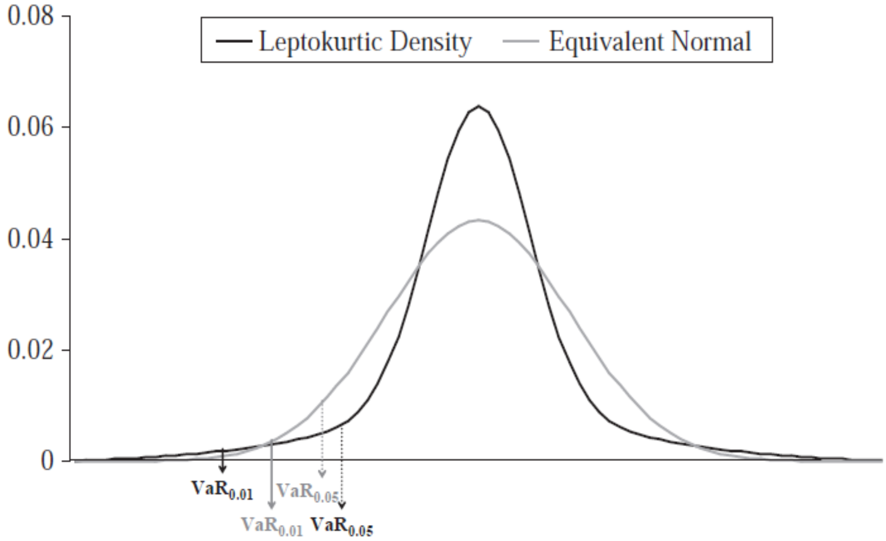
2.3.2 Leptokurtic Distribution

The leptokurtic distribution is a case of kurtosis that represents the attribute of flatness or peakedness of a distribution. Hence, in a leptokurtic distribution there are many scores close to the mean with few scores outlying symmetrically on both sides of central tendency.

It is worth nothing that the kurtosis of a normal distribution is 3, which means it is called leptokurtic distribution if the kurtosis is higher than 3, and it is platykurtic distribution when the kurtosis is lower than 3.

The Figure 2.7 illustrates the comparison between the leptokurtic distribution and normal distribution straightforward. There has more returns clustered around the mean in the leptokurtic distribution.

Figure 2.7 Leptokurtic distribution and normal distribution



Source: by Luc, B. (2012)

2.3.3 Leverage Effect

The leverage effect is indicated as a negatively tendency between an asset's volatility and the asset's returns. Typically, the asset's volatility declines due to the rising asset price, and vice versa. And as noted by Engle, R. (1993), that "Negative returns seemed to be more important predictors of volatility than position returns. Large price declines forecast greater volatility than similarly large price increases." In brief, compared with a stock price increasing, there is a larger volatility when the stock price declines.

Normally, it is allowed to parametrize the leverage effect with assuming that the volatilities are functions of price levels when stochastic volatility models are used. There are four steps to estimate the leverage parameter:

a) firstly, define the quantities which are to be estimated,

$\rho(t)dt = \langle dX(t), d\sigma^2(t)\rangle, \gamma^2(t)dt = \langle d\sigma^2(t), d\sigma^2(t)\rangle, \forall t \in [0, T];$

b) then, the volatility of the volatility and the leverage parameters can be estimated due to these quantities,

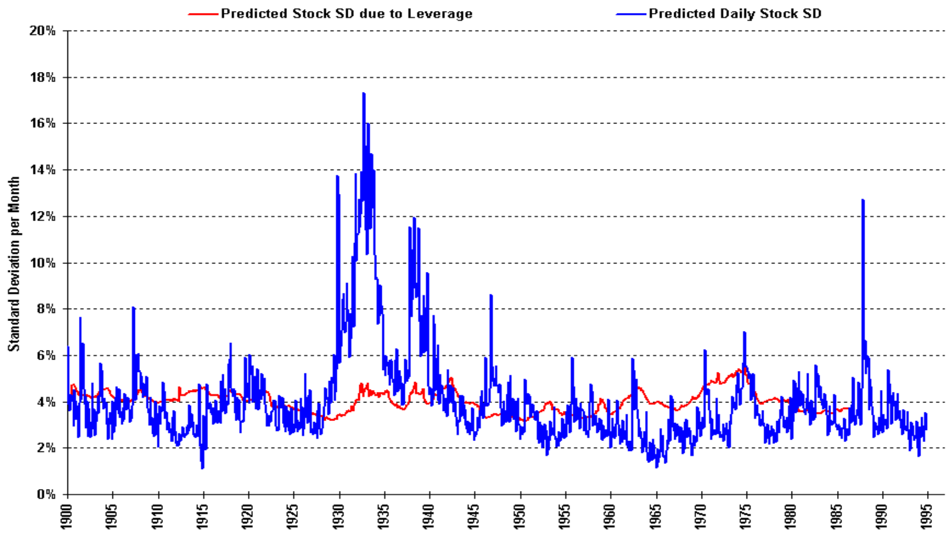
$\rho(t)dt = \xi\sigma^2(t)\eta, \gamma^2(t) = \xi^2\sigma^2(t);$

c) it can be obtained that,

$$\xi\eta = \frac{\rho(t)}{\sigma^2(t)};$$

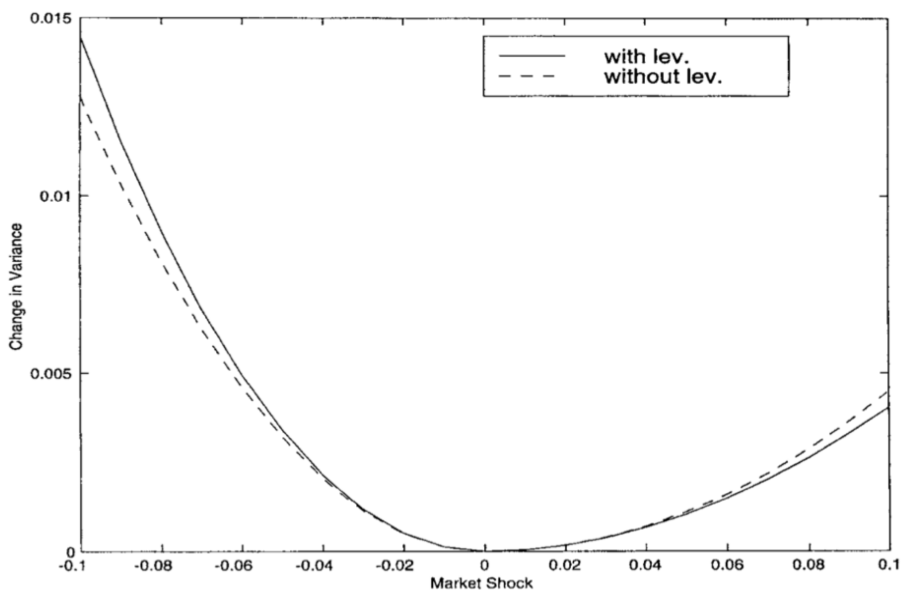
d) using b) and c) to estimate the leverage parameter(η).

Figure 2.8 Predicted stock volatility and effects of leverage



Source: by William, G. (1989)

Figure 2.9 Variance impact curve for the market portfolio



Source: by Bekaert, G. and Wu, G. (1997)

The Figure 2.8 shows that predictions of monthly standard deviation of stock returns based on daily data and changing financial leverage influents the level of stock return volatility from 1900 to 1987. Here, the effect of leverage is calculated by a time series of aggregate firm value divided by stock value, which has the same mean as the predictions of volatility from the regression model.

The Figure 2.9 illustrates how the market shock affects the market variance with or without the leverage level.

3 Methodology

The objective of this thesis is using the volatility spillover effects to analyze the interrelationship among the European equity markets. Therefore, the essential stuff is comprehending what the volatility spillover effect is, and how the volatility spillover effect works. Whatever, it will be expressed in this chapter.

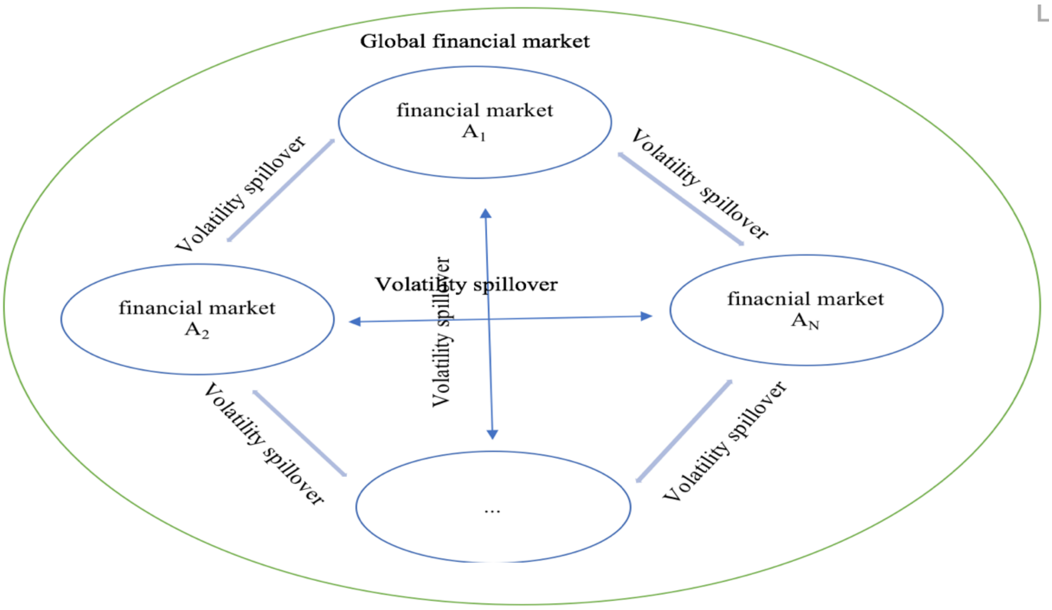
In the first subchapter, the basic information of the volatility spillover effect will be described clearly. Moreover, there is a brief account of the literature relating to the volatility spillover effects, it will make readers clearer where the effects from, and if the one wants to know more, he/she can find the original literatures. The most vital parts in this chapter are describing the price spillover using VAR model and ARCH model. About VAR model, it will be indicated from the fundamental interpretation, the stationarity, and the advantages and disadvantages. There will have four main sorts of ARCH models will be illustrated, which are ARCH model, GARCH model, AR/GARCH model and EGARCH model (Bauwens et al, 2012). There still have some kinds of GARCH models – MGARCH model, etc., but they will not be used in this work, therefore they will not be described.

3.1 Volatility Spillover Effect and Its Importance

In this age of change, the human society is progressing rapidly on various fields. The financial market integration has become especially relevant over the last two decades. In addition, the substantial development of technology has allowed information to be conveyed more freely through global financial markets than ever before. The linkages between different stock markets in different region have grown stronger. Therefore, it is significant for portfolio managers and financial institutions that understanding the linkages between different financial markets. As volatility is measured by variance or standard deviation of returns, the researchers always use it to measure the total risk of financial assets (Brooks, 2002). Therefore, not only were the return causality linkages investigated, but also volatility spillover effect was measured. Volatility spillover effect is often used as a measure of the value at risk and hedging strategies of financial assets. Nowadays, as the emerging markets are becoming more and more important, economists start to pay attention to the emerging markets instead of only focus on developed counties (ex: The United State, Japan, the Britain, and etc.). For instance, in the stock markets, the degree of linkages between the emerging stock markets and developed stock markets has a significant effect to the investors who come from the developing or developed countries.

The liberalization of financial markets and capital flows are more integrated than ever before due to the progresses in the information spreading and trading technology. It is obviously both in developing and developed countries. The isolation domestic market would be reduced with management of the global news and trading of international finance. Moreover, those factors contribute to the single market to react to the news and shacks generated from other countries (Singh, Kumar, and Pandey, 2010). The linkage plays a pivotal role in pricing of domestic equites and international hedging strategy. The activities of the foreign cooperative partners would have a strong impact to domestic stock returns and volatilities with strong linkage while weak linkage contributes to hedging gain through diversification of international investing portfolio.

Figure 3.1 The volatility spillover in financial markets



Source: by Author

Volatility, which can be illustrated as a measure of fluctuation of price of a financial instrument with time, plays an increasingly key role in the financial markets. More and more researchers devote their attention to modeling and forecasting the volatility of financial returns for understanding its meaning and optimizing the financial decisions.

Currently, the volatility spillover effect is an important aspect of volatility. It indicates that a market volatility is influenced not only by itself but also by volatility coming from other market, as showing in the Figure 3.1. for instance, the financial crisis in the American in 2008 led to a huge wave of returns in the rest of the world. Moreover, the volatility spillover effect is an extensive existence in different types of financial markets. Meanwhile, the volatility spillover effect can stimulate the process of volatility transmission from one financial market to another.

3.2 Literature Review

The study of financial market integration that a movement in one market would affects a movement in others is significant to investors and portfolio theories. Modeling volatility, which is in financial time series, has been paid much attention since the introduction of the Autoregressive Conditional Heteroskedasticity (ARCH) model of Engle (1982). Following Ross (1989) and Chan, Chan and Karolyi (1991) provided evidences that "it is the volatility of an asset's price, and not the asset's simple price change, that is related to the rate of flow of information to the market." After that, there was a great deal of literature evaluating volatility spillover across financial markets from different countries. Janakiramanan and Lamba (1998) made a view that portfolios were invested in proximity of the domestic while the market also tend to influence one another due to the closely geography and economy. Moreover, the integration is a consequence of more familiar political and economic cooperation through the middle of countries (Johansson and Ljungwall, 2009).

It is obvious that stock market integration among developed counties was caused great concern at that time. Theodosssiou and Lee (1993) used a multivariate GARCH model to censor the nature and degree of independence of stock matket of the U.S., Britain, Germany, Japan, Canada, then they found that it was existed from the U.S. stock markets to others that statistically significant mean spillovers. Since the European Union (EU) is a free trade and monetary body of 27-member countries, the financial markets integration among different European countries has been generating. Therefore, numerous researchers have studied the linkages of stock markets between different European countries as the strong policy coordination and economic ties between EU and European Monetary Union (EMU). Gelos and Sahay (2000) argue that the geographic variations among the various national stock markets are changing less and less obvious with financial innovation, the advance of international finance and global integration. Furthermore, Harrison and Moore (2009) conducted an investigation of co-movement in stock markets between the developed markets of Western Europe and the developing markets of Central and Eastern Europe. Bubak, Kocenda and Zikes (2011) found the evidence of statistically significant volatility spillovers among foreign exchange markets in the Central Europe through studied dynamics of the volatility transmission between the Central European currencies and the foreign exchange of EUR/USD that used model-free estimates of daily exchange rate volatility, which based on intraday data.

It should be clearly that even the Sims, C. (1980) put forward the Vector Autoregressions (VAR) model, it was utilized by Singh (2010) that the price spillover effects were estimated by VAR model. Moreover, using the three steps of AR/EGAECH model to estimate the volatility spillover effects was put forward by Christiansen, C. (2007).

Nevertheless, there are extensive studies described the relationship between the stock price and the volatility spillover effect. However, the studies of comparing the Western, Central and Eastern European stock markets were not that much. With the changing of the European financial market, a detailed study of its interrelation of stock markets is timely.

3.3 Univariate Volatility Models

The analysis of the financial time series indicated that there are three main characters of the rate of return of the financial time series – volatility clustering, leptokurtic distribution and leverage effect, which are non-classical phenomenon. Therefore, the homoscedasticity cannot be satisfied with the traditional econometric method, a severe result of the financial time series would be caused with modeling and statistic inference by traditional regression model. Due to that, Engle (1982) put forward a different view of Autoregressive Conditional Heteroskedasticity (ARCH) model, following Bollerslev (1986) did a simple and direct linear scalability to generating the Generalized Autoregressive Conditionally Heteroskedastic (GARCH) model. After that, more and more transformation of the ARCH generated.

In this subchapter the ARCH, GARCH, AR/GARCH, EGARCH models will be described (Rachev et al., 2007).

3.3.1 ARCH Model

The ARCH model can detect the variation of the financial data form one period to another one effectively. Hence, the ARCH model has been widely used to describe the volatility of the variables between finance and capital market, especially stock price, exchange rate, price of forward etc., following is the process:

$$Y_t = \boldsymbol{Q}_t \boldsymbol{\beta} + \varepsilon_t, \tag{3.1}$$

$$\varepsilon_t | \phi_{t-1} \sim N(0, h_t), \tag{3.2}$$

$$h_t = h\left(\varepsilon_{t-1}, \cdots, \varepsilon_{t-p}, a\right). \tag{3.3}$$

Where, $t = 1,2,3 \ldots T$; Y_t is the explained variable at time t, and the Q_t is the explanatory variable at time t; ε_t is white noise with $V(\epsilon) = \sigma^2$; ϕ_t is the information set available at time t; h_t is the conditional variance. Moreover, formulas can be described as:

$$Y_t = \phi_1 Y_{t-1} + \phi_2 Y_{t-2} + \cdots + \phi_p Y_{p-1} + \varepsilon_t, \tag{3.4}$$

$$h_t = a_0 + a_1 \varepsilon_{t-1}^2 + \cdots + a_q \varepsilon_{t-q}^2, \tag{3.5}$$

$$\varepsilon_t = \sqrt{h_t} v_t. \tag{3.6}$$

Where, $a_0 > 0, a_t \geq 0 (i = 0, \cdots, q), E(v_t) = 0, E({v_t}^2) = 1$. As be shown in the equation (3.5), the h function is q-th order linear (in the squares), and the model, we are summarizing is the first-order linear model of the ARCH model. The error terms, ε_t, are unconditional fat-tail distribution, meanwhile, the conditional variance, h_t, can reflect the specialty of the changes of variables in the financial markets that "large and small errors tend to cluster together (in contiguous time periods)" by McNees (1979). Moreover, as be shown in equation (3.5), it is obvious that the various of the ε_t is decided by ε_{t-1}^2 to ε_{t-q}^2, therefore the various of the ε_t would be huge if the ε_{t-1} is huge, which means that the ε_{t-1} has a positive effect on future volatility in the market while the value of q decided the duration of a random variable. The higher the q is, the longer the duration has. The phenomena of volatility clustering are common in financial markets, especially the volatility of stock yield.

Even though the ARCH model has numerous advantages, there still have some disadvantages of it.

a) The model assumes that positive and negative shocks have the same effects on volatility. In practice, it is well known that asset prices respond differently to positive and negative shocks.

b) ARCH model is comparatively restrictive. For example, in an ARCH (1) model, the a_1 must be in $(1, \frac{1}{\sqrt{3}})$ for a limited fourth moment. The constraint becomes complicated for higher order ARCH model.

c) Unless q is huge, volatility maintains relatively short amount during a specific period.

3.3.2 GARCH Model

The equation (3.5) illustrates the distributed lags model of h_t. The method, the lagged terms of h_t joined, generated for against an excess of the lagged terms of ε_t^2. Bollerslev (1986) got GARCH model due to the ARCH model, which allows for more flexible lag structure.

According to the ARCH process, just changing the structure of (3.5), we can get the process of GARCH (p, q).

$$h_t = a_0 + a_1\varepsilon_{t-1}^2 + \cdots + a_q\varepsilon_{t-q}^2 + \theta_1 h_{t-1} + \cdots \theta_p h_{t-p},$$
$$= a_0 + \sum_{i=1}^{q} a_i\varepsilon_{t-i}^2 + \sum_{j=1}^{p} \theta_j h_{t-j},$$
$$= a_0 + a(L)\varepsilon_t^2 + \theta(L)h_t. \quad (3.7)$$

Where,

$p \geq 0, q \geq 0;$

$a_0 \geq 0, a_i \geq 0, i = 1, \cdots, q;$

$\theta_j \geq 0, j = 1, \cdots, p.$

The GARCH (p, q) should be kept as wide-sense stationary, hence, the $a(L) + \theta(L) < 1$. The conditional variance is a linear function of past sample variance only in the ARCH(q) process, however, the lagged conditional variance is allowed in the GARCH (p, q) process as well. Moreover, this not hard to find that when $p = 0$, the GARCH $(0, q)$ is ARCH (q), and when $p = q = 0$, the ε_t is a simply white noise.

In the GARCH model, there has a basic requirement that the white noise, ε_t, denote a real-valued discrete-time stochastic process and the average of the ε_t is naught. Sometimes the regression equation could not adequately fetch the information of ε_t. the residual sequence may have the autocorrelation instead of stochastic process. Based on the above, the first step is checking if the regression model of resident has homoscedasticity. If it does not have, the GARCH model can be used. The process on the above form the AR(m)/GARCH(p, q) model.

$$Y_t = \phi_1 Y_{t-1} + \phi_2 Y_{t-2} + \cdots + \phi_p Y_{p-1} + \varepsilon_t, \quad (3.8)$$
$$\varepsilon_t = \textstyle\sum_{k=1}^{m} \beta_j \varepsilon_{t-k} + v_t, \quad (3.9)$$
$$v_t = \sqrt{h_t} e_t, \quad (3.10)$$
$$h_t = a_0 + a(L)\varepsilon_t^2 + \theta(L)h_t. \quad (3.11)$$

Where, the $Var(vt) = h_t$, and $e_t \sim N(0,1)$.

3.3.3 The GARCH$(1, 1)$ Model

The GARCH(1,1) process is the simplest but useful GARCH process to do financial analysis. The GARCH(1,1) model is indicated as:

$$h_t = a_0 + a_1\varepsilon_{t-1}^2 + \theta_1 h_{t-1}, \quad (3.12)$$

where, $a_0 > 0, a_1 \geq 0, \theta_1 \geq 0$. Moreover, $a_1 + \theta_1 < 1$ cause the process is wide-sense stationarity. There is a theorem of the GARCH(1,1) process.

If the 2mth moment wants to exist, there is a necessary and sufficient condition,

$$\mu(a_1,\theta_1,m) = \sum_{j=0}^{m} \binom{m}{j} c_j a_1^j \theta_1^{m-j} < 1, \tag{3.13}$$

where, m is a positive integer; $c_0 = 1; c_j = \prod_{j=1}^{j}(2j-1), (j = 1,2 \cdots m)$. And the $2m$-th moment can be showed as,

$$E(\varepsilon_t^{2m}) = c_m\left[\sum_{n=0}^{m-1} c_n^{-1} E(\varepsilon_t^{2n}) a_0^{m-n} \binom{m}{m-n} \mu(a_1,\theta_1,n)\right] \times [1-\mu(a_1,\theta_1,m)]^{-1}, \tag{3.14}$$

where the proof of this theorem shows in Bollerslev (1986).

Therefore, the coefficient of kurtosis of the $\mathrm{GARCH}(1,1)$ can be calculated. Moreover, the fourth-order moment should be used to calculate the calculation of the kurtosis, hence,

$$\begin{aligned} k &= (E(\varepsilon_t^4) - 3E(\varepsilon_t^2)^2)E(\varepsilon_t^2)^{-2} \\ &= 6a_1^2(1-\theta_1^2 - 2a_1\theta_1 - 3a_1^2)^{-1}. \end{aligned} \tag{3.15}$$

There is an assumption that the kurtosis is greater than naught. Therefore, the $\mathrm{GARCH}(1,1)$ process is leptokurtic.

3.3.4 EGARCH Model

According to above, it is obviously that there are some limitations in the GARCH model. If the coefficients of the model are negative, GARCH model could not be used. Moreover, GARCH model also cannot give the explanation for leverage effects. Besides, the feedback between conditional variance and mean cannot be do directly in the GARCH model.

Because of those reasons, Nelson (1991) put forward an asymmetric GARCH model, which is called exponential GARCH or EGARCH model, commonly represents below:

$$\begin{cases} \varepsilon_t = \sigma_t \eta_t \\ ln\sigma_t^2 = \omega + \sum_{i=1}^{q} \alpha_i g(\eta_{t-i}) + \sum_{j=1}^{p} \beta_j ln\sigma_{t-j}^2, \\ g(\eta_t) = \theta\eta_t + \gamma[|\eta_t| - E(|\eta_t|)] \end{cases} \tag{3.16}$$

where, $\{\alpha_i\}, i = 1,2,\cdots,q, \{\beta_j\}, j = 1,2,\cdots,p$ are nonrandom and real scalable series; moreover, $g(\cdot)$ should be satisfied with $E_{t-i}(g(\eta_t)) = 0$. It is easy to be observed when $\theta < 0$, with the same size of volatility, the amplification of conditional variance with negative fluctuation is surpass than with positive fluctuation, which expresses asymmetry. In practice, the equation (3.16) could be simplified as:

$$ln\sigma_t^2 = \omega + \sum_{i=1}^{q}\left(\theta_i \left|\frac{\varepsilon_{t-i}}{\sigma_{t-i}}\right| + \gamma_i \frac{\varepsilon_{t-i}}{\sigma_{t-i}}\right) + \sum_{j=1}^{p} \beta_j ln\sigma_{t-j}^2. \tag{3.17}$$

Specially, in the $\mathrm{EGARCH}(1,1)$ model, the conditional variance equation is:

$$ln\sigma_t^2 = \omega + \theta_1 \left|\frac{\varepsilon_{t-1}}{\sigma_{t-1}}\right| + \gamma_1 \frac{\varepsilon_{t-1}}{\sigma_{t-1}} + \beta_1 ln\sigma_{t-1}^2. \tag{3.18}$$

The $\mathrm{EGARCH}(1,1)$ model is usually used to discuss the asymmetric effect of the prices in stock markets. In the equation (3.16), when $\gamma \neq 0$, it means the distraction is asymmetric to effect of stock price; by contrast, when $\gamma < 0$, the negative exogenous shock surpasses than positive exogenous shock about affecting the price of financial products, γ, here, is called leverage effect.

The parameter estimation of the EGARCH model is commonly got by method of maximum likehood, the distribution of $\{\eta_t\}$ do not only adopt the standardized normal distribution ($\eta \sim N(0,1)$), but also use generalized error distribution (GED) with a mean of zero and a variance of one, the density of GED is given by:

$$f(\eta_t) = \frac{v exp\left[-\frac{1}{2}|\eta_t/\lambda|^v\right]}{\lambda 2^{(1+1/v)}\Gamma(1/v)},$$

where, $-\infty < \eta_t < +\infty, 0 < v \leq \infty$, $\Gamma(\cdot)$is a gamma function, and

$$\lambda = \left[2^{-2/v}\Gamma(1/v) \Big/ \Gamma(3/v)\right]^{1/2}.$$

When $v = 2, \lambda = 1$, $\{\eta_t\}$ has a standardized normal distribution. For $v < 2$, the distribution of $\{\eta_t\}$ has thicker tails than normal, the kurtosis is higher than 3; nevertheless, for $v > 2$, the distribution of $\{\eta_t\}$ has thinner tails than normal, and

$$E|\eta_t| = \frac{\lambda 2^{1/v}\Gamma(2/v)}{\Gamma(1/v)}.$$

The difference between the EGARCH model and GARCH model:

a) The volatility of EGARCH model, measured by conditional variance (η_t), is a specific multiplicative function of lagged innovations. By contrast, volatility of GARCH model is an additive function of the lagged error term of ε_t^2.

b) The positive and negative things are able to have asymmetrical volatility.

In summary, because the EGARCH model do not have parameter restrictions, the probability of instability of optimal routines is declined.

3.4 Price Spillover Model – VAR model

Christopher Sims (1980) described a new flexible and tractable framework for analyzing financial time series, which is named as Vector Autoregressions (VAR) model. While a VAR is a n-variable linear model with n-equations in which each variable is explained by its own lagged values, moreover it also be explained by current and past values of the remaining $n - 1$ variables, a common autoregression is a single-variable linear model, using lagged values of a variable to explain its own.

A VAR model of p-th order is written as:

$$\boldsymbol{y}_t = \boldsymbol{c} + \boldsymbol{\phi}_1\boldsymbol{y}_{t-1} + \cdots + \boldsymbol{\phi}_p\boldsymbol{y}_{t-p} + \boldsymbol{\epsilon}_t, \tag{3.19}$$

where $\boldsymbol{y}_t$: $(N \times 1)$; $\boldsymbol{\phi}_i$: $(N \times N)$; $\boldsymbol{\epsilon}_t$: $(N \times 1)$;

$E(\boldsymbol{\epsilon}_t) = 0$; $E(\boldsymbol{\epsilon}_t\boldsymbol{\epsilon}'_\tau) = \begin{cases} \boldsymbol{\Omega} & t = \tau \\ \boldsymbol{0} & t \neq \tau \end{cases}$ ($\boldsymbol{\Omega}$ positive definite matrix).

A VAR model is model with a vector generalization of a scalar autoregression. Moreover, each variable is regressed not only on p lags of its own but on p of other variables lags as well.

$$[\boldsymbol{I}_N - \boldsymbol{\phi}_1 L - \cdots - \boldsymbol{\phi}_p L^p]\boldsymbol{y}_t = \boldsymbol{c} + \boldsymbol{\epsilon}_t$$

$$\boldsymbol{\phi}(L)\boldsymbol{y}_t = \boldsymbol{c} + \boldsymbol{\epsilon}_t, \tag{3.20}$$

where, $\boldsymbol{\phi}(L)(N \times N)$ is a matrix polynomial of L and the element (i, j) is a scalar polynomial in L. Overall, it can be called unrestricted VAR model if there is equation (3.19) or (3.20).

In the VAR model, as every equation has lagged values of endogenous variables and they have no connection with $\boldsymbol{\epsilon}_t$, the Ordinary Least Square Method (OLS) could be used to forecast the right-hand side of every equation in turn. The VAR model will be applied to estimate the price spillover effect, and this approach was utilized for instance by Singh (2010).

3.4.1 The Stationarity of VAR Model

When a pulsation impact is put on one equation of the VAR model, if the strike will disappear gradually, which means the system is stable, and vice versa.

Following is the example of first-order VAR model,

$$\boldsymbol{y}_t = \boldsymbol{c} + \boldsymbol{\phi}_1\boldsymbol{y}_{t-1} + \boldsymbol{\epsilon}_t, \tag{3.21}$$

when $t = 1$, there is

$$\boldsymbol{y}_1 = \boldsymbol{c} + \boldsymbol{\phi}_1\boldsymbol{y}_0 + \boldsymbol{\epsilon}_1, \tag{3.22}$$

when $t = 2$, with the iterative analysis using, the formula is got,

$$\boldsymbol{y}_2 = \boldsymbol{c} + \boldsymbol{\phi}_1\boldsymbol{y}_1 + \boldsymbol{\epsilon}_2 = \boldsymbol{c} + \boldsymbol{\phi}_1(\boldsymbol{c} + \boldsymbol{\phi}_1\boldsymbol{y}_0 + \boldsymbol{\epsilon}_1) + \boldsymbol{\epsilon}_2$$
$$= (\boldsymbol{I} + \boldsymbol{\phi}_1)\boldsymbol{c} + {\boldsymbol{\phi}_1}^2\boldsymbol{y}_0 + \boldsymbol{\phi}_1\boldsymbol{\epsilon}_1 + \boldsymbol{\epsilon}_2, \tag{3.23}$$

when $t = 3$, the formula is

$$\boldsymbol{y}_3 = \boldsymbol{c} + \boldsymbol{\phi}_1\boldsymbol{y}_2 + \boldsymbol{\epsilon}_3 = \boldsymbol{c} + \boldsymbol{\phi}_1\left[(\boldsymbol{I} + \boldsymbol{\phi}_1)\boldsymbol{c} + {\boldsymbol{\phi}_1}^2\boldsymbol{y}_0 + \boldsymbol{\phi}_1\boldsymbol{\epsilon}_1 + \boldsymbol{\epsilon}_2\right] + \boldsymbol{\epsilon}_3$$
$$= \left(\boldsymbol{I} + \boldsymbol{\phi}_1 + {\boldsymbol{\phi}_1}^2\right)\boldsymbol{c} + {\boldsymbol{\phi}_1}^3\boldsymbol{y}_0 + {\boldsymbol{\phi}_1}^2\boldsymbol{\epsilon}_1 + \boldsymbol{\phi}_1\boldsymbol{\epsilon}_2 + \boldsymbol{\epsilon}_3, \tag{3.24}$$

above all, the general formula is

$$\boldsymbol{y}_t = \left(\boldsymbol{I} + \boldsymbol{\phi}_1 + {\boldsymbol{\phi}_1}^2 + \cdots {\boldsymbol{\phi}_1}^{t-1}\right)\boldsymbol{c} + {\boldsymbol{\phi}_1}^t\boldsymbol{y}_0 + \sum_{i=0}^{t-1} {\boldsymbol{\phi}_1}^i\boldsymbol{\epsilon}_{t-i}. \tag{3.25}$$

According to the equation (3.25), the independent value y_t has the relationship with vector **c**, vector $\boldsymbol{y}_0$, and vector $\boldsymbol{\epsilon}_t$, it depends on the result after strikes of that three vectors that the system is stable or not.

If the VAR system is stable, the conclusions are:

a) If $t = 1$, putting a unit strike on $\boldsymbol{c}$, when time reached to t, the effect is

$$(\boldsymbol{I} + \boldsymbol{\phi}_1 + \boldsymbol{\phi}_1{}^2 + \cdots \boldsymbol{\phi}_1{}^{t-1}).$$

When $t \to \infty$, the effect is a limited value, which is $(\boldsymbol{I} - \boldsymbol{\phi}_1)^{-1}$.

b) If putting a unit strike on $\boldsymbol{y}_0$, the effect will be $\boldsymbol{\phi}_1{}^t$ when time is t. Moreover, if $t \to \infty$, $\boldsymbol{\phi}_1{}^t \to 0$, the effect vanished.

c) Observing $\sum_{i=0}^{t-1} \boldsymbol{\phi}_1{}^i \boldsymbol{\epsilon}_{t-i}$, the further the strike of white noise is, the lower the effect is.

Through the analysis of first-order equation, it is easy to get that autoregression process has a long memory ability to pulsation impact of innovation. Similarly, if the response of the endogenous variable will not disappear over time with a pulsation impact of innovation, it is the non-stationary process of VAR model.

3.4.2 Advantages and Disadvantages of VAR Model

The VAR model is a popular macroeconomic framework, numerous researchers would like to use it. Why is it fairly popular? There will be three main reasons below:

a) Since all variables in the VAR model are endogenous, it is not necessary to specify which variable is exogenous or endogenous.

b) The VAR model, which allows the value of a variable to depend on more than its own lags or combinations of white noise terms, is more general than ARMA model.

c) The OLS can be used on each equation, as there are no contemporaneous terms on the right-hand side of the equations.

Even though the VAR model has a vast number of advantages, there still have some weaknesses of it.

a) The VAR model is a theoretical model, it is hard to practice.

b) It is not easy to decide the proper lag length.

c) There are many parameters. For instance, if there are x equations for y variables, and the lag is k, there are $(g + kg^2)$ parameters that should be estimated.

d) It is hard to ensure if all components of the VAR model need to keep stationary.

Overall, the VAR model still is an essential instrument in macroeconomic research.

3.5 Volatility Spillover Models – AR/EGARCH model

The three steps of AR/GARCH model used to estimate the volatility spillover effects between the American and European bond market by Christiansen (2007). In this thesis, the same approach as above will be applied.

Firstly, the American return was got from a univariate AR/GARCH (1,1) model. Then, the univariate AR/GARCH (1,1) model was used to estimate the aggregate European return with an extended version. Besides, the return for individual European stock market was estimated by the extended univariate AR/GARCH (1,1) model. However, Nelson (1991) indicated that the constraints parameters of the GARCH model has to be positive as well as the size of volatility had no relationship with the sign of unexpected return. Thus, the GARCH model is not able to distinguish the leverage effect on volatility. Hence, for explaining the leverage effect, the EGARCH model will be used to instead of GARCH model in this thesis, in which using the AR/EGARCH (1,1) model to investigate the effects of the chosen stock markets.

Firstly, the American return is shown as:

$$R_{us,t} = \phi_{0,us} + \phi_{1,us} R_{us,t-1} + \varepsilon_{us,t}, \tag{3.26}$$

where, $\varepsilon_{us,t} \sim N(0, \sigma_{us,t}^2)$, $\sigma_{us,t}^2$ is the conditional variance of the American stock market. $\phi_{1,us}$ represses the lagged return of the American return influent itself. And according to the EGARCH (1,1) model, the conditional variance is

$$ln\sigma_{us,t}^2 = \omega_{us,t} + \theta_{1,us} \left| \frac{\varepsilon_{us,t-1}}{\sigma_{us,t-1}} \right| + \gamma_{1,us} \frac{\varepsilon_{us,t-1}}{\sigma_{us,t-1}} + \beta_{us} ln\sigma_{us,t-1}^2. \tag{3.27}$$

where, β_{us} is the persistence of volatility, $\gamma_{1,us}$ controls the leverage effect on volatility by positive or negative returns. More specifically,

$$\begin{cases} \frac{\varepsilon_{us,t-1}}{\sigma_{us,t-1}} > 0, means\ the\ effect\ of\ the\ shock\ \varepsilon_{us,t-1}\ is\ (\theta_{1,us} + \gamma_{1,us}) \left(\frac{\varepsilon_{us,t-1}}{\sigma_{us,t-1}} \right) \\ \frac{\varepsilon_{us,t-1}}{\sigma_{us,t-1}} < 0, means\ the\ effect\ of\ the\ shock\ \varepsilon_{us,t-1}\ is\ (\theta_{1,us} - \gamma_{1,us}) \left(\frac{\varepsilon_{us,t-1}}{\sigma_{us,t-1}} \right) \\ \frac{\varepsilon_{us,t-1}}{\sigma_{us,t-1}} = 0, means\ the\ variance\ to\ shocks\ is\ symmtric \end{cases}.$$

Moreover, the aggregate European return is shown as:

$$R_{EU,t} = \phi_{0,EU} + \phi_{1,EU} R_{EU,t-1} + \varphi_{EU} R_{us,t-1} + \mu_{EU} \varepsilon_{us,t} + \varepsilon_{EU,t}, \tag{3.28}$$

As can be seen from the equation (3.28), its own lagged return and the American lagged return influent the aggregate European return. Furthermore, φ_{EU} and μ_{EU} estimate the return and volatility spillover effect from the American stock market to Eurozone stock market respectively. And according to the EGARCH (1,1) model, the conditional variance is

$$ln\sigma_{EU,t}^2 = \omega_{EU,t} + \theta_{1,EU} \left| \frac{\varepsilon_{EU,t-1}}{\sigma_{EU,t-1}} \right| + \gamma_{1,EU} \frac{\varepsilon_{EU,t-1}}{\sigma_{EU,t-1}} + \beta_{EU} ln\sigma_{EU,t-1}^2. \tag{3.29}$$

The individual European stock market is shown as:

$$R_{i,t} = \phi_{0,i} + \phi_{1,i}R_{i,t-1} + \varphi_i R_{us,t-1} + \delta_i R_{EU,t-1} + \mu_i \varepsilon_{us,t} + \psi_i \varepsilon_{EU,t} + \varepsilon_{i,t}, \tag{3.30}$$

where, $i = 1,2,3,4$, which represents four chosen countries. The return of each country depends on its own lagged return, the American lagged return and European lagged return. φ_i and μ_i estimate the return and volatility effect from the American stock market, whereas the δ_i and ψ_i measure the regional return and volatility effect. Besides, $\varepsilon_{i,t} \sim N(0, \sigma_{i,t}^2)$, thus,

$$ln\sigma_{i,t}^2 = \omega_i + \theta_{1,i}\left|\frac{\varepsilon_{i,t-1}}{\sigma_{i,t-1}}\right| + \gamma_{1,i}\frac{\varepsilon_{i,t-1}}{\sigma_{i,t-1}} + \beta_i ln\sigma_{i,t-1}^2. \tag{3.31}$$

The unexpected return from each stock market is donated as:

$$e_{us,t} = \varepsilon_{us,t}, \tag{3.32}$$

$$e_{EU,t} = \mu_{EU}\varepsilon_{us,t} + \varepsilon_{EU,t}, \tag{3.33}$$

$$e_{i,t} = \mu_i \varepsilon_{us,t} + \psi_i \varepsilon_{EU,t} + \varepsilon_{i,t}, \tag{3.34}$$

$\varepsilon_{us,t}$, $\varepsilon_{EU,t}$ and $\varepsilon_{i,t}$ are assumed to be independent. Thus, the conditional variance of unexpected return in country i can be indicated as:

$$h_{i,t} = E\left(e_{i,t}^2 \middle| I_{t-1}\right) = \mu_i^2\sigma_{us,t}^2 + \psi_i^2\sigma_{EU,t}^2 + \sigma_{i,t}^2. \tag{3.35}$$

In addition, the variance ratio is able to detect which stock market affects the volatility more, the American stock market or the Eurozone stock market. The formulas are showing as:

$$VR_{i,t}^{us} = \frac{\mu_i^2\sigma_{us,t}^2}{h_{i,t}}, \tag{3.36}$$

$$VR_{i,t}^{EU} = \frac{\psi_i^2\sigma_{EU,t}^2}{h_{i,t}}. \tag{3.37}$$

Except the influences from the American stock market and the Eurozone stock market, it also can be affected by itself,

$$VR_{i,t}^{i} = 1 - VR_{i,t}^{us} - VR_{i,t}^{EU} = \frac{\sigma_{i,t}^2}{h_{i,t}}. \tag{3.38}$$

4 Data Sample Description

In this thesis, we will analysis and compare if the volatility of the American or Eurozone stock market have an effect on the volatility of French, German, British and Swiss stock markets. Therefore, a brief account of chosen stock markets will be in the first part. Then, descripting and analyzing the six stock indexes from six chosen stock markets respectively. Lastly, for the purpose of this thesis, the total time period is divided into three sub periods, and statistics in each period will be descripted.

4.1 Characteristics of Investigated Stock Markets

For the purpose of this thesis there were selected four important stock markets – French stock market and German stock market, which are European Union members; British stock market and Swiss stock market, which are not European Union members. Therefore, this subchapter will illustrate the fundamental information of those four stock markets.

4.1.1 French Stock Market

The Paris Bourse, also called Paris Stock Exchange, is an essential stock market in France. There are two other French stock markets – Financial Futures Market (MATIF) and the Financial Options Market (MONEP).

There are four different markets operated in Paris Bourse.

a) Firstly, it is the Official Stock Exchange, which is called Marche Official. The market is dedicated for comparatively large companies, on which at least 25% of their equity publicly held.

b) Then, it is the Second Market, which is called Second Marche. This market accepts those companies, which are not large enough to be traded in the Marche Official. It is considered as a temporary level for companies.

c) Moreover, it is the New Market, which is called Le Nouveau Marche. This market is intended for growth companies, e.g., small, young companies with high risk. Companies can list without a profitability or trading record.

d) Lastly, the Over-the-Counter Market, not a permanent market, is used for temporary transactions between non-listed companies.

4.1.2 German Stock Market

As one of the financial center in Euro areas, Germany has eight stock exchanges, which are sited in Frankfurt, Dusseldorf, Munich, Stuttgart, Hanover, Hamburg, and Bremen respectively. The Frankfurt Stock Exchange (FSE) is the largest stock exchange in Germany, accounting for approximately 75% of the total trading volume. It is a joint stock company in which the main shareholders are bank members. The Dusseldorf is the second largest one with representing about 10% of the trading volume. Therefore, these are just small parts of total trading volume to other stock exchanges.

There are different market segments in German stock exchanges. The first place is the regulated market, which is divided into prime standard and general standard. Moreover, the expected total market value of all shares must be over EUR 1.25 million if companies want to be listed in the regulated market, unless in which the shares of the same class were listed in the same stock market already. Then, it is the open market, which is divided into entry standard listing in the qualified open market and quotation board for secondary listings (unqualified open market). The companies have pay the share capital at least EUR 750,000 to be in this market.

4.1.3 British Stock Market

Speaking of British stock market, the London Stock Exchange (LSE) is an essential stock market in the Britain, which is called the International Stock Exchange of the United Kingdom and the Republic of Ireland formally. The LSE, playing an important role in the development of global capital markets, is one of the world's largest and most international stock exchanges. The LSE provides the widest choices of routes to market, which are available to both UK and international companies. Moreover, there are about 3,000 companies from more than 70 counties that listed and traded on British stock market.

The key benefits of the LSE are:

a) It can provide access to capital for growth, meanwhile it is enable enterprises to raise finance for further development.

b) It can create market shares of the enterprise and broaden the shareholder base.

c) It will place an objective market value on the business of enterprise.

d) It is capable to increase the ability of company to make acquisitions and use quoted shares as currency.

e) It can augment the loyalty of suppliers and customers.

Furthermore, the LSE runs three markets, which is showing below:

a) Firstly, it is about the Official List – the largest market, which is intended for large companies that have substantial public floating and a history of business activity. And this market is divided into an international section and a nation one, so that the non-British stocks can be traded on.

b) Secondly, Unlisted Securities Market, set up in 1980 to cater for smaller enterprises, has met only limited success. Nevertheless, it stopped allowing new companies listing and was closed at the end of 1996.

c) Lastly, the Alternative Investment Market, set up in 1995, is a new attempt to build a market for smaller companies. It does not have any requirements for minimum trading period or number of shares in the public compared with the Official List.

4.1.4 Swiss Stock Market

The SIX Swiss Exchange, established in 1993, is a central link in the value chain of the Swiss stock market. It organizes, operates and regulates significate factors of the capital market infrastructure, and it also provides extensive services on global ranges. Moreover, it is one of the four business areas of the SIX, which has: securities trading (SIX Swiss Exchange), financial information services (SIX Financial Information), payment services (SIX Payment Services) and securities services (SIX Securities Services). And there are 150 domestic and foreign shareholders joined in the SIX as owners.

The SIX is consistently developing its infrastructure for the Swiss financial center, and the Swiss financial center, which is attractive, diversified, and also has a remarkable international network, is one of the best in the world. The SIX propose to improve consistently as part of an active interlocution between Swiss market participants and authorities. Moreover, the Swiss authorities also support open markets in advance.

4.2 Description of Investigated Indexes

In this subchapter, six indexes - CAC 40, DAX 30, FTSE 100, SMI 20, EURO STOXX 50 and S&P 500 - from chosen counties and areas will be indicated and analyzed.

4.2.1 Paris Stock Index CAC 40

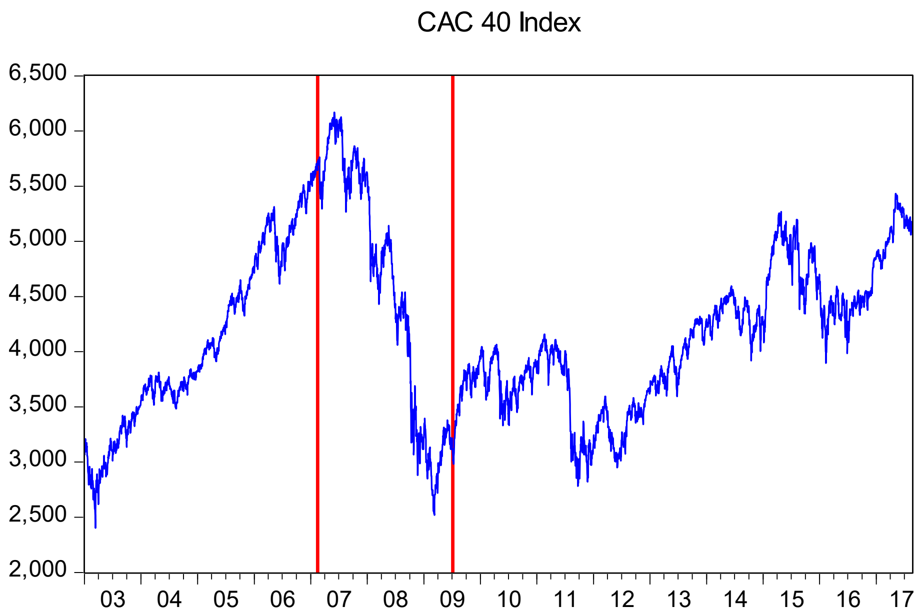
The CAC 40 is a benchmark French stock market index. It describes a capitalization-weighted measure of the 40 most important enterprises on the Euronext Paris. Moreover, the market capitalization had been €1457.5 billion until March 29, 2018[1]. The most famous companies, consisted the index, were AXA, L'Oréal, Atos, etc. Therefore, this thesis uses the CAC 40 Index to analysis French stock market.

The index value of CAC 40 Index is calculated as the result of the basic level multiplied by the sum of the prices multiplied by the corresponding weights and divided by the adjustment coefficient multiplied by the basis capitalization. The formula is shown below:

$$I_t = 1000 \times \frac{\sum_{i=1}^{N} Q_{i,t} F_{i,t} f_{i,t} C_{i,t}}{K_t \sum_{i=1}^{N} Q_{i,0} C_{i,0}}, \tag{4.1}$$

where, t is day of calculation, N is number of constituent equities in index, $Q_{i,t}$ is number of shares of equity i on day t, $F_{i,t}$ is free float of equity i, $f_{i,t}$ is capping factor of equity i, $C_{i,t}$ is price of equity i on day t, K_t is adjustment coefficient for base capitalization on day t, $Q_{i,0}$ is number of shares of equity i on index base data, $C_{i,0}$ is price of equity i on index base day.

Chart 4.1 The CAC 40 Index from 01/01/2003 to 22/08/2017



Source: by Author

As can be seen from the Chart 4.1, the line chart shows the CAC 40 Index from the beginning of 2003 to the August of 2017 while the whole figures are divided into three sub-

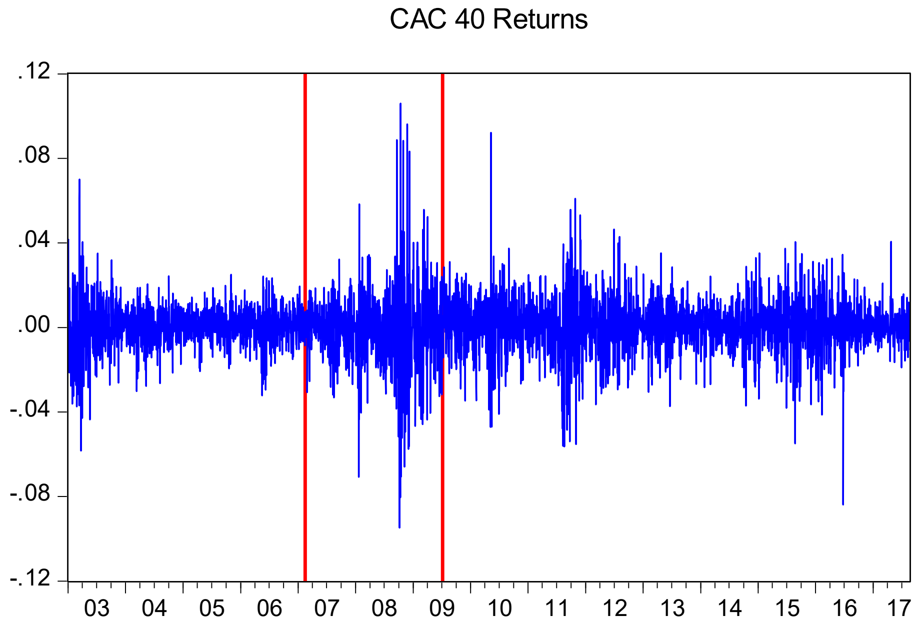
[1] https://www.euronext.com/en/products/indices/FR0003500008-XPAR/market-information

periods by two red lines with February 8, 2007 and July 30, 2009 respectively.

More specifically, before the former red line, the main trend of the line was consistently increase, and the line reached the bottom at around 2,400 points on March of 2003. In February 8, 2007, the line reached the peak at about 5,700 points in the first sub-period. Moreover, between the two red lines, there was a steadily decline basically with peaking at approximately 6,100 points on July of 2007 and bottoming out at approximately 2,500 points on February of 2009. After July 30, 2009, with a gradually upward trend basically, there were two substantial recessions – the former one was around May of 2011, when the index dropped from approximately 3,700 points to 2,600 points; the latter one was from April of 2015 to February of 2016, on which the index declined from approximately 5,200 to 3,900 points respectively.

As shown in the Chart 4.2, this line chart shows the returns of CAC 40 Index from the beginning of 2003 to the August of 2017 while the whole figures are divided into three sub-periods by two red lines with February 8, 2007 and July 30, 2009 respectively. More precisely, the volatility of returns between the two red lines was nearly five times as high as the returns before the former red line as well as nearly three times as high as the returns after the latter red line.

Chart 4.2 The CAC 40 Returns from 01/01/2003 to 22/08/2017

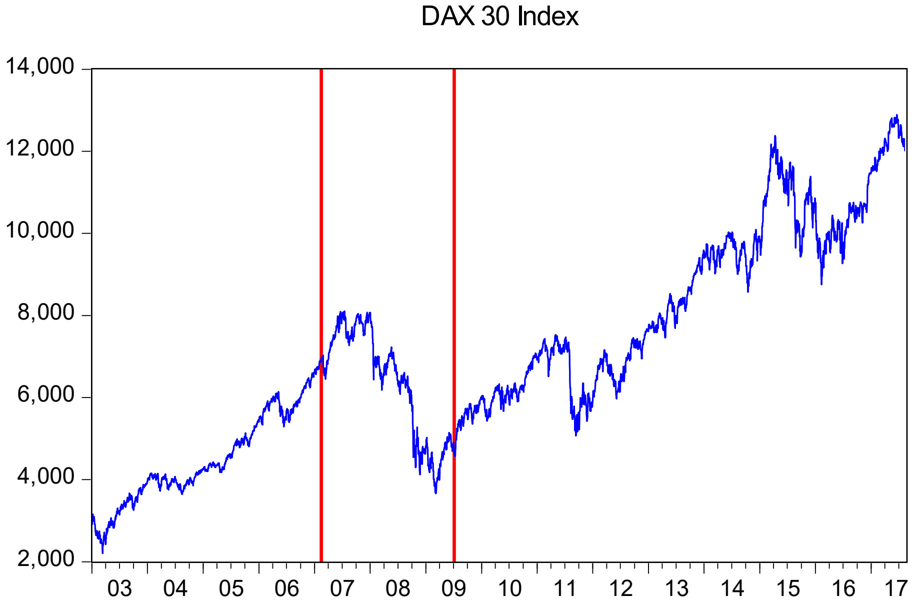


Source: by Author

4.2.2 Frankfurt Stock Index DAX 30

The DAX 30 Index is a benchmark index in the German stock market. This index, a blue-chip stock market index, measures the share performance of the 30 largest German enterprises in terms of market capitalization and exchange turnover.

Chart 4.3 The DAX 30 Index from 01/01/2003 to 22/08/2017



Source: by Author

Moreover, the 30 enterprises contained in DAX 30 account for approximately 80% of the market capitalization listed in Germany, which had been €971.8 billion until February 28, 2017[2]. Besides, the most popular companies, listed on the DAX 30, were Allianz, BMW, Adidas, etc. Therefore, this thesis uses the DAX 30 Index to analysis German stock market.

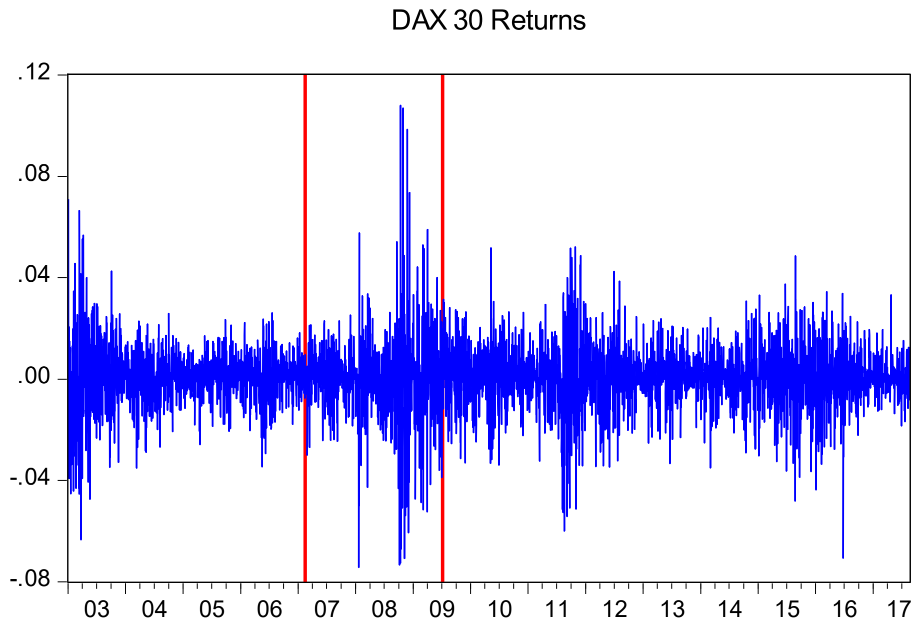
As can be seen from the Chart 4.3, the line chart shows the DAX 30 Index from the beginning of 2003 to the August of 2017 while the whole figures are divided into three sub-periods by two red lines with February 8, 2007 and July 30, 2009 respectively.

To be more specific, before the former red line, the main trend of the line was consistently increase, and the line reached the bottom at around 2,100 points on March of 2003. In February 8, 2007, the line reached the peak at about 6,800 points in the first sub-period. Moreover, between the two red lines, there was a steadily decline basically with peaking at approximately 7,900 points on July of 2007 and bottoming out at approximately 3,600 points on March of 2009. After July 30, 2009, with a gradually upward trend basically, there were two substantial recessions – the former one was around May of 2011, when the index dropped from approximately 6,900 points to 4,900 points; the latter one was from April of 2015 to February

[2] https://www.dax-indices.com/documents/599858594/616692974/Factsheet_DAX.pdf

of 2016, on which the index declined from approximately 11,900 to 9,000 points.

Chart 4.4 The DAX 30 Returns from 01/01/2003 to 22/08/2017



Source: by Author

As shown in the Chart 4.4, this line chart shows the returns of DAX 30 Index from the beginning of 2003 to the August of 2017 while the whole figures are divided into three sub-periods by two red lines with February 8, 2007 and July 30, 2009 respectively. More precisely, the volatility of returns between the two red lines was nearly three times as high as the returns before the former red line as well as nearly twice as high as the returns after the latter red line.

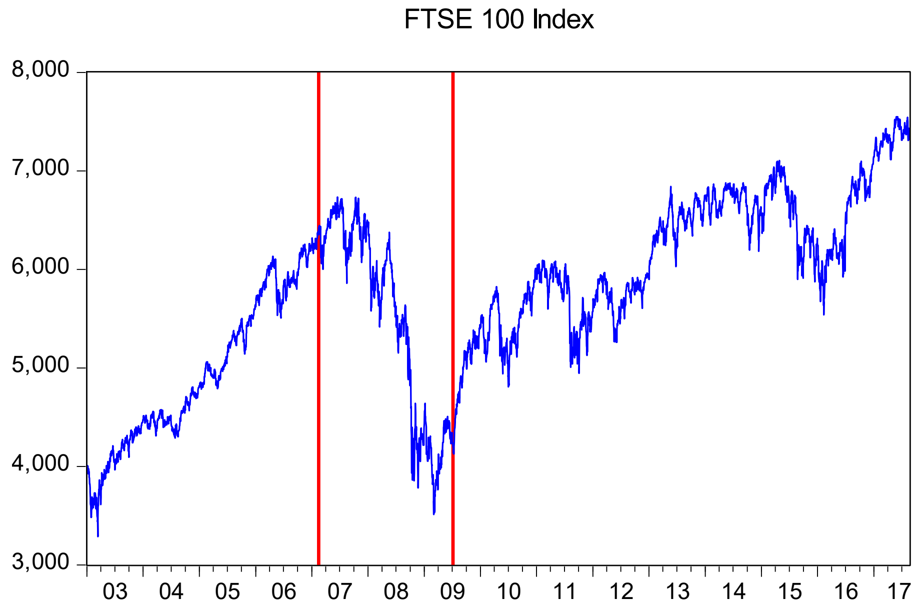
4.2.3 London Stock Index FTSE 100

The FTSE 100 is a basic and important British stock market index. And this index is comprised by 100 most capitalized companies, which listed on the London Stock Exchange. the 100 companies - Coca-Cola HBC AG, HSBC, Lloyds Banking Group, etc. - contained in FTSE 100 account for approximately 81% of the market capitalization listed in London Stock Exchange, which had been £2.054 trillion until January of 2018[3]. Hence, the FTSE 100 is suitable to be as the British stock market indicator.

As can be seen from the Chart 4.5, the line chart shows the FTSE 100 Index from the beginning of 2003 to the August of 2017 while the whole figures are divided into three sub-periods by two red lines with February 8, 2007 and July 30, 2009 respectively.

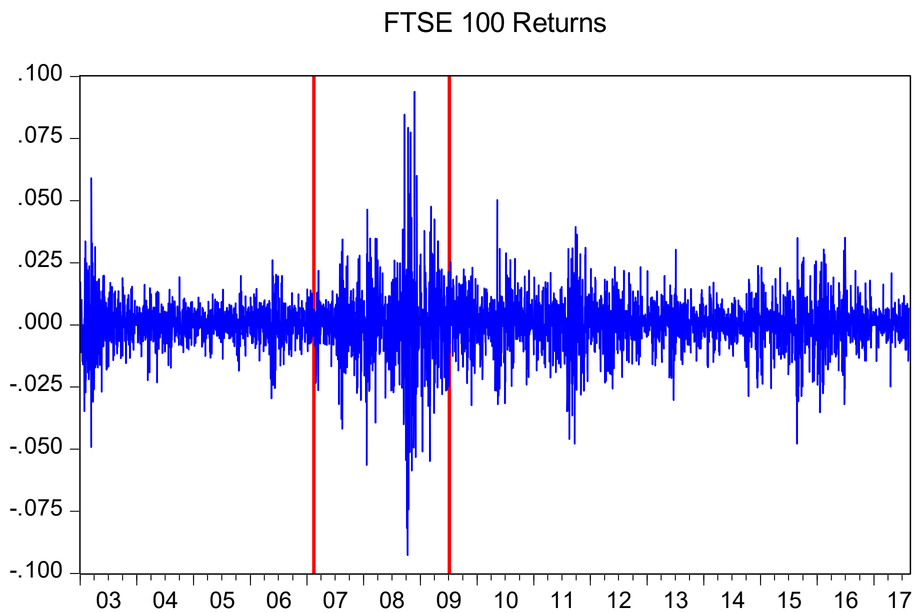
[3] "FTSE 100 index factsheet"

Chart 4.5 The FTSE 100 Index from 01/01/2003 to 22/08/2017



Source: by Author

Chart 4.6 The FTSE 100 Returns from 01/01/2003 to 22/08/2017



Source: by Author

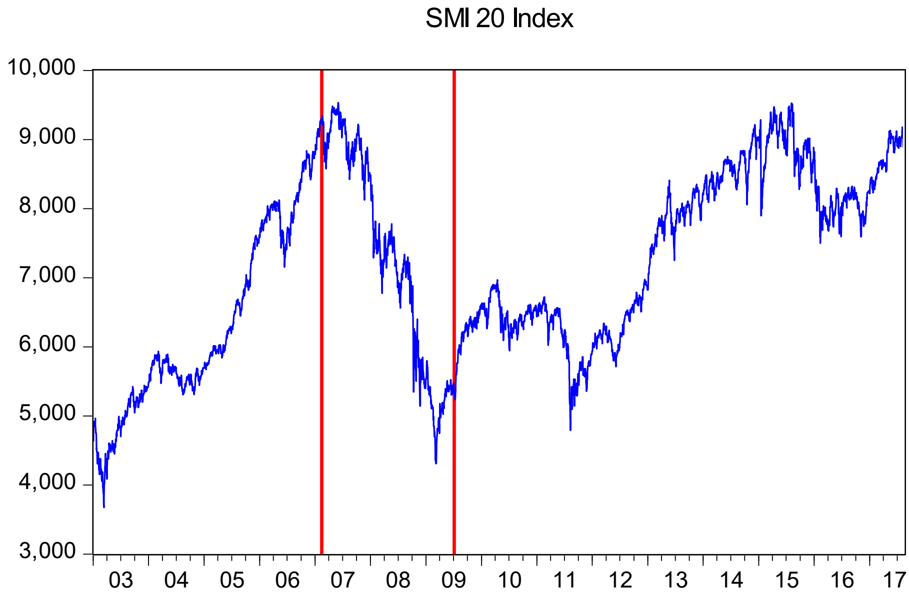
To be more specific, before the former red line, the main trend of the line was consistently increase, and the line reached the bottom at around 3,200 points on March of 2003. In February 8, 2007, the line reached the peak at about 6,400 points in the first sub-period. Moreover, between the two red lines, there was a steadily decline basically with peaking at approximately 6,700 points on July of 2007 and bottoming out at approximately 3,400 points on February of 2009. After July 30, 2009, with a gradually upward trend basically, there were two substantial recessions – the former one was around May of 2011, when the index dropped from approximately 5,800 points to 4,800 points; the latter one was from April of 2015 to February of 2016, on which the index declined from approximately 6,900 to 5,600 points.

As shown in the Chart 4.6, this line chart shows the returns of FTSE 100 Index from the beginning of 2003 to the August of 2017 while the whole figures are divided into three sub-periods by two red lines with February 8, 2007 and July 30, 2009 respectively. More precisely, the volatility of returns between the two red lines was nearly five times as high as the returns before the former red line as well as nearly three times as high as the returns after the latter red line.

4.2.4 Zurich Stock Index SMI 20

The SMI 20 (Swiss Market Index), a blue-chip index, is a major Swiss stock market index. And this index is comprised by 20 largest and most liquid equities of the entire Swiss market. The SMI 20 amounts for approximately 85% of the free-float capitalization of Swiss stock market, which had been 1,003 CHF trillion until February 29, 2016[4]. Hence, the SMI 20 is a well Swiss stock market indicator to analyze the condition of Swiss stock market.

Chart 4.7 The SMI 20 Index from 01/01/2003 to 22/08/2017



Source: by Author

The index value of SMI 20 is calculated by dividing the market capitalization of all

[4] https://www.stoxx.com/document/Bookmarks/CurrentFactsheets/SMI.pdf

securities, which is as follow:

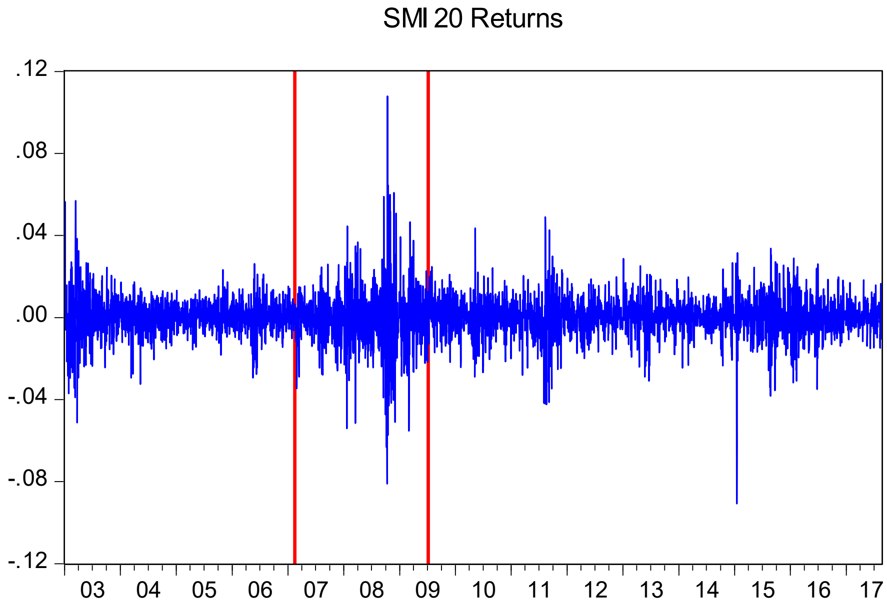
$$I_s = \frac{\sum_{i=1}^{M} p_{i,s} x_{i,t} f_{i,t} K_{i,t} r_s}{D_t}, \tag{4.2}$$

where, t is current day, s is current time on day t, I_s is current index level at time s, M is number of issues in index, $p_{i,s}$ is last-paid price of security i, $x_{i,t}$ is number of shares of security i on day t, $f_{i,t}$ is free float for security i on day t, $K_{i,t}$ is capping factor for security i on day t, r_s is current CHF exchange rate at time s, D_t is divisor on day t.

As can be seen from the Chart 4.7, the line chart shows the SMI 20 Index from the beginning of 2003 to the August of 2017 while the whole figures are divided into three sub-periods by two red lines with February 8, 2007 and July 30, 2009 respectively.

To be more specific, before the former red line, the main trend of the line was consistently increase, and the line reached the bottom at around 3,700 points on March of 2003. In February 8, 2007, the line reached the peak at about 9,200 points in the first sub-period. Moreover, between the two red lines, there was a steadily decline basically with peaking at approximately 9,500 points on July of 2007 and bottoming out at approximately 4,200 points on February of 2009. After July 30, 2009, with a gradually upward trend basically, there were two substantial recessions – the former one was around May of 2011, when the index dropped from approximately 6,400 points to 4,600 points; the latter one was from April of 2015 to March of 2016, on which the index declined from approximately 9,400 to 7,200 points.

Chart 4.8 The SMI 20 Returns from 01/01/2003 to 22/08/2017



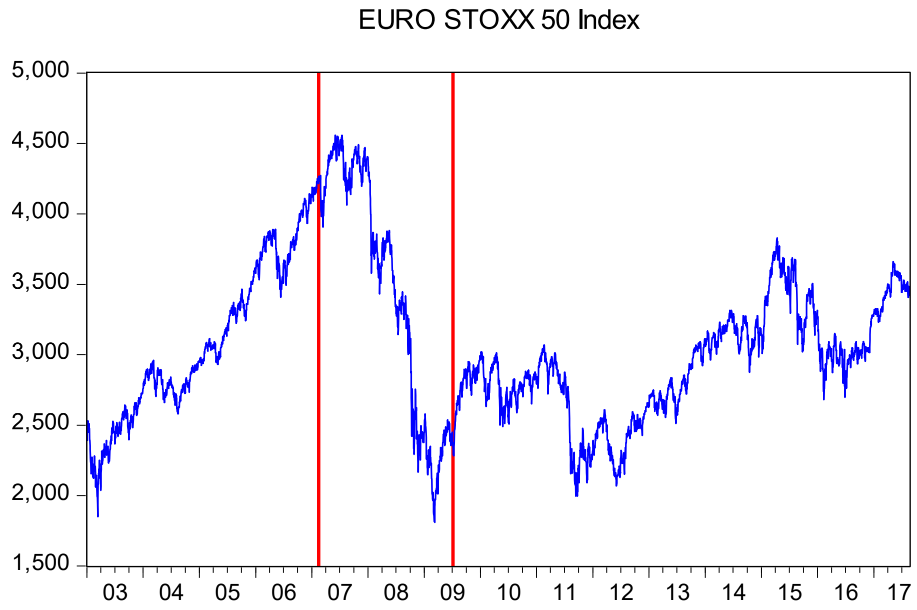
Source: by Author

As shown in the Chart 4.8, this line chart shows the returns of SMI 20 Index from the beginning of 2003 to the August of 2017 while the whole figures are divided into three sub-periods by two red lines with February 8, 2007 and July 30, 2009 respectively. More precisely, the volatility of returns between the two red lines was nearly four times as high as the returns before the former red line as well as nearly three times as high as the returns after the latter red line.

4.2.5 Eurozone Index EURO STOXX 50

The EURO STOXX 50 Index is constituted by 50 largest companies – Adidas, Allianz, BMW, etc. - among the 19 super sectors in terms of free-float market cap in 11 Eurozone countries. The EURO STOXX 50 amounts for approximately 60% of the free-float capitalization of EURO STOXX Total Market Index, and the market capitalization had been €2.771 trillion until March 29, 2018[5]. Therefore, this thesis uses the EURO STOXX 50 Index as an approximation of European stock market to analysis European stock market.

Chart 4.9 The EURO STOXX 50 Index from 01/01/2003 to 22/08/2017



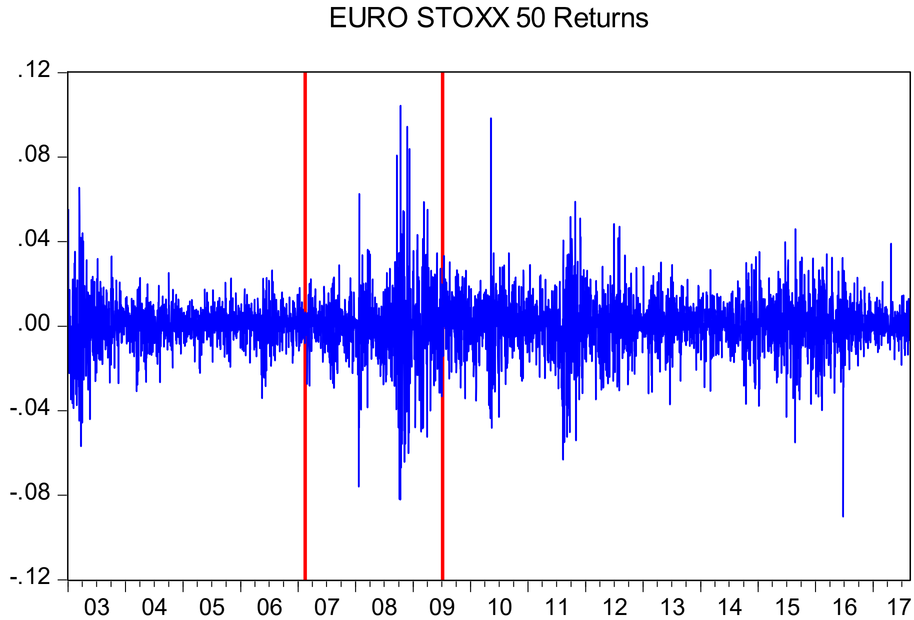
Source: by Author

As can be seen from the Chart 4.9, the line chart shows the EURO STOXX 50 Index from the beginning of 2003 to the August of 2017 while the whole figures are divided into three sub-periods by two red lines with February 8, 2007 and July 30, 2009 respectively.

[5] https://www.stoxx.com/document/Bookmarks/CurrentFactsheets/SX5GT.pdf

To be more specific, before the former red line, the main trend of the line was consistently increase, and the line reached the bottom at around 1,800 points on March of 2003. In February 8, 2007, the line reached the peak at about 4,200 points in the first sub-period. Moreover, between the two red lines, there was a steadily decline basically with peaking at approximately 4,500 points on July of 2007 and bottoming out at approximately 1,750 points on February of 2009. After July 30, 2009, with a gradually upward trend basically, there were two substantial recessions – the former one was around the beginning of 2011, when the index dropped from approximately 3,000 points to 2,000 points; the latter one was from February of 2015 to January of 2016, on which the index declined from approximately 3,700 to 2,600 points.

Chart 4.10 The EURO STOXX 50 Returns from 01/01/2003 to 22/08/2017



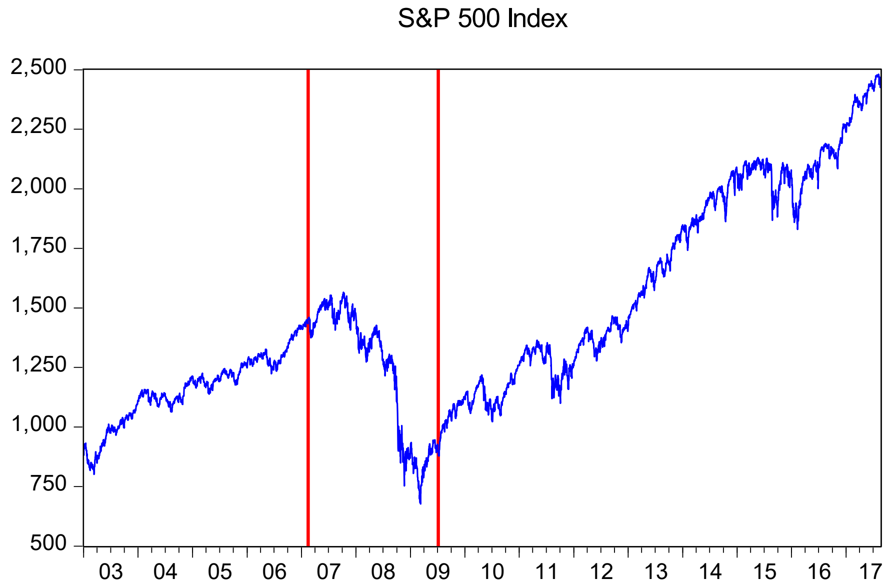
Source: by Author

As shown in the Chart 4.10, this line chart shows the returns of EURO STOXX 50 Index from the beginning of 2003 to the August of 2017 while the whole figures are divided into three sub-periods by two red lines with February 8, 2007 and July 30, 2009 respectively. More precisely, the volatility of returns between the two red lines was nearly four times as high as the returns before the former red line as well as nearly twice as high as the returns after the latter red line.

4.2.6 US Index S&P 500

The S&P 500 (standard & Poor's 500), a US stock market index, is comprised by the market capitalizations of 500 large companies having common stock listed on the NYSE or NASDAQ, and the market capitalization had been $23.596 trillion until March 31, 2018. This index is one of the best representations of the American stock market, hence, this thesis uses the S&P 500 Index as an approximation of financial condition in US stock market to analysis the US stock market.

Chart 4.11 The S&P 500 Index from 01/01/2003 to 22/08/2017



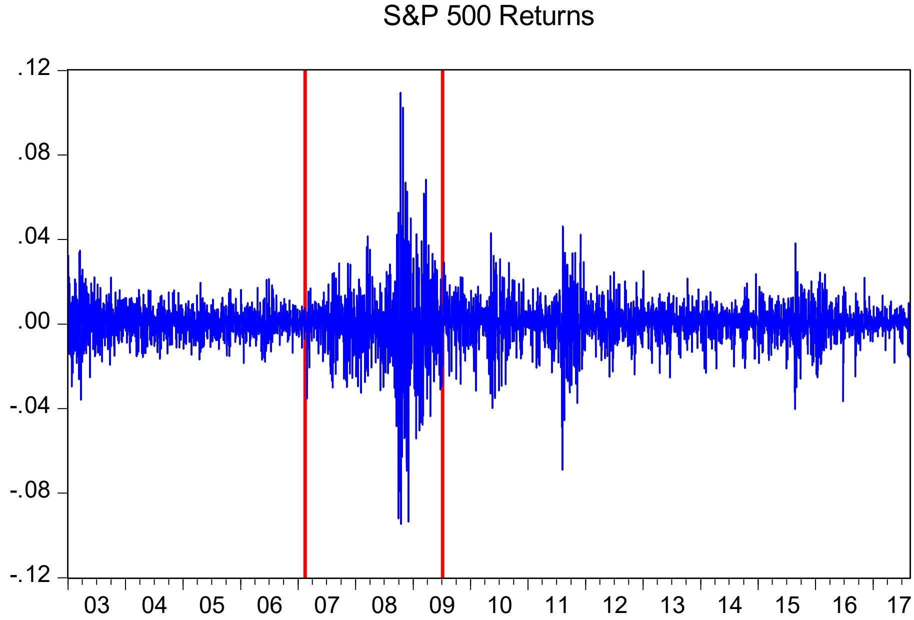
Source: by Author

As can be seen from the Chart 4.11, the line chart shows the S&P 500 Index from the beginning of 2003 to the August of 2017 while the whole figures are divided into three sub-periods by two red lines with February 8, 2007 and July 30, 2009 respectively.

To be more specific, before the former red line, the main trend of the line was consistently increase, and the line reached the bottom at around 800 points on February of 2003. In February 8, 2007, the line reached the peak at about 1,400 points in the first sub-period. Moreover, between the two red lines, there was a steadily decline basically with peaking at approximately 1,550 points on September of 2007 and bottoming out at approximately 700 points on February of 2009. After July 30, 2009, with a gradually upward trend basically, the bottom was 900 points on July 30, 2009 as well as the peak was approximately 2,450 points on August 22, 2017.

As shown in the Chart 4.12, this line chart shows the returns of S&P 500 Index from the beginning of 2003 to the August of 2017 while the whole figures are divided into three sub-periods by two red lines with February 8, 2007 and July 30, 2009 respectively. More precisely, the volatility of returns between the two red lines was nearly six times as high as the returns before the former red line as well as after the latter red line.

Chart 4.12 The S&P 500 Returns from 01/01/2003 to 22/08/2017



Source: by Author

4.3 Descriptive Statistics of Used Time Series

In this subchapter, firstly, the fundamental information of return will be described, and the formulas of one-period simple return and one-period log return will be shown. Then, the testing sub periods will be defined as well as the reason of it will be interpreted. Finally, the basic statistics of chosen countries and areas in each period will be descripted.

4.3.1 Returns in Financial Modeling

The essential aim of investment in the financial market is to get profits without excessive risks. A successful investment is to make the maximum revenue with a given capital, which could be measured by return. A return is a proportion of the change of price compared with the initial price. The asset returns reveal more attractive statistical performance than asset prices own.

Here, the P_t refer to the price of an asset at time t. There are various definitions for the asset returns. In this thesis, we will just introduce one-period log return, which will be used in this thesis.

Firstly, holding an asset from t to $t + 1$, the value of the asset will change from P_t to P_{t+1}.

Assuming there are no dividends paid during the period. Therefore, the one-period simple return can be shown as:

$$R_{t+1} = \frac{P_{t+1} - P_t}{P_t} \tag{4.3}$$

R_{t+1}, commonly writing as $100R_{t+1}\%$, is the profit rate of asset from t to $t+1$, which denotes the percentage of profit with the initial capital P_t. This is properly useful when the time unit is really small (e.g., a day, an hour).

Another description of the simple return R_{t+1} is called one-period log return, which is shown as:

$$r_t = logP_{t+1} - logP_t = \log(P_{t+1}/P_t) = \log(1 + R_{t+1}) \tag{4.4}$$

It should be noted that a log return is the logarithm of a gross return, moreover, $logP_{t+1}$ and $logP_t$ are called as the log price. Furthermore, when the values are relatively small, $r_t = \log(1 + R_{t+1}) \approx R_{t+1}$, where the two returns are approximately same.

4.3.2 Definition of Testing Sub Periods

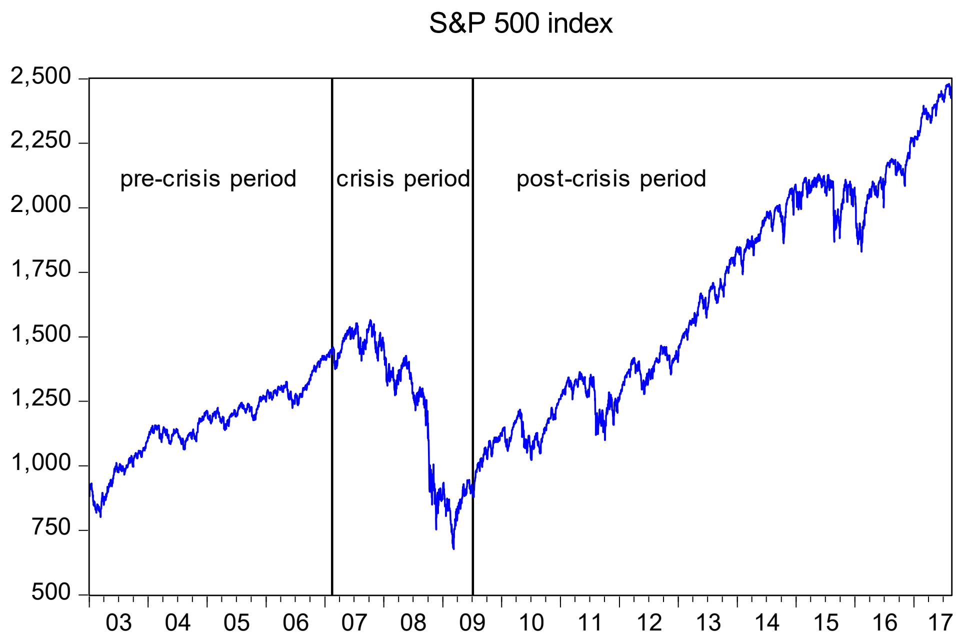
The division of basic testing period from the beginning of 2003 year to August 2017 takes into account the development of the S&P 500 index as well as significant events of a global nature that occurred during testing period. These include the global financial crisis and the subsequent debt crisis.

The period from 2003 to 2017 was divided into three sub periods in order to capture different price and volatility spillover effects. The three main parts are showing in the Chart 4.13 and as follows:

a) The first test period (01/01/2003-07/02/2007), which can be called a pre-crisis period, includes a steady growth of the S&P 500 index. The global financial markets are growing at this time; the US stock market is no longer under the influence of real estate bubbles or bubbles caused by Internet companies. There is no apparent slump in the market due to the terrorist attack on September 11, 2001. The end of the period is set for February 7, 2007, when HSBC bank announces losses linked to US subprime mortgages. For this reason, this day represents the end of the pre-crisis period and the next day the beginning of the global financial crisis for the purpose of this thesis.

b) The second sub-test period (08/02/2007-30/06/2009), which can be described as a crisis period, is characterized by an economic recession. This sub-period includes a shock in the form of the global financial crisis, when higher stock index volatility was evident. Since October 10, 2007, there has been a steady fall in the US stock market. The recession in the US lasted the longest in the history of the US economy. The US National Economic Research Authority NBER officially announced June 30, 2009 the end of the global financial crisis.

Chart 4.13 Three sub-period in S&P 500 Index



Source: by Author

c) The third test period (01/07/2009-22/08/2017), which can be called the post-crisis period, follows the previous sub period. It begins July 1, 2009, when world stock markets recovered from the global financial crisis and started to grow slowly. The end of this sub-period is August 22, 2017 and this is the longest time interval.

4.3.3 Descriptive Statistics in the Pre-Crisis Period

In this subchapter, the fundamental statistics of chosen countries and areas in the pre-crisis period will be descripted. As can be seen from the Table 4.1, there are six groups of basically statistical data of daily returns based on six markets in the pre-crisis period respectively.

More specifically, in those six stock markets, all the means of returns were positive, which represented that all given stock markets had upward trends of stock price during this period basically, even the minimum of returns were negative. Moreover, most standard deviations of returns were around 0.009, therefore, the volatility of the returns were not obvious. Furthermore, whereas the skewness of return in Swiss stock market, which was negatively skewed distribution (-0.0058), skewed to the left; all others were positively skewed distribution, skewed to the right. Additionally, the kurtosis of all returns surpassed than normal distribution (kurtosis = 3), donated as leptokurtic distribution.

Table 4.1 The basically statistical data of daily returns in pre-crisis period

	Eurozone	USA	France	Germany	UK	Switzerland
Mean	3.85E-04	3.34E-04	4.15E-04	5.82E-04	3.21E-04	4.60E-04
Median	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Maximum	0.0655	0.0348	0.0700	0.0709	0.0590	0.0569
Minimum	-0.0569	-0.0359	-0.0583	-0.0634	-0.0492	-0.0513
Std. Dev.	0.0092	0.0065	0.0090	0.0105	0.0070	0.0079
Skewness	0.0349	0.1554	0.0732	0.0496	0.1133	-0.0058
Kurtosis	10.2255	6.6470	10.7635	9.9348	11.2421	10.7059

Source: by Author

4.3.4 Descriptive Statistics in Crisis Period

In this subchapter, the fundamental statistics of chosen countries and areas in the crisis period will be identified. As shown in the Table 4.2, it was calculated that the basically statistical data of daily returns based on six markets in the crisis period.

Table 4.2 The basically statistical data of daily returns in crisis period

	Eurozone	USA	France	Germany	UK	Switzerland
Mean	-6.53E-04	-5.21E-04	-6.83E-04	-4.16E-04	-4.63E-04	-6.20E-04
Median	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Maximum	0.1044	0.1096	0.1059	0.1080	0.0938	0.1079
Minimum	-0.0821	-0.0947	-0.0947	-0.0743	-0.0927	-0.0811
Std. Dev.	0.0164	0.0170	0.0167	0.0160	0.0155	0.0142
Skewness	0.0832	-0.1692	0.2030	0.3578	-0.0323	0.2323
Kurtosis	11.2206	11.7073	11.8207	12.9931	11.1221	11.5807

Source: by Author

To be more exact, in the first place, compared with means of returns in pre-crisis period, the means of returns in crisis period were negative, which represented that the basically trends of given counties and areas were decline even through positive returns were existing. Moreover, all standard deviations of returns (0.016) were nearly twice as high as the standard deviations of returns in the pre-crisis period. It expressed that the fluctuations of returns were much stronger than in the pre-crisis period. Furthermore, whereas the skewness of returns in the US and UK stock market, which were negatively skewed distributions (-0.1692 and -0.0323 respectively), skewed to the left; all others were positively skewed distribution, skewed to the right. Additionally, the kurtosis of all returns surpassed than distributions in the pre-crisis period respectively.

4.3.5 Descriptive Statistics in the Post-Crisis Period

In this subchapter, the fundamental statistics of chosen countries and areas in the post-crisis period will be illustrated. According to the Table 4.3, the basically statistical data of daily returns was calculated based on six markets in the post-crisis period.

Table 4.3 The basically statistical data of daily returns in post-crisis period

	Eurozone	USA	France	Germany	UK	Switzerland
Mean	1.21E-04	3.27E-04	1.64E-04	3.12E-04	1.85E-04	1.69E-04
Median	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Maximum	0.0985	0.0463	0.0922	0.0521	0.0503	0.0490
Minimum	-0.0901	-0.0690	-0.0838	-0.0707	-0.0478	-0.0907
Std. Dev.	0.0112	0.0079	0.0110	0.0106	0.0082	0.0081
Skewness	-0.1459	-0.4756	-0.1571	-0.2829	-0.1751	-0.7985
Kurtosis	9.6708	10.4420	9.2778	7.5173	7.4072	13.3796

Source: by Author

To be more precise, in those six stock markets, all the means of returns were positive, which represented that all given stock markets had upward trends of stock price during this period basically even through there were some negative returns. However, the means here were lower than the means before crisis. Moreover, standard deviations of returns were from 0.0079 to 0.0112, which was almost same as before crisis, therefore, the volatility of the returns were not obvious. Furthermore, the most difference here was the skewness of every stock market, and all of them were negatively skewed distribution. Additionally, the kurtosis of all returns was similar with the kurtosis before crisis, which surpassed than normal distribution (kurtosis = 3), donated as leptokurtic distribution.

5 Empirical Findings

In this chapter, the univariate EGARCH (1,1) model, non-linear model, will be used to estimate among chosen stock markets in each period firstly. Then, the VAR models will be used to estimate the price spillover effect for each stock market in each period. Moreover, the AR/EGARCH Volatility Spillover Model is established to estimate and test the return and volatility spillover effect for all periods by using joint Walt tests and compute variance ratios. Finally, according to the estimations of those models, the summary for price and volatility spillover effect in each stock market will be described.

5.1 Estimation of Univariate Volatility Models using EGARCH Model

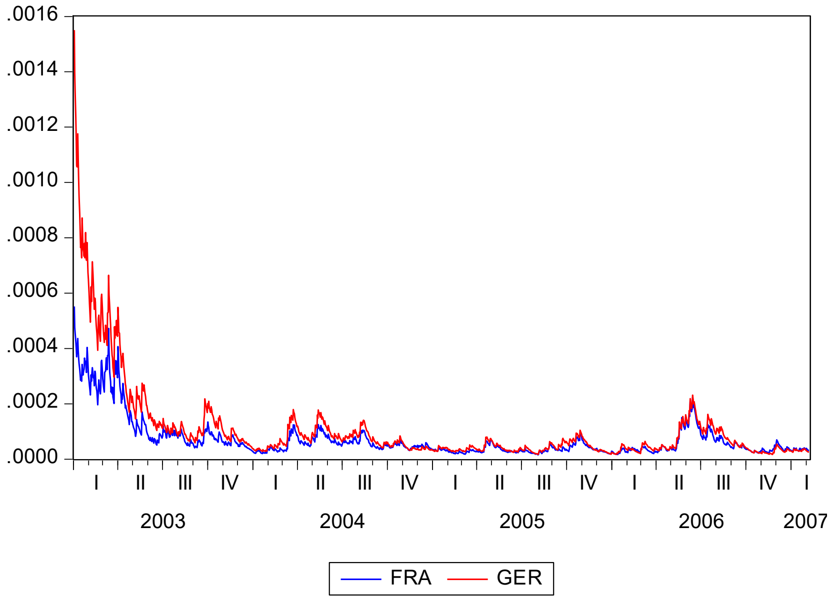
In this subchapter, the univariate EGARCH (1,1) model will be estimated for among chosen stock markets in each period. Firstly, checking the results from the Annex 1, no matter which period or which stock markets, all parameters are statistically significant, *p*-values of which are smaller than level of significance 5%. Therefore, volatility of all chosen countries in each period can be estimated by using EGARCH (1,1) model. Hence, firstly, we will analyze and compare conditional variances of two stock markets in EU (French and German stock markets) as well as conditional variances of two stock markets out of EU (Swiss and British stock markets) respectively. Then, summarizing the results of all stock markets.

5.1.1 Pre-Crisis Period

In this section, the conditional variances for all stock markets will be analyzed and compared from the beginning of 2003 to February 7, 2007.

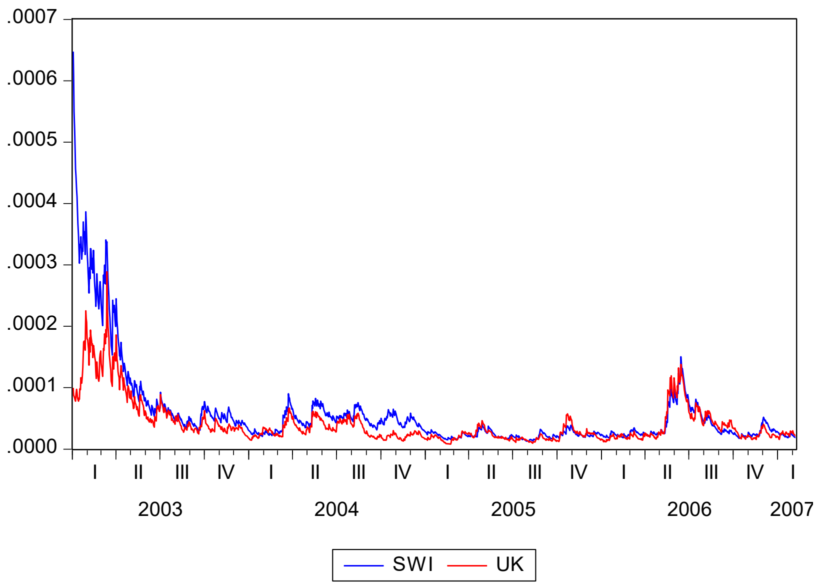
As can be seen from the Chart 5.1, it indicates the conditional variances for French and German stock markets during pre-crisis period. More specifically, the conditional variances for German and French stock markets were approximately 0.00155 and 0.00055 respectively in the beginning of 2003, which were the highest values of volatilities probably caused by the dot-com bubble from 1997 to 2001. However, there were consistently decreases from January 1, 2003 to May of 2003 in both stock markets. Moreover, after May of 2003, even though there were some slight volatility, the conditional variances in both stock markets were lower than 0.0002, which is quite little.

Chart 5.1 The conditional variances for stock markets in EU



Source: by Author

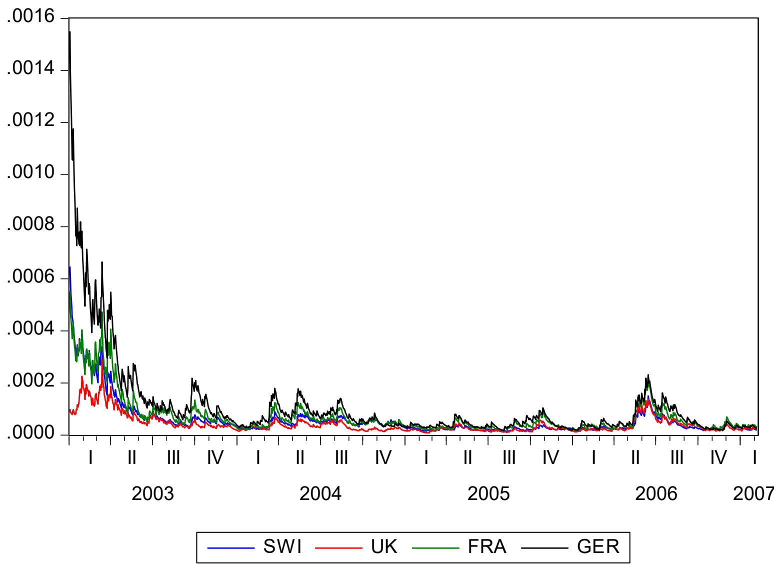
Chart 5.2 The conditional variances for stock markets out of EU



Source: by Author

As shown in Chart 5.2, it describes the conditional variances for Swiss and British stock markets before crisis. To be more specific, the highest conditional variances Swiss and British stock markets were about 0.00065 and 0.0001on January 1, 2003 respectively, which were probably caused by the bubble of dot-com. Nevertheless, there was a dramatic decline from the January 1, 2003 to May of 2003 in Swiss stock market. And there was a steep fall of conditional variance between around 0.0003 and 0.00005 from March of 2003 to July of 2003 in British stock market. Further, after the July of 2003, the conditional variances in both stock markets were lower than 0.0001 with modest volatility.

Chart 5.3 The conditional variances for all stock markets



Source: by Author

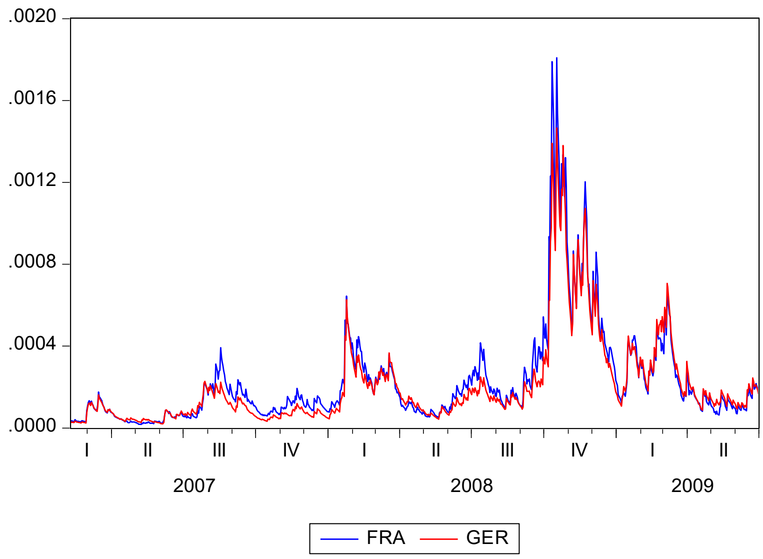
It is manifest from the Chart 5.3 that the conditional variances for all chosen stock markets were illustrated before the global financial crisis. To be more precise, the bubble of dot-com possible had a stronger effect in EU stock markets in 2003. Besides, the conditional variances for French and German stock markets were always higher than the conditional variances for Swiss and British stock markets, which means there was relatively obvious volatility in EU stock markets compared with stock markets out of EU.

5.1.2 Crisis Period

In this section, the conditional variances for all stock markets will be analyzed and compared from the February 8, 2007 to June 30, 2009.

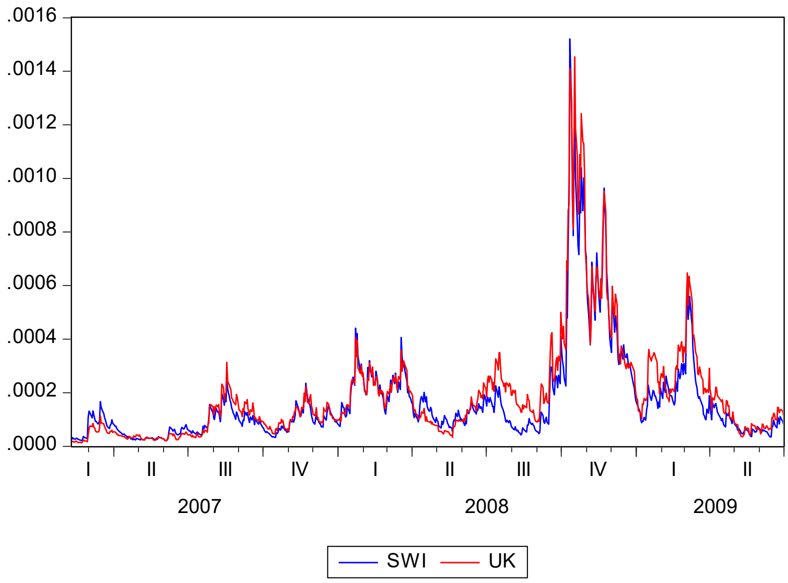
As shown in the Chart 5.4, it illustrates the conditional variances for French and German stock markets during crisis period. To be more exact, the conditional variances in both stock markets had stronger volatility in this period than in pre-crisis period. Moreover, between February 8, 2007 and August of 2008, the conditional variances reached the peak at 0.0007 on January of 2008, which was almost 7 times than in pre-crisis period. After January of 2008, the conditional variance of French stock market shot up from 0.0001 to 0.0018 rapidly, as well as the conditional variance of German stock market soared from 0.0001 to 0.0015 substantially. However, after that, the conditional variances of both stock markets dramatically plunged to around 0.0001, which proved the crisis ended.

Chart 5.4 The conditional variances for stock markets in EU



Source: by Author

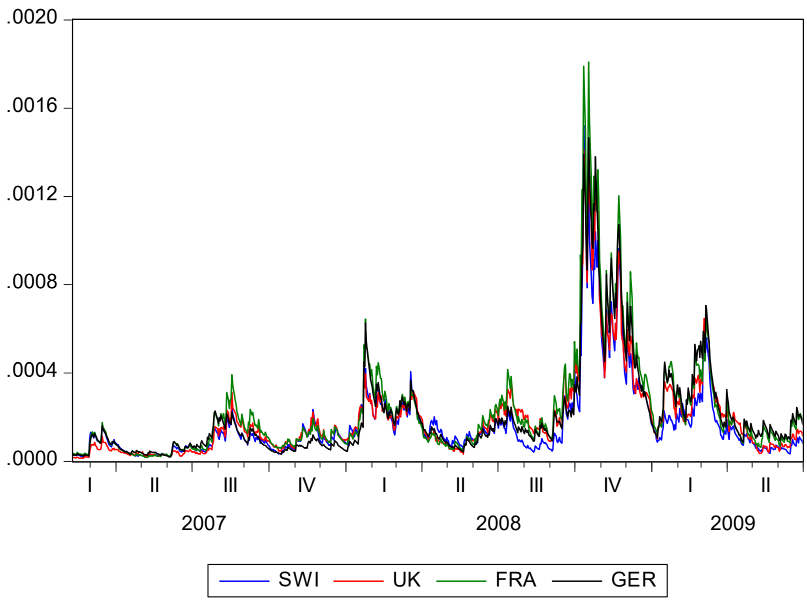
Chart 5.5 The conditional variances for stock markets out of EU



Source: by Author

According to the Chart 5.5, it indicates the conditional variances for Swiss and British stock markets during crisis period. More exactly, the conditional variances in both stock markets had stronger volatility in this period than in pre-crisis period. Moreover, between February 8, 2007 and September of 2008, the conditional variances reached the peak at 0.0004 on January of 2008, which was almost 8 times than in pre-crisis period. After January of 2008, the conditional variances of both stock markets shot up from 0.0001 to 0.0015 rapidly. However, after that, the conditional variances of both stock markets dramatically plunged to lower than 0.0001, which were almost same as before crisis.

Chart 5.6 The conditional variances for all stock markets



Source: by Author

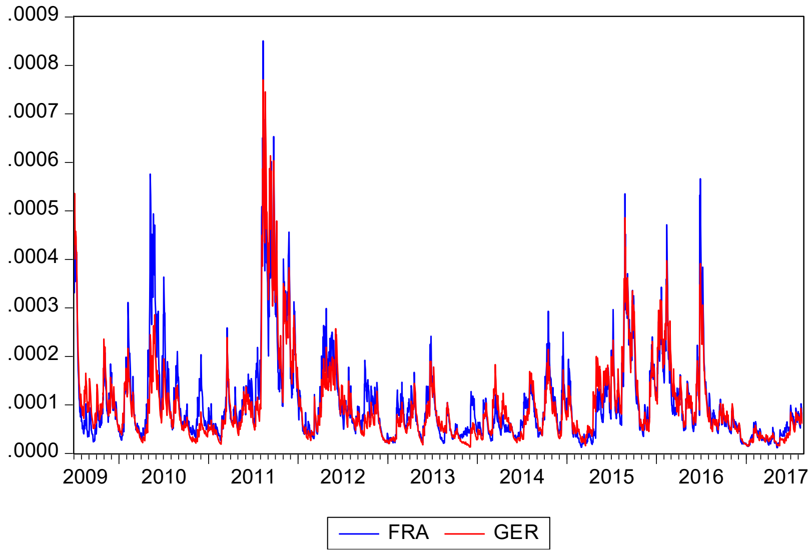
As can be seen from the Chart 5.6, the conditional variances for all chosen stock markets were described in the global financial crisis. More specifically, it does not matter if the stock market was from EU or not, the volatility was almost same in each stock market, which means the global financial crisis had a severe influence in all stock markets.

5.1.3 Post-Crisis Period

In this part, the conditional variances for all stock markets will be analyzed and compared from the July 1, 2009 to August 22, 2017.

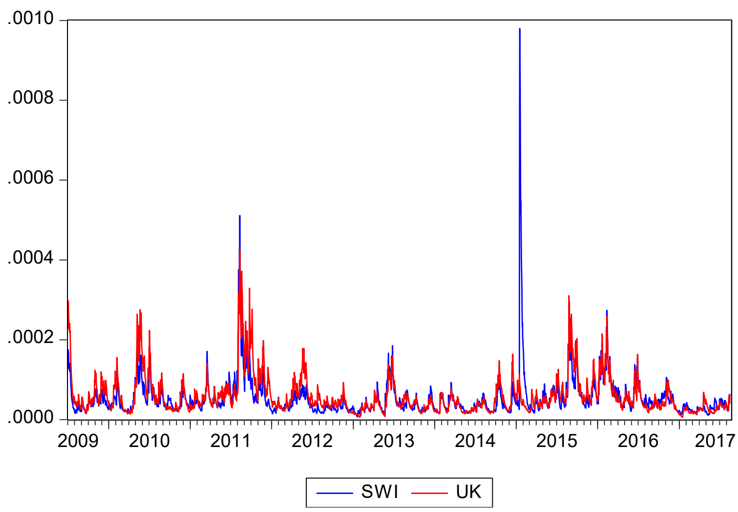
As can be seen from the Chart 5.7, it describes the conditional variances for French and German stock markets after the crisis period. More exactly, the trend of the volatility was almost same in two stock markets, and the conditional variances were between 0 to 0.0008 approximately, which was a half of the highest conditional variance for each stock market in crisis period.

Chart 5.7 The conditional variances for stock markets in EU



Source: by Author

Chart 5.8 The conditional variances for stock markets out of EU

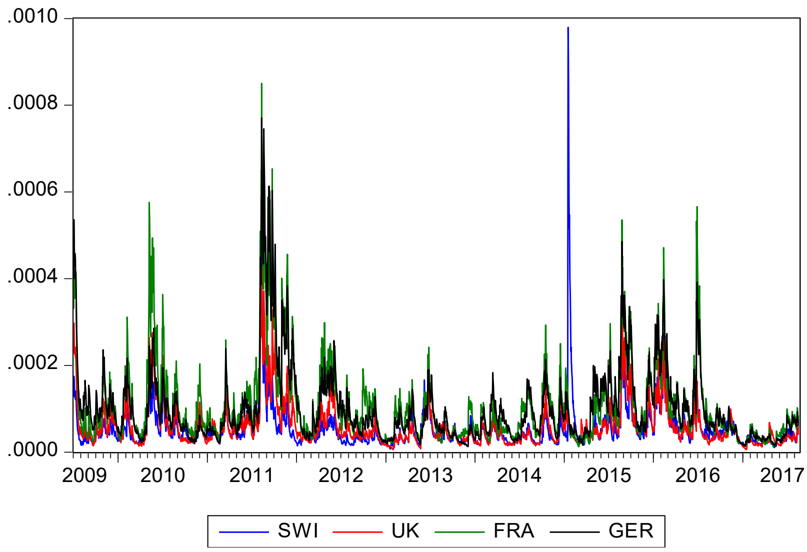


Source: by Author

As show in the Chart 5.8, it indicates the conditional variances for Swiss and British stock markets after crisis period. More specifically, the volatilities in two chosen stock markets had a nearly consistent degree. However, in the beginning of 2015, the conditional variance of Swiss stock market had a substantial increase from around 0.00002 to 0.001; then it plunged to approximately 0.00002 significantly in the February of 2015. It was because that the Swiss franc shot up and the stock market briefly collapsed when on January 15, 2015.

As can be seen from the Chart 5.9, the conditional variances for all chosen stock markets were described after the global financial crisis. To be more specific, it does not matter if the stock market was from EU or not, the trend of volatility was almost same in each stock market. Moreover, the conditional variances of French and German stock markets were always higher than the conditional variances of Swiss and British stock markets.

Chart 5.9 The conditional variances for all stock markets



Source: by Author

5.2 Estimation of Price Volatility Spillover Models

In this subchapter, the estimation of VAR models will be used for pre-crisis period, crisis period and post-crisis period as defined in subchapter 3.4. The daily indexes are not stationary. Here will use the logarithmic returns of daily indexes, which are stationary, to represent the results. Furthermore, the tables below will only show the data that rejects the null hypothesis at 5% significance level. This thesis chooses six indexes to analyze the estimation of VAR models, and all results will be shown at the end of the thesis (Annexes 2). The lag length was always based on the values of Akaike Information Criterion.

5.2.1 Pre-Crisis Period

In this section, the estimation of VAR (7) model will be used for pre-crisis period. As can be seen from the Table 5.1, it describes relationships among six indexes, with 7 lagged of each index, and in this table, there just are the returns that are statistically significant at 5%

confidence level.

Table 5.1 VAR (7) model for pre-crisis period

	CAC_R		DAX_R		UKX_R		SMI_R
CAC_R (-7)	0.389350	DAX_R (-1)	-0.215192	CAC_R (-6)	-0.197435	CAC_R (-6)	-0.216506
DAX_R (-4)	-0.239867	DAX_R (-4)	-0.349531	CAC_R (-7)	0.239084	CAC_R (-7)	0.410422
EUR_R (-4)	0.481953	EUR_R (-4)	0.588265	DAX_R (-1)	-0.106386	DAX_R (-4)	-0.15191
EUR_R(-6)	0.308581	UKX_R (-1)	-0.235036	DAX_R (-4)	-0.215225	DAX_R (-6)	-0.195327
EUR_R (-7)	-0.449779	UKX_R (-2)	-0.170444	EUR_R (-4)	0.273352	EUR_R (-6)	0.384055
UKX_R (-1)	-0.192121	SPX_R (-1)	0.392066	UKX_R (-1)	-0.29918	EUR_R (-7)	-0.352713
UKX_R (-2)	-0.168036	SPX_R (-2)	0.232838	SPX_R (-1)	0.383602	UKX_R (-1)	-0.112176
SPX_R (-1)	0.443869	SPX_R (-3)	0.143132	SPX_R (-2)	0.139246	UKX_R (-2)	-0.121464
SPX_R (-2)	0.193017	SMI_R (-2)	0.152012	SPX_R (-3)	0.113328	SPX_R (-1)	0.393812
SPX_R (-3)	0.162819	SMI_R (-3)	-0.14408			SPX_R (-2)	0.148382
SPX_R (-5)	0.119473					SPX_R (-3)	0.111569
SMI_R (-2)	0.118891					SMI_R (-3)	-0.104636
						SMI_R (-4)	-0.127772
Adj. R^2	0.087187		0.071464		0.111432		0.095467
F-statistic	4.388502		3.730395		5.448959		4.744255

Source: by Author

More specifically, for return of CAC 40 Index, its own lagged value (-7) was an important independent variable. And there were five other stock indexes as the important independent variables, and it seemed the S&P 500 Index had a significant influence on it. For DAX 30 Index, its own lagged values (-1 and -4) were important independent variables. And there were four other stock indexes as the important independent variables, and it seemed the S&P 500 Index had a significant influence on it. For FTSE 100 Index, its own lagged value (-1) was an important independent variable. And there were four other stock indexes as the important independent variables, and it seemed the S&P 500 Index had a significant influence on it. For SMI 20, its own lagged values (-3 and -4) were important independent variables. And there were five other stock indexes were integrated with it. Compared those two spillover effects, except the European seventh lagged returns had negative effects on French and Swiss stock markets, all others were positive, and the US spillover effects were stranger than the European spillover effects.

Moreover, compared with the Euro stock market, it seemed that the American stock market played a pivotal role in all other chosen stock markets. Furthermore, cause the adjusted R^2 (between 7% to 11%) were too low, the VAR model was not capable to account for all variability in chosen stock markets.

5.2.2 Crisis Period

Table 5.2 VAR (9) model for crisis period

	CAC_R		DAX_R		UKX_R		SMI_R
CAC_R (-1)	-0.543342	CAC_R (-1)	-0.623127	CAC_R (-1)	-0.406559	CAC_R (-4)	0.396039
CAC_R (-9)	0.450591	CAC_R (-2)	0.409731	CAC_R (-9)	0.408737	DAX_R (-3)	0.330992
DAX_R (-2)	0.301288	CAC_R (-4)	0.438904	DAX_R (-2)	0.278614	DAX_R (-4)	0.272211
DAX_R (-4)	0.268223	CAC_R (-9)	0.462844	DAX_R (-3)	0.279693	DAX_R (-7)	0.432451
DAX_R (-7)	0.493888	DAX_R (-7)	0.399807	DAX_R (-4)	0.282914	DAX_R (-8)	0.295428
DAX_R (-8)	0.457892	EUR_R (-2)	-0.562571	DAX_R (-7)	0.457751	EUR_R (-4)	-0.692729
EUR_R (-2)	-0.521491	EUR_R (-4)	-0.682672	DAX_R (-8)	0.396731	EUR_R (-8)	-0.511034
EUR_R (-4)	-0.663075	SPX_R (-1)	0.327132	UKX_R (-5)	-0.216959	SPX_R (-1)	0.386094
SPX_R (-1)	0.423652	SPX_R (-2)	0.213893	EUR_R (-4)	-0.751199	SPX_R (-2)	0.231138
SPX_R (-2)	0.243042	SPX_R (-3)	0.337338	SPX_R (-1)	0.422268	SPX_R (-3)	0.295429
SPX_R (-3)	0.379646	SPX_R (-4)	0.172929	SPX_R (-2)	0.239995	SPX_R (-4)	0.128019
SPX_R (-4)	0.184030	SPX_R (-5)	0.119642	SPX_R (-3)	0.361225	SPX_R (-5)	0.145939
SPX_R (-5)	0.132073	SPX_R (-6)	0.111151	SPX_R (-4)	0.199072	SPX_R (-6)	0.144978
SPX_R (-6)	0.144535	SPX_R (-7)	0.194922	SPX_R (-5)	0.135929	SPX_R (-7)	0.217376
SPX_R (-7)	0.202306	SPX_R (-8)	0.165360	SPX_R (-6)	0.118876	SPX_R (-8)	0.131319
SPX_R (-8)	0.146826	SMI_R (-4)	-0.171392	SPX_R (-7)	0.224219	SPX_R (-9)	0.119281
SPX_R (-9)	0.099173	SMI_R (-8)	-0.255014	SPX_R (-8)	0.159620	SMI_R (-8)	-0.160982
SMI_R (-8)	-0.199352	SMI_R (-9)	-0.188661	SPX_R (-9)	0.128124	SMI_R (-9)	-0.170845
SMI_R (-9)	-0.185958			SMI_R (-8)	-0.15207		
Adj. R^2	0.251245		0.191478		0.268547		0.258965
F-statistic	6.424737		4.828676		6.935452		6.649665

Source: by Author

In this section, the estimation of VAR (9) model will be used for crisis period. As shown in the Table 5.2, it describes relationships among six indexes, with 9 lagged of each index, and in this table, there just are the results of rejecting the null hypothesis.

More specifically, for return of CAC 40 Index, its own lagged values (-1 and -9) were important independent variables. And there were four other stock indexes as the important independent variables, and it seemed the S&P 500 Index and DAX 30 had significant influences on it. For DAX 30 Index, its own lagged value (-7) was an important independent variable. And there were three other stock indexes as the important independent variables, and it seemed the S&P 500 Index and CAC 40 Index had significant influences on it. For FTSE 100 Index, its own lagged value (-5) was an important independent variable. And there were five other stock indexes as the important independent variables, and it seemed the S&P 500 Index and DAX 30 had significant influences on it. For SMI 20, its own lagged values (-8 and -9) were important independent variables. And there were four other stock indexes were integrated with it. and it seemed the S&P 500 Index and DAX 30 had significant influences on it. In addition, the US spillover effects were positive and influential, while the European spillover effects were negative and weak.

Moreover, compared with information of pre-crisis period, there were obvious relationships among chosen stock markets, and the American stock market and German stock market played pivotal roles in all other chosen stock markets during crisis period. Besides, the adjusted R^2 (from 19% to 27%) in this period were much higher than in pre-crisis period, which represented the level of adjusted R^2 are more significant in financial crisis. The VAR model could explain more proportion of variability in financial crisis.

5.2.3 Post-Crisis Period

In this section, the estimation of VAR (6) model will be used for crisis period. As shown in the Table 5.3, it describes relationships among six indexes, with 6 lagged of each index, and in this table, there just are the results of rejecting the null hypothesis.

More specifically, for return of CAC 40 Index, its own lagged value (-3) was an important independent variable. And there were two other stock indexes as the important independent variables, and it seemed the S&P 500 Index had a significant influence on it. For DAX 30 Index, there were three other stock indexes as the important independent variables, and it seemed the S&P 500 Index had a significant influence on it. For EURO STOXX 50 Index, there were three other stock indexes as the important independent variables, and it seemed the S&P 500 Index had a significant influence on it. For SMI 20, there were four other stock indexes were integrated with it, and it seemed the S&P 500 Index had a significant influence on it. Compared with the European market, the US spillover effects were much stranger and positive.

Table 5.3 VAR (6) model for post-crisis period

	CAC_R		DAX_R		UKX_R		SMI_R
CAC_R (-3)	-0.276256	CAC_R (-3)	-0.214714	EUR_R (-3)	0.170885	CAC_R (-3)	-0.182916
UKX_R (-6)	-0.130467	UKX_R (-6)	-0.169884	UKX_R (-1)	-0.088613	EUR_R (-3)	0.196754
SPX_R (-1)	0.372477	SPX_R (-1)	0.360533	UKX_R (-6)	-0.092491	UKX_R (-6)	-0.087227
SPX_R (-2)	0.143758	SPX_R (-2)	0.143529	SPX_R (-1)	0.359921	SPX_R (-1)	0.316554
SPX_R (-3)	0.114518	SPX_R (-3)	0.107188	SPX_R (-2)	0.139318	SPX_R (-2)	0.151915
				SPX_R (-3)	0.080688	SPX_R (-3)	0.099493
				SMI_R (-1)	-0.065304		
Adj. R^2	0.037349		0.037528		0.059198		0.056486
F-statistic	4.205141		4.221106		6.198108		5.945766

Source: by Author

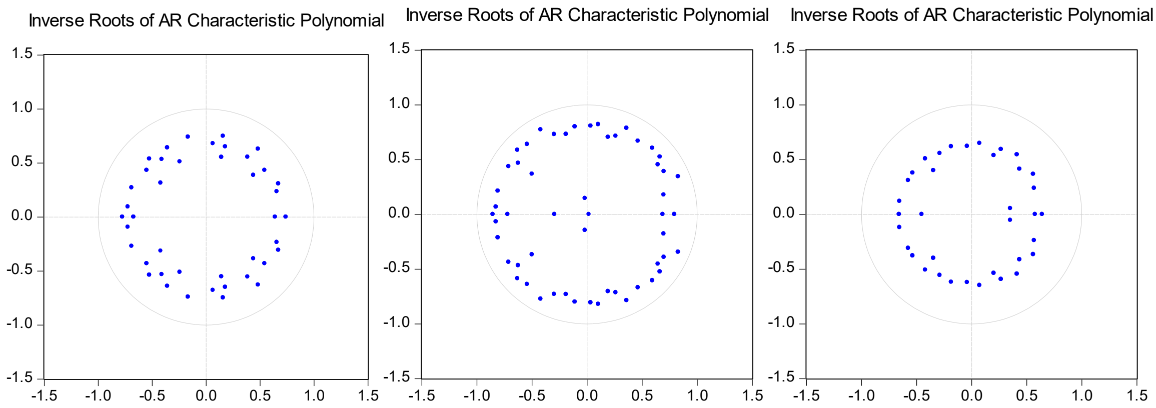
Furthermore, the S&P 500 Index influenced the behavior of investors in chosen stock markets during the post-crisis period. Hence, the American stock market played a pivotal role in all other chosen stock markets during this period. Besides, the adjusted R^2 (between 3% and 6%) turned back to small size after crisis. Therefore, the VAR model was not capable to account for all variability in chosen stock markets in this period.

In summary, the American stock market always played more important role in chosen stock market compared with the Eurozone stock market during chosen periods. Moreover, The VAR models just were capable to explain a portion of proportion of variability in crisis period.

For satisfying the stationary conditions, the VAR models should be used to identify the hysteresis p. The autocorrelation of the error term will be property severe if the lag is extremely small, which leads to the inconsistent estimations of parameters. On the one hand, the p-value, which is in VAR model, can eliminate the autocorrelation of the error term. On the other hand, if p-value is too big, the degree of freedom will be decline, moreover, it will impact the validity of the model parameter estimator. In summary, the p-value should be appropriate.

Besides, the estimated VAR is stationary if all roots have modulus less than one and lie inside the unit circle, vice versa. Therefore, as can be seen from the Chart 5.10, all roots were in the unit circle, which provided estimated VAR models were stationary during the chosen periods.

Chart 5.10 Inverse roots of AR characteristic polynomial during chosen periods



Source: by Author

5.3 Estimation of AR/EGARCH Volatility Spillover Models

In this subchapter, in the first place, the AR/EGARCH Volatility Spillover Model, as defined in the subchapter 3.5, is established to test the return and volatility spillover effect for all periods. Moreover, the joint Wald tests are used to test the robustness of the results in each model. Besides, the variance ratios will be applied for testing the quantified significance of the volatility spillover effect on each chosen stock market from the American and Eurozone stock markets. In addition, the level of significance is set as 5% in this model.

5.3.1 Pre-Crisis Period

In this section, the results of AR/EGARCH Volatility Spillover Model, Joint Wald Tests and variance ratio in pre-crisis period will be illustrated.

According to the equation (3.30) and (3.31), the results of parameters are showing in the Table 5.4 from the Annexes 3(a) – (d). It is manifest from this table that the summary statistics of chosen stock markets before crisis period by AR/EGARCH Volatility Spillover Model as well as the "*" in the table means the value is significant at 5% significant level.

More specifically, the lagged returns ($\phi_{1,i}$) of all chosen stock markets were negative or no 1st-order autocorrelation, while the statistics of lagged returns of Eurozone and British stock markets were significant. Moreover, the legged return of the US market (φ_i), affecting the return of each stock market, were all significant, whereas, the lagged return of the Eurozone market (δ_i), impacting the return for each stock market, were insignificant totally. Furthermore, the volatility spillover effects from the US market (μ_i), influencing the return for each stock market, were all significant except in the British stock market, also, the volatility spillover effects from the Eurozone market (ψ_i) were significant for four chosen stock markets. Besides, because the $\gamma_{1.i}$ of each stock market was negative, in spite of the parameters of German and Swiss stock markets were insignificant, the asymmetric volatility effects still existed. Except in the French stock market, the persistence of volatility was significant in other three stock markets.

Table 5. 4 Summary of AR/EGARCH volatility spillover models – pre-crisis period

	USA	EU	FRA	GER	UK	SWI
$\phi_{0,i}$	0.00007	0.00031*	0.00048*	0.00060*	0.00041*	0.00056*
$\phi_{1,i}$	-0.01668	-0.21237*	-0.02428	-0.01584	-0.05980*	-0.05549
φ_i	x	0.36083*	0.02173*	-0.02392*	0.05936*	0.06320*
δ_i	x	x	0.02123	0.01932	-0.00013	0.04285
μ_i	x	0.61115*	-0.03081*	0.03221*	0.01546	-0.05339*
ψ_i	x	x	0.97076*	1.04013*	0.62595*	0.73239*
ω_i	-0.00389	-0.16060*	-12.12448*	-0.07329*	-13.75275*	-6.58518*
$\theta_{1.i}$	-0.00264	0.06822*	0.31872*	0.06142*	0.31163*	0.31037*
$\gamma_{1.i}$	-0.04677*	-0.06489*	-0.10096*	-0.01220	-0.11656*	-0.03866
β_i	0.99944*	0.98919*	0.06839	0.99775*	-0.17236*	0.43388*

Source: by Author

As can be seen from Table 5.5, the results of the joint Wald tests for four different hypotheses are indicated. The first null hypothesis is: H_0^1: $\varphi_i = \delta_i = 0$ (no mean spillover effect); secondly, the null hypothesis is: H_0^2: $\mu_i = \psi_i = 0$ (no volatility spillover effect); then, the null hypothesis is: H_0^3: $\varphi_i = \mu_i = 0$ (no the American spillover effect); lastly, the null hypothesis is: H_0^4: $\delta_i = \mu_i = 0$ (no the Eurozone spillover effect).

More specifically, for the first joint Wald test, it does not matter testing by *F* test or Chi test, parameters of German stock market accepted the H_0^1, which means no mean spillover effects in German stock market. for the second, third and fourth joint Wald test, all parameters of all chosen stock markets rejected the H_0^2 for two tests, which means all stock markets had volatility spillover effects from the US and Eurozone markets.

Table 5. 5 Joint Wald Tests of AR/EGARCH models – pre-crisis period

		FRA	GER	UK	SWI
Wald 1 (No mean spillover effects)	F-statistic	4.4079	2.4398	9.4684	12.2954
	Probability	0.0123	0.0875	0.0001	0.0000
	Chi-square	8.8158	4.8795	18.9368	21.5908
	Probability	0.0122	0.0872	0.0001	0.0000
Wald 2 (No volatility spillover effects)	F-statistic	36399.08	13404.34	4334.994	4036.660
	Probability	0.0000	0.0000	0.0000	0.0000
	Chi-square	72798.15	26808.67	8669.988	8073.321
	Probability	0.0000	0.0000	0.0000	0.0000
Wald 3 (No US spillover effects)	F-statistic	19.6356	10.1139	8.8565	17.3109
	Probability	0.0000	0.0000	0.0002	0.0000
	Chi-square	39.2711	20.2278	17.7129	34.6218
	Probability	0.0000	0.0000	0.0001	0.0000
Wald 4 (No European spillover effects)	F-statistic	22321.38	10243.94	2576.708	2615.296
	Probability	0.0000	0.0000	0.0000	0.0000
	Chi-square	44642.76	20487.88	5153.417	5230.592
	Probability	0.0000	0.0000	0.0000	0.0000

Source: by Author

Table 5. 6 Variance ratios of AR/EGARCH models – pre-crisis period

		FRA	GER	UK	SWI
VR_USA	Mean	0.261	0.276	0.421	0.468
	St. dev.	0.406	0.427	0.627	0.651
VR_EUR	Mean	0.154	0.182	0.128	0.215
	St. dev.	0.231	0.256	0.186	0.351
VR_*i*-th country	Mean	0.585	0.542	0.451	0.317
	St. dev.	0.781	0.742	0.638	0.486

Source: by Author

According to the equation (3.36), (3.37) and (3.38), the results of variance ratios for each stock market are showing in the Table 5.6. To be more specific, for French, German and British stock markets, the local volatility spillover effect was the most conditional variance of unexpected return, which was 0.585, 0.542 and 0.451 respectively; the US volatility spillover effect – 0.261, 0.276 and 0.421 respectively, was relatively small compared to the local effect;

while, the Eurozone volatility spillover effect was the smallest in those three stock markets (0.154, 0.182 and 0.128 respectively). For Swiss stock market, the most conditional variance of unexpected return was from the US volatility spillover effect (0.468), then it was the local volatility spillover effect (0.317), the Eurozone volatility spillover effect still was the last one (0.215).

5.3.2 Crisis Period

In this section, all conditions and explanations were shown in Subchapter 5.3.1. And the results of parameters in crisis period are showing in the Table 5.7 from the Annexes 3(e) – (h).

Table 5.7 Summary of AR/EGARCH volatility spillover models – crisis period

	USA	EU	FRA	GER	UK	SWI
$\phi_{0,i}$	0.00011	-0.00037	-0.00043*	-0.00001	-0.00013	-0.00052*
$\phi_{1,i}$	-0.12516*	-0.17961*	-0.00479	0.04166	-0.04254	0.01188
φ_i	x	0.26897*	0.02925*	-0.02329*	0.05455*	0.06707*
δ_i	x	x	-0.00772	-0.01176	-0.00655	-0.00892
μ_i	x	0.12883*	-0.00101	0.02282*	0.02714*	0.04078*
ψ_i	x	x	0.99153*	0.94487*	0.83891*	0.70370*
ω_i	-0.10832*	-0.16235*	-11.5589	-0.82011*	-11.92646*	-11.83917*
$\theta_{1.i}$	0.04167*	0.06766*	0.01000	0.25180*	0.49009*	0.49242*
$\gamma_{1.i}$	-0.11138*	-0.12473*	0.01000	0.03039	-0.02609	-0.05999
β_i	0.99100*	0.98739*	0.01000	0.94506*	-0.08798	-0.10344

Source: by Author

More specifically, the lagged returns ($\phi_{1,i}$) of all chosen stock markets were no 1^{st}-order autocorrelation, while the statistics of lagged returns of Eurozone and US stock markets were significant. Moreover, the parameters of legged return of the US market (φ_i) were all significant and positive except it was negative in German stock market, whereas, the parameters of legged return of the Eurozone market (δ_i) were negative and insignificant totally. Furthermore, the parameters of volatility spillover effects from the US market (μ_i) were all positive and significant except in the French stock market, also, the parameters of volatility spillover effects from the Eurozone market (ψ_i) were positive and significant for four chosen stock markets. Besides, in spite of the parameters of all chosen stock markets were insignificant, the asymmetric volatility effects still existed in the British and Swiss stock markets. Except in the German stock market ($\beta_i = 0.945$), the persistence of volatility was insignificant in each stock market.

Table 5.8 Joint Wald Tests of AR/EGARCH volatility spillover models – crisis period

		FRA	GER	UK	SWI
Wald 1 (No mean spillover effects)	F-statistic	7.7259	3.6054	11.0214	14.4984
	Probability	0.0005	0.0276	0.0000	0.0000
	Chi-square	15.4519	7.2107	22.0428	28.9968
	Probability	0.0004	0.0272	0.0000	0.0000
Wald 2 (No volatility spillover effects)	F-statistic	18021.51	16516.16	8958.953	4501.540
	Probability	0.0000	0.0000	0.0000	0.0000
	Chi-square	36043.02	33032.31	17917.91	9003.081
	Probability	0.0000	0.0000	0.0000	0.0000
Wald 3 (No US spillover effects)	F-statistic	9.5700	16.7489	11.1046	14.9681
	Probability	0.0001	0.0000	0.0000	0.0000
	Chi-square	19.1401	33.4979	22.2092	29.9393
	Probability	0.0001	0.0000	0.0000	0.0000
Wald 4 (No European spillover effects)	F-statistic	18021.51	8366.165	4035.008	1965.213
	Probability	0.0000	0.0000	0.0000	0.0000
	Chi-square	36043.02	16732.33	8070.015	3930.427
	Probability	0.0000	0.0000	0.0000	0.0000

Source: by Author

The results of joint Wald tests in crisis period are showing in the Table 5.8. For the all joint Wald tests, all parameters of all chosen stock markets rejected the H_0^2 for two tests, which means all stock markets had volatility spillover effects from the US and Eurozone markets.

Table 5.9 Variance ratios of AR/EGARCH volatility spillover models – crisis period

		FRA	GER	UK	SWI
VR_USA	Mean	0.316	0.303	0.385	0.398
	St.dev.	0.396	0.358	0.472	0.509
VR_EUR	Mean	0.084	0.157	0.178	0.192
	St.dev.	0.120	0.241	0.268	0.302
VR_*i*-th country	Mean	0.644	0.540	0.437	0.410
	St.dev.	0.862	0.728	0.631	0.617

Source: by Author

As shown in the Table 5.9, it indicates the results of variance ratios in crisis period. To be more exact, the local volatility spillover effect was the most conditional variance of unexpected return for four stock markets, and the proportion of variance ratios rose compared with before crisis period, accounting for 0.644, 0.540, 0.437 and 0.410 in French, German, British and Swiss stock markets respectively. Moreover, the proportion of variance ratios for the US volatility spillover effect was also rose to 0.316, 0.303 and 0.385 in French, German and British stock markets respectively, while, it decreased to 0.398 in Swiss stock markets. Besides, the variance ratios of Eurozone volatility spillover effect still were the lowest one in each stock market.

5.3.3 Post-Crisis Period

In this portion, all conditions and hypotheses were shown in Subchapter 5.3.1. And the results of parameters in crisis period are showing in the Table 5.10 from the Annexes 3(i) – (l).

Table 5.10 Summary of AR/EGARCH volatility spillover models – post-crisis period

	USA	EU	FRA	GER	UK	SWI
$\phi_{0,i}$	0.00036*	0.00004	0.00001*	0.00023*	0.00015*	0.00017*
$\phi_{1,i}$	-0.03068	-0.13829*	0.01437	0.04971*	-0.02688	0.00081
φ_i	x	0.23801*	0.24941*	0.23408*	0.24233*	0.20381*
δ_i	x	x	-0.15423*	-0.17070*	-0.11539*	-0.07808*
μ_i	x	0.95454*	0.93941*	0.88516*	0.68204*	0.58326*
ψ_i	x	x	0.95035*	0.88695*	0.55018*	0.53395*
ω_i	-0.27716*	-12.24440*	-15.7555*	-12.38794*	-13.03210*	-12.59789*
$\theta_{1.i}$	0.08078*	0.36115*	0.31335*	0.30110*	0.37934*	0.39877*
$\gamma_{1.i}$	-0.16215*	-0.00442	-0.01602	-0.01294	-0.02218	-0.01999
β_i	0.97882*	-0.21279*	-0.22586*	-0.03809	-0.1356*	-0.10763*

Source: by Author

More precisely, the lagged returns ($\phi_{1,i}$) of all chosen stock markets were no 1st-order autocorrelation, whereas the statistics of lagged returns of Eurozone and German stock markets were significant. Moreover, the parameters of legged return of the US market (φ_i), were significant and positive in all chosen stock market, whereas, the parameters of legged return of the Eurozone market (δ_i), were negative and significant totally. Furthermore, the parameters of volatility spillover effects from the US market (μ_i) were all positive and significant, also, the volatility spillover effects from the Eurozone market (ψ_i) were positive and significant for four chosen stock markets. Besides, in spite of the parameters of all chosen stock markets were insignificant, the asymmetric volatility effects still existed in all stock markets. Except in the German stock market, the persistence of volatility was significant in each other stock market, even though they were too low.

The results of joint Wald tests after crisis period are showing in the Table 5.11, which were really same as the results in crisis period. For the all joint Wald, all stock markets had volatility spillover effects from the US and Eurozone markets.

Table 5.11 Joint Wald Tests of AR/EGARCH models – post-crisis period

		FRA	GER	UK	SWI
Wald 1 (No mean spillover effects)	F-statistic	1208.493	434.8963	294.4104	177.9683
	Probability	0.0000	0.0000	0.0000	0.0000
	Chi-square	2416.985	869.7926	588.8208	355.9366
	Probability	0.0000	0.0000	0.0000	0.0000
Wald 2 (No volatility spillover effects)	F-statistic	95539.16	31671.48	10693.08	8175.616
	Probability	0.0000	0.0000	0.0000	0.0000
	Chi-square	191078.3	63342.97	21386.17	16351.23
	Probability	0.0000	0.0000	0.0000	0.0000
Wald 3 (No US spillover effects)	F-statistic	40615.79	15117.52	6139.329	4028.268
	Probability	0.0000	0.0000	0.0000	0.0000
	Chi-square	81231.58	30235.05	12278.66	8056.537
	Probability	0.0000	0.0000	0.0000	0.0000
Wald 4 (No European spillover effects)	F-statistic	47394.23	16088.97	4114.200	3556.617
	Probability	0.0000	0.0000	0.0000	0.0000
	Chi-square	94788.47	32177.94	8228.399	7113.234
	Probability	0.0000	0.0000	0.0000	0.0000

Source: by Author

As can be seen from the Table 5.12, it describes the results of variance ratios after crisis period. More exactly, the US volatility spillover effect, taking the place of the local volatility spillover effect, was the most conditional variance of unexpected return for four stock markets, accounting for 0.647, 0.605, 0.624 and 0.523 in French, German, British and Swiss stock markets respectively. Moreover, the proportion of variance ratios for the Eurozone volatility spillover effect was also rose to 0.238, 0.286 and 0.215 in French, German and British stock markets respectively, while, it decreased to 0.157 in Swiss stock markets. Besides, the variance ratios of local volatility spillover effect changed a lot in each stock market.

Table 5.12 Variance ratios of AR/EGARCH models – post-crisis period

		FRA	GER	UK	SWI
VR_USA	Mean	0.647	0.605	0.624	0.523
	St. dev.	0.786	0.726	0.758	0.653
VR_EUR	Mean	0.238	0.286	0.215	0.157
	St. dev.	0.228	0.304	0.245	0.189
VR_*i*-th	Mean	0.115	0.109	0.226	0.320
	St. dev.	0.116	0.127	0.274	0,368

Source: by Author

5.5 Summary of Results

This chapter used the VAR and AR/EGARCH models to estimate the price and volatility spillover effects with the theories described in the chapter 3. Having considered all the estimations and analyses above, in the first place, the EGARCH model was used to estimate the volatility of each stock market in each period. Compared with those four stock markets, the volatilities of stock markets in EU always were higher a little bit than the volatilities of stock markets out of EU in each period. Moreover, compared the three periods, the global financial crisis caused violent volatility the most in each stock market.

Then, there were two spillover models, the VAR and AR/EGARCH models, to estimate the price and volatility spillover effects between two markets (the US and Eurozone stock markets) and four stock markets (German, French, Swiss and British stock markets).

For the VAR model, it is obviously that the US stock market was more influential than Eurozone stock markets for four stock markets. In addition, the US volatility spillover effect impacted four stock markets the most during the global financial crisis. Moreover, as can be seen from the Table 5.13, for the pre-crisis period, whereas the European market had positive and negative effects both as well as had slight influence, the US spillover effects were positive and more influential. In the crisis period, the European spillover effects were negative and slight, while the US spillover effects were positive and much stranger. For post-crisis period, even the European and US spillover effects were both positive, the European spillover effects could be ignored compared with the US spillover effects.

Table 5.13 Summary of VAR models

EU-Sp-Ef/US-Sp-Ef	France	Germany	Britain	Switzerland
Pre-crisis period	+,-/++	+/++	+/++	+,-/++
Crisis period	-/+++	-/+++	-/+++	-/+++
Post-crisis period	×/++	×/++	+/++	+/++

Source: by Author

"+": positive effect; "++": stranger than "+"; "+++": stranger than "++"; "-": negative effect; "×": do not have effect.

For AR/EGARCH model, whereas most of the US effects were positive, most of the Eurozone effects were negative for four stock markets in crisis and post-crisis periods, besides, the US mean spillover was greater than the Eurozone stock market for all stock markets in all periods. However, the Eurozone volatility spillover had been greater than the US volatility spillover for all stock market until post-crisis period, in which the two markets volatility spillover effects were almost same.

Table 5.14 Summary of comparing the parameters of AR/EGARCH Models

	Pre-crisis period	Crisis period	Post-crisis period
$\|\varphi_i\|$	$\|\varphi_{Sw}\|>\|\varphi_{UK}\|>\|\varphi_{Ge}\|>\|\varphi_{Fr}\|$	$\|\varphi_{Sw}\|>\|\varphi_{UK}\|>\|\varphi_{Fr}\|>\|\varphi_{Ge}\|$	$\|\varphi_{Fr}\|>\|\varphi_{UK}\|>\|\varphi_{Ge}\|>\|\varphi_{Sw}\|$
$\|\delta_i\|$	$\|\delta_{Sw}\|>\|\delta_{Fr}\|>\|\delta_{Ge}\|>\|\delta_{UK}\|$	$\|\delta_{Ge}\|>\|\delta_{Sw}\|>\|\delta_{Fr}\|>\|\delta_{UK}\|$	$\|\delta_{Ge}\| > \|\delta_{Fr}\|>\|\delta_{UK}\|>\|\delta_{Sw}\|$
$\|\mu_i\|$	$\|\mu_{Sw}\|>\|\mu_{Ge}\|>\|\mu_{Fr}\|>\|\mu_{UK}\|$	$\|\mu_{Sw}\|>\|\mu_{UK}\|>\|\mu_{Ge}\|>\|\mu_{Fr}\|$	$\|\mu_{Fr}\|>\|\mu_{Ge}\|>\|\mu_{UK}\|>\|\mu_{Sw}\|$
$\|\psi_i\|$	$\|\psi_{Ge}\|>\|\psi_{Fr}\|>\|\psi_{Sw}\|>\|\psi_{UK}\|$	$\|\psi_{Fr}\|>\|\psi_{Ge}\|>\|\psi_{UK}\|>\|\psi_{Sw}\|$	$\|\psi_{Fr}\|>\|\psi_{Ge}\|>\|\psi_{UK}\|>\|\psi_{Sw}\|$

Source: by Author

Besides, as can be seen in the Table 5.14, European volatility spillover effects always had larger influence in German and French stock market in all periods basically, while the US mean and volatility spillover effects always had greater influence in Swiss and British stock markets except post-crisis period normally. With the time going on, we can see, the European and US spillover effects were partial to EU stock markets (German and French stock markets) gradually.

Table 5.15 Summary of Joint Wald Tests

Pre-crisis/crisis/post-crisis	France	Germany	Britain	Switzerland
Mean spillover effect	Y/Y/Y	N/Y/Y	Y/Y/Y	Y/Y/Y
Volatility spillover effect	Y/Y/Y	Y/Y/Y	Y/Y/Y	Y/Y/Y
US spillover effect	Y/Y/Y	Y/Y/Y	Y/Y/Y	Y/Y/Y
European spillover effect	Y/Y/Y	Y/Y/Y	Y/Y/Y	Y/Y/Y

Source: by Author

"Y": has effect; "N": does not have effect.

Table 5.16 Summary of mean of Variance ratios

	France	Germany	Britain	Switzerland
Pre-crisis	Fr>US>EU	Ge>US>EU	Br>US>EU	US>Sw>EU
Crisis	Fr(↑)>US(↑)>EU(↓)	Ge(Δ)> US(↑)>EU(↓)	Br(↑)> US(↓)>EU(↑)	Sw(↑)> US(↓) >EU(↓)
Post-crisis	US(↑)>EU(↑)>Fr(↓)	US(↑)>EU(↑)>Ge(↓)	US(↑)>Br(↓)>EU(↑)	US(↑)>Sw(↓)>EU(↓)

Source: by Author

"↑": higher compared with last period; "↓": lower compared with last period.

Furthermore, after the joint Wald tests, we can see from the Table 5.15, all effects had in all stock markets in all periods except the mean spillover effects for German stock market in pre-crisis period.

Moreover, in the Table 5.16, the local volatility spillover effects had the biggest proportion for each stock market before post-crisis period. However, the US volatility spillover effects replaced the local volatility spillover effects to be the most important. Besides, except the Swiss stock market, the EU spillover effects were more influential in all other stock markets after crisis.

6 Conclusion

Nowadays, with progressing rapidly on various fronts of human society, financial integration is becoming a significant goal of the finance as well as the stock market plays an increasingly critical role in financial market. Thus, researching and analyzing the financial integration is an important step to improve the global finance. The volatility spillover effect is essential tool to present financial integration. To be more specific, the more influential the volatility spillover effect is, the deeper the degree of financial integration is. Hence, the volatility spillover effect is increasingly prevalent in the contemporary world.

Including the introduction, in which the briefly stated the focus of the thesis as well as summarized the main content of each chapter, and conclusion, there was six parts totally. The chapter 2 described the fundamental characteristics of financial markets and financial time series. The chapter 3 illustrated the basic theories and formulas of methodologies for estimating price and volatility spillover effects. The chapter 4 indicated the sample description of data and preliminary analysis of chosen stock markets. The chapter 5 was the most significant part in this thesis, in which the price and volatility spillover effects were estimated and tested.

The goal of the thesis was to estimate the price and volatility spillover effects among US and Eurozone stock markets and four local stock markets by using VAR and AR/EGARCH models in three periods. More precisely, in the first step, the price spillover effects were used to estimate based on VAR model. In the next step, the univariate non-linear volatility models were estimated for each market and subperiod. Finally, the shocks in US and Eurozone as estimated by univariate non-linear models were utilized in AR/EGARCH model in order to estimate price and volatility spillover effects in selected European stock market and variance ratios were computed.

Based on all the arguments offered above, the main goal of the thesis was fulfilled. The price and volatility spillover effects were quit distinguishing among investigated stock markets in the three periods. More specifically, the volatility of US and European stock markets affected the volatility of four investigated local stock markets in each period. And after the global financial crisis, the effects were more influential among investigated stock markets, it probably caused by the one step closer of the global integration.

Moreover, about the former sub-goal, the VAR models were built as well as the price spillover effects were measured. More specifically, the VAR (7) model, VAR (9) model and VAR (6) model were built to estimate the price spillover effects in three subperiods respectively. In addition, compared with pre-crisis and post-crisis periods, the Eurozone stock market had negative influences in all investigated stock markets in crisis period, an obvious difference of European spillover effects. Besides, even the US spillover effects in all subperiods were positive, however, it had much more influential in crisis period. Finally, after compared, the European spillover effects were much weaker than the US spillover effects in all investigated stock markets in all subperiods.

In terms of the latter sub-goal, it was estimated that an impact volatility spillover effects on investigated stock markets in three subperiods. To be more specific, firstly, the AR/EGARCH model could be made in all investigated stock markets in all subperiods, as well as, except the European mean spillover effects, all other spillover effects were significant in given stock markets. Secondly, the US spillover effects were more and more influential in investigated stock markets by computed variable ratios from the beginning of 2003 to August of 2017, whereas, the European spillover effects were less and less important.

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List of Abbreviations

ARCH Model: Autoregressive Conditional Heteroskedasticity Model

DJIA: Dow Jones Industrial Average Index

EGARCH Model: Exponential Generalized Autoregressive Conditional Heteroskedasticity Model

EMU: European Monetary Union

EU: European Union

FSE: Frankfurt Stock Exchange

GARCH Model: Generalized Autoregressive Conditional Heteroskedasticity Model

GDP: Gross Domestic Product

IPO: Initial Public Offerings

LSE: London Stock Exchange

MATIF: Financial Futures Market

MONEP: Financial Options Market

VAR Model: Vector Autoregressions Model

WWII: World War II

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Ostrava dated 27/4/2018

Bc. Lingling Ding

Student's name and surname

List of Annexes