How the GARCH structure of the GBP has changed after the EU referendum and did the releases of Brexit news impacted the volatility of the GBP?

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Brexit and the volatility of the GBP

How the GARCH structure of the GBP has changed after the EU referendum and did the releases of Brexit news impacted the volatility of the GBP?

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EXECUTIVE SUMMARY

During these last three years, the term Brexit takes up the front page of many newspapers. This term refers to the decision of the British population to leave the European Union. Nonetheless, this Brexit term is also associated with the term uncertainty. The decision to leave will reshape the economic relationship between the EU and the UK. Moreover, it should be emphasized that this business relationship accounts for 50% of the total international trade of the United Kingdom. Therefore, this could explain why the British financial markets were affected by a negative shock on the 24th of June 2016, the day of the Brexit announcement.

The purpose of this paper is to investigate on the relationship between the volatility of the British pound and the Brexit uncertainty. This research is tackled through two questions. The first question analyzes the change in the volatility structure of the GBP after the EU referendum. This volatility structure corresponds to the structure of one of the most famous volatility models, the GARCH model. Several methods are used in order to develop an answer. The second question focuses on the volatility of the post-referendum period and how this level of volatility has been impacted by the Brexit announcements. In order to answer to this question, several GARCH models are implemented.

Concerning the results of this research, it is demonstrated that the innovation terms have less impact in the volatility structure of the GBP in the post-referendum period and the unconditional variance of the post-referendum period is lower than the unconditional variance of the pre-referendum period. Then, through the implementation of several GARCH models, the results show that only the Brexit announcements that occurred between May 2018 and May 2019 impacted the volatility of the GBP.

The conclusion of this paper states that the reason why the Brexit announcements only had an impact during this last year could be explained through the fear of a no-deal. Therefore, the more the news related to the Brexit was closer to the settlement date of the Brexit, the more it impacted the volatility because nothing was still agreed. In the future, with Boris Johnson as new PM and who is a Eurosceptic, the volatility of the GBP may be expected to keep increasing.

Keyword: Brexit, exchange rate, event-study, volatility, GARCH

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LIST OF ABBREVIATIONS

AIC – Akaike Information Criteria

AR – Autoregressive

ARMA – Autoregressive Moving Average

ARCH – Autoregressive Conditional Heteroskedasticity

BIC – Bayesian Information Criteria

BOE – Bank of England

BOJ – Bank of Japan

Brexit – Refer to the withdrawal of UK from the EU

CAD – Canadian Dollar

CHF – Confoederatio Helvetica Franc

CUSUM – Cumulative Sum

DEK – Danish Krone

DJI – Dow Jones Index

EEC – European Economic Community

EGARCH – Exponential Generalized Autoregressive Conditional Heteroskedasticity

EU – European Union

EUR – Euro

FDI – Foreign Direct Investment

FED – The Federal Reserve System

FTSE 100 – The Financial Times Stock Exchange 100 Index

FTSE EUROTOP 100 - The Financial Times Stock Exchange European 100 Index

GARCH – Generalized Autoregressive Conditional Heteroskedasticity

GBP – British Pound

GDM – German Deutsche Mark

GDP – Gross Domestic Product

HQC – Hannan-Quinn Information Criteria

JPY – Japanese Yen

LM – Lagrange Multiplier

MA – Moving Average

M&A – Mergers and Acquisitions

NOK – Norwegian Krone

PM – Prime Minister

TS – Time Series

USD – United States Dollar

UK – United Kingdom

US – United States

VaR – Value at Risk

PREFACE

This research thesis was carried out as part of the Master's degree in Economic Sciences with a specialization in Finance, which is supervised by the HEC Liège, Management School of the University of Liège.

This research aims to shed light on the impact of the Brexit on the volatility of the British pound. First, through the GARCH model, the volatility structure is analyzed in order to see how this structure has changed after the EU referendum. Then, the Brexit announcements are added in a GARCH model through the use of a dummy variable in order to capture the impact of these announcements on the volatility of the GBP. This research stops at the 24^{th} May 2019.

An important point that the author would like to highlight is that the volatility of the British pound is investigated through two exchange rates, the EUR/GBP and the GBP/USD exchange rates. This choice comes from the fact the USA and the EU constitute the two most important trading partners of the UK with more than 50% of their international trade. Therefore, every time that the author mentions the volatility of the British pound, it will constitute the volatility of the two exchange rates, the EUR/GBP and the GBP/USD.

Furthermore, the programming languages used in order to proceed to this research are RStudio and MATLAB.

1. Introduction

On the 24th June 2016, the pound sterling plunged to a 31-year low and the British Stock Exchange index felt by more than 8% (Allen & Davies, 2016). On that day, the British financial markets were affected by a negative shock which is the result announcement of the EU referendum and against the odds, the UK decided to leave the EU (Tabeshian, 2018). Nowadays, no one can anticipate the future economic relationship between the UK and the EU. Furthermore, according to several economic reports, this uncertainty is reflected in the volatility of the British financial markets (Elliott, 2019).

Due to the recent nature of the Brexit, a few papers analyze the British stock market volatility related to this event. However, until now, nothing was investigated on the GBP volatility which results from the Brexit. This paper aims to investigate on the volatility of the British currency through two exchange rates, the EUR/GBP and the GBP/USD. This choice regarding the exchange rates analyzed is linked to the fact that the EU and the USA constitute the two main trading partners of the UK.

The first part of this paper is related to a short explanation on the Brexit and the economic relationship between the EU and the UK. Then, the literature review shows what has been written so far regarding the event-study in the volatility field. Afterwards, the data generated from the EUR/GBP and GBP/USD exchange rates are briefly explained as well as the different methodologies which are undertaken in order to deliver the results. The findings are available in the empirical result which is divided up into two parts. The first part contains the development and the answer related to the change in the GARCH structure of the exchange rates after the EU referendum and the second part is related to how the Brexit announcements impacted the volatility of the two exchange rates analyzed.

Then, the conclusion of this paper summarizes the findings and deliver several comments related to the future level of volatility of the GBP for the coming months. Furthermore, several extensions of research related to this subject are provided at the end of this paper.

2. Background

2.1. Brexit

2.1.1. Pre-Referendum

Despite the fact that the financial markets were surprised by the decision of the UK to leave the EU, it should be reminded that among the 27 EU Member States, the UK is the country which shows the highest level of Euroscepticism (European Commission, 2009). Even a few years after the ratification of the European Communities Act 1972[1], a referendum was held in 1975 on whether the UK should remain in the European Communities (May, 1999). Over the years, this skepticism towards the EU kept increasing in the UK[2] and the origin of the last referendum organized dates from the year 2012 (Montagu, 2018).

In 2012, David Cameron, the Prime Minister of the UK, refused several times the request of other members of the Conservative party to organize a referendum related to the membership of the UK in the EU. This request was based on the fact that according to the British ministers, the EU represented a threat to the UK sovereignty (Watt, 2012). Nonetheless, facing an increasing pressure, the PM announced that an EU referendum would be hold if the Conservatives won the election (Watt, 2013). Finally, the Conservative party won the election with a majority in the Commons (Hawkins, Keen & Nakatudde, 2015). Thereupon, the European Union Referendum Act 2015 was introduced into Parliament in order to start the implementation of the referendum (Uberoi, 2015).

As soon as the referendum has been officialized, many opinion polls emerged and demonstrated a majority in favor of remaining in the EU[3] (Cooper, 2016). Concerning the debate between the two sides of the referendum, those who were in favor of a withdrawal from the EU argued that it would allow the UK to fully manage the control of the immigration. Moreover, a withdrawal would also give more freedom to the UK in terms of trade deals with other countries in the world. Another argument was the willingness to reduce the EU bureaucracy and regulation which is perceived as not efficient and costly for the Eurosceptics. On the other hand, the

[1] "The 1972 European Communities Act was the piece of legislation that brought the UK into the Europe Union: it gives EU law supremacy over UK national law."
(Institute for Government): https://www.instituteforgovernment.org.uk/explainers/1972-european-communities-act

[2] See *appendix* 1: Increase of Euroscepticism in the UK.

[3] See *appendix* 2: EU Referendum vote intention

Remainers believed that a withdrawal from the EU would decrease the UK influence over the business world. They also feared that it would reduce the national security by losing the total access to the common European criminal databases. An additional fear on this side was the job losses and the decrease in investments in the UK because of the Brexit[4] (Arato, 2016).

2.1.2. Post-Referendum

After several months of debates, manifestations and propaganda, the final result was announced on Friday 24th June 2016. The EU referendum resulted in a majority of 51.9% in favor of leaving the European Union (The Economist, 2016). The British financial markets were negatively impacted by this unexpected result (Allen & Davies, 2016). Then, at the announcement of this result, David Cameron resigned from his position of PM and a few weeks later, Theresa May was chosen to become the new PM of the UK (Elgot, 2016). Afterwards, the preparation for the Brexit negotiations started and, on the 16th March 2017, the British Parliament passed the Brexit Bill[5] which constituted the first step to trigger Article 50 (Asthana, Mason & O'Caroll, 2017). On the 29th March 2017, Theresa May delivered a letter to the European Council in order to invoke Article 50. The reception of this notification represented the beginning of the 2-years negotiation of the Brexit between the EU and the UK (Asthana, Steward & Walker, 2017).

Several negotiation rounds were held between the two parties in order to deliver an agreement on the withdrawal and after one year of negotiation, a draft agreement was settled (Chakelian, 2018). At the beginning of the month of July 2018, Theresa May presented the final version of her deal related to the Brexit which is called the Chequers plan[6] and the purpose behind this agreement is to allow the UK to leave but to keep a close relationship with the EU. This deal was perceived as a "soft deal" and because of this plan, several ministers of the British government decided to resign from their position (Merrick, 2018). Two months later, Theresa May presented this Chequers plan at the EU summit. Nonetheless, the European leaders refused it because of several disagreements related to the Irish border. In front of this situation, the PM requested more concrete arguments and explained that a no deal is better than a bad deal for the UK (Hopps, 2018).

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[4] See *appendix* 3: EU Referendum. The reasons to leave and reasons to remain

[5] "A bill is a formal statement of a planned new law that is discussed before being voted on. (Cambridge Dictionary): https://dictionary.cambridge.org/dictionary/english/bill

[6] See *appendix* 4: 12 points of the Chequers plan.

In November 2018, a withdrawal agreement is reached between Theresa May and the European Council. Nonetheless, despite the fact that the Cabinet of Theresa May approved the agreement, several Eurosceptics ministers of the Cabinet are not convinced by this deal and decided to resign (Crerar & Weaver, 2018). This deal is accepted by the European leaders at the end of November (Boffey & Renkins, 2018). The following step is that the withdrawal agreement has to be accepted by the House of Commons. Nonetheless, this vote was presented several times and every time get rejected by the Commons. Between January and March 2019, the British political climate was getting worse day after day and British politicians were not able to find a solution. Therefore, after discussions with the EU, the Brexit is postponed to the 31st October 2019 and at the end of May, Theresa May resigned from her position of PM[7] (Stewart, 2019).

2.1.3. The possible outcomes

Regarding the negotiations related to the Brexit, several outcomes may arise. However, these different outcomes are classified among three categories. The soft Brexit, the hard Brexit and the no-deal[8] (Kettle, 2019). In the context of the "soft deal", the UK would keep a close relationship with the EU and would remain in the EU single market. According to the economists, this deal would be the least damaging due to the fact that it would minimize the disruptions on the trade between the two economic areas (Reid, 2019).

Concerning the "hard Brexit", the UK would stop being a member of the single market of the EU and therefore, it would allow the British to establish new trade agreements with other countries. Then, through the agreements that would have been reached, they will keep trading with some European partners. Nonetheless, the realization of new trade agreements is time-consuming and before the introduction of a new trade agreement, the UK would have to use the World Trade Organization rules[9]. If the British are out of the custom union, the importation would become more expensive and this constitutes a threat for the businesses in the UK (Sims, 2016).

The last possibility is the "no deal". This would occur if no agreement is reached before the 31st October 2019[10]. In this case, trade agreements with the Member States of the EU would not be

[7] Further information related to post-referendum period are available in the part that explains the data.
[8] See *appendix* 5: Probabilities of different Brexit scenario (May 2018)
[9] Through the WTO rules, additional tariffs would be applied on the trade between the two economic areas.
[10] See *appendix* 6: Probabilities evolution of a no-deal Brexit (May 2019)

valid anymore and they would have to start from zero in order to develop new trade agreements with European countries (O'Carroll, 2019). The majority of economists explains that this situation is the worst situation that could arise and should be avoided. According to the BoE, a no deal would be worse than the 2008 financial crisis with a decrease of the GDP of 8% and the unemployment could rise to 7.5% (Partington, 2018).

2.2. Economic relationship between the EU and the UK

The UK is one of the leading economies in the world and many households in this country are dependent on the international trade. The dependency of the UK to the international economy could be perceived through the part of this international trade in percentage of the GDP. In 2017, international trade represented 61.1% of the British GDP and exports accounted for 30% of the British GDP (Department for International Trade, 2019).

Concerning the main trading partners of the UK, in 2017 the USA accounted for 15% of the international trades of the UK. Then the Germany is the second biggest trading partner of the UK with 11% of their total international trade. The two following countries are the Netherlands and France which represented 7% of their world trade (Department for International Trade, 2019). From a broader perspective, in 2017, the trade with the members of the European Union accounted for 48.3% of the total UK foreign trades with 44% of the total UK exports and 53% of the total UK imports (Ward, 2019). A further indicator related to the globalization of the UK is the FDI. The main directions of the British FDI are the United States, the Netherlands, Luxembourg, France and Spain (Department for International Trade, 2019).

All these figures lead to the conclusion that international trade is important for the British economy. However, in the context of the Brexit Referendum, the interpretation of these figures is different among Remainers and Brexiteers. According to both sides, the application of the referendum would reshape the business relationships of the UK. In the mind of the Remainders, the leaving vote would hurt the British economy for the reason that many treaties with the UE Members States would be canceled and therefore, trade with EU countries will decrease. On the other hand, according to the Brexiters the referendum will represent an opportunity. Their wish is to be freer in their trade decisions, to trade with other countries but still keeping EU Members States as important trading partners. They are convinced that the withdraw from the EU will allow UK to gain more independence in term of international business and that they will develop business treaties with other economies that are becoming important such as emerging economies (Blitz, Pickard & Parker, 2019). However, the majority of the British people would prefer to avoid the “no deal” option which would bring more uncertainty in the UK economy (Douglas & MacDonald, 2019).

2.3. Motivation of the research

According to several reports, the uncertainty related to the Brexit already impacted the British pound and its level of volatility. Nonetheless, there is no empirical evidence related to this statement. Therefore, through an empirical investigation, this paper will provide with the opportunity to develop a better understanding on the impacts of the Brexit referendum and the announcements related to the Brexit negotiations on the volatility of the British currency. This research could be useful for bankers who manage the currency transactions of their corporate clients that purchase or sell GBP and for asset managers who have British stock in their portfolio.

3. Literature review

Due to the recent nature of the Brexit, there is no paper that is investigating the change in the volatility of the GBP after the EU referendum and the impact of news concerning the Brexit and its negotiations on the volatility of the British currency. Nonetheless, several papers inquire similar questions related to the volatility of different financial assets. These investigations examine the occurrence of a break in the volatility structure of financial securities and the impact of announcements and/or news on the volatility of financial markets.

In the paper "Effects of Brexit on the financial markets: An empirical study methodology and GARCH models" written by Atieh Tabeshian in 2018, the author aims to investigate on the reaction of several financial markets on the announcement of the result of the EU referendum. In order to realize her research, she examines two different questions. In the first one, the purpose is to know whether the Brexit was a surprise for three different exchange rates and two financial indexes. She undertakes this part through the analysis and the comparison of the abnormal returns and the cumulative abnormal returns at the moment of the Brexit result announcement. However, this first methodology does not concur with the question in this paper.

Then, the second analysis tackled in her paper seems to show similarity with the first question in this research which is the change in the volatility of the GBP after the EU referendum. In her analysis, Atieh Tabeshian examines the volatility of the FTSE 100[11] and the FTSE EUROTOP100[12] before and after the result related to the Brexit decision. Regarding the data, she uses the daily returns of these indexes that are situated between the 23rd June 2015 and the 23rd June 2017. In order to differentiate the volatility between these two time-periods, the author uses a GARCH (1,1) model in which she introduces a dummy variable that enables to observe for a change in the volatility between two different periods of time. Therefore, to implement the dummy variable, all observations in her time series whose date is prior to the EU referendum

[11] "an index that tracks the 100 largest public companies by market capitalization that trade on the London Stock Exchange (LSE). The FTSE 100 represents roughly 80 percent of the LSE's market capitalization. FTSE is an acronym for the Financial Times and the LSE, its original parent companies."
(Investopedia): https://www.investopedia.com/terms/f/footsie.asp

[12] "The FTSE Eurotop 100 Index represents the performance of the 100 most highly capitalized blue-chip companies in Europe."
(FTSE): https://www.ftse.com/products/indices/European

result have a value equal to 1 and the observations after the EU referendum result have a value of 0.

Regarding the results of this inquiry, they demonstrate that the level of volatility for both indexes, the FTSE 100 and the FTSE EUROTOP100, decreased during the post-referendum period. Furthermore, the dummy variables in each GARCH (1,1) models are significant which supports the observation from the sign of the dummy variable. In order to increase the robustness of her observations related to the level of volatility after the Brexit referendum, the author decided to estimate additional GARCH (1,1) models including the dummy variable. These additional volatility models were implemented with data 2 months before and 2 months after the referendum, 2 weeks before and 2 weeks after the referendum and 5 days before and 5 days after the referendum. The results of these extra GARCH models are consistent with the initial GARCH models, meaning that the volatility was higher before the EU Referendum.

Besides the implementation of a dummy variable in GARCH models, there exist additional methods in the literature which investigate on the change in the volatility structure. A further option is the CUSUM test. In the paper "Structural breaks and GARCH models of exchange rate volatility" written by David Rapach and Jack Strauss in 2008, the authors treat the use of the CUSUM test in order to determine if there exists any empirical relevance of a structural break for GARCH models. Furthermore, this research emphasizes volatility models on exchange rates. The authors generate their observations through the use of daily nominal exchange rates which allow them to compute the daily returns of the US Dollar against seven other currencies. The time period which is analyzed in this article starts from January 1980 and ends on August 2005. Moreover, before the implementation of the GARCH and CUSUM test, the authors check the possibility to use these models through several statistics such as the Ljung-Box statistics which provides information on the serial correlation and the Lagrange multiplier statistics which gives information on the presence of ARCH effects. The study of these statistics shows that the investigation on the volatility of these exchange rate returns should be implemented through a GARCH process.

After the application of the CUSUM test, the authors observe the existence of structural breaks for all the exchange rates except the JPYUSD exchange rate. Only one single structural break is signaled by the test for the DEKUSD, GDMUSD, NOKUSD exchange rates. Two structural breaks are observed for the CHFUSD and the GBPUSD. Finally, three structural breaks are shown for the CADUSD. The dates of the occurrence of the structural breaks for the GBPUSD are the 2nd November 1981 and the 9th March 1993. According to the authors, a majority of these variance breaks detected by the test reveals to be associated with important economic events. The second break for the GBPUSD which happened in 1993 could be explained by the end of the Exchange Rate Mechanism crisis that occurred in Europe.

Then, they continue their research through the computation of several GARCH (1,1) models. They implement a GARCH (1,1) model for each exchange rate and also for each subsample of time periods that are defined by the apparition of structural breaks. The majority of these GARCH models shows persistence in the volatility. An additional observation which comes from the volatility modelling for the subsample time periods is that every structural break provides an important shift in the intercept term and these shifts lead to significant change in the unconditional variances across the different time periods.

In "Testing for structural breaks in GARCH models" written in 2008 by Daniel Smith, the author extends the literature related to the CUSUM test. As the previous researchers in this field, he investigates on the ability of several tests to detect structural breaks in GARCH models. The statistical tests that are analyzed are the LM and CUSUM tests. Concerning the empirical result of this research, the author examines 12 different time series which all start in 1990. Among these 12 time series, 4 time series are daily returns generated from exchange rate series, the CADUSD, the JPYUSD, the GBPUSD and the GDMUSD exchange rate. These data sets start in January 1990 and finish in March 2003 except the GDMUSD whose time series stops in December 1999. The author provides a summary statistic in which he notices that the four exchange rates show the lowest unconditional variance among all the time series that are investigated.

Concerning the empirical results in this investigation for the exchange rates, only the CADUSD exchange rate shows significant result concerning a structural break. Regarding the three other exchange rate series, there is no evidence of a structural break. Furthermore, the weakest evidence for the occurrence of a structural break is in the GDMUSD exchange rate. According to the author, an explanation for the fact that there is no break is that the GARCH models for the exchange rate series are well specified over the time period analyzed.

In the empirical literature, it exists another method which allows to detect for a change in the volatility structure. In the paper "Dow Jones Index, GARCH (1,1) and change-points" written in 2008 by Tharanga Wickramarachchi, the author aims to investigate on the appropriateness of a GARCH (1,1) model for the daily Dow Jones Index stock returns. The author extends his research through the examination of possible changepoints in the GARCH process. In order to find an answer to this last question, the author decides to implement the bootstrapping method on the GARCH (1,1) process which has been confirmed to be an appropriate model for the DJI returns.

The author will use the returns of the Dow Jones Index between January 1997 and December 2006 in order to implement the bootstrapping process. He divides the time series in two sub-periods. The first one starts in January 1997 and ends the December 2003. The other time series starts in January 2004 and the end of this series is the December 2006. Through the Bootstrap methodology, the author observes several changes in the GARCH (1,1) parameters which reveal themselves to be significant.

Then, the second part of this thesis focuses on the impact of Brexit announcements on the GBP volatility. Therefore, different papers related to the impact of announcements and news on the volatility of financial markets are discussed. The empirical literature on the impact of news on exchange rate volatility has gained more and more interest in recent decades. The first studies in the 1980's exploited daily return data and simple regression. Nonetheless, these earliest studies did not deliver conclusive results (Aggarwal & Schirm, 1992). In 1990's, the arrival of high-frequency data and development of several GARCH-models (Bollerslev et al., 1992) helped to improve the analysis of the impact of announcements and news on exchange rate volatility.

Then, the impact of announcements on exchange rate returns and the volatility of returns have been investigated extensively. The two most analyzed exchange rates are DEM/USD and the GBP/USD (Goodhart et al., 1993). In the majority of these researches, the news have been selected through the headlines of Reuters[13] or also scheduled macroeconomic news. In all these papers, the results indicate that the announcements cause a jump in the level of the exchange rate, and therefore, increase the volatility. In the case of intra-day volatility research, news increases the volatility from an hour to two hours after the availability of the information

[13] "Reuters is a global information provider headquartered in London, England, that serves professionals in the financial, media and corporate markets."
(Investopedia): https://www.investopedia.com/terms/r/reuters.asp

(Andersen & Bollerslev, 1998). Moreover, more recent studies have shown that the impact of announcements significantly endure for several days (Evans & Lyons, 2008).

This paper related to the GBP volatility does not answer to the questions through the use of intraday data. Consequently, an example of a paper that treats daily data is “Central bank intervention and exchange rate volatility” written by Kathryn Dominguez in 1998. In this paper, the author intents to observe if the central bank interventions impact the volatility of exchange rates. The exchange rates used in her study are the dollar-mark and dollar-yen. Consequently, the interventions analyzed are the US, German and Japanese central bank interventions. Then, the time period of this study is between 1985 and 1994 and the author uses the daily returns of the exchange rates.

In order to answer to her question, the author measures the volatility of the exchange rates through a GARCH (1,1) model. In this model, the author includes dummy variables that are related to the reported and secret[14] central banks interventions. According to the result, the variance effect for both exchange rates was highly persistent during this period. Then, publicly known FED intervention increased the volatility of both exchange rates. On the other hand, the secret intervention from the FED also increased significantly the volatility of the exchange rates analyzed in this study. Regarding the BOJ interventions, the effect on the volatility of the dollar yen was also positive and significant. An interesting observation is that according to the GARCH model, the reported Bundesbank interventions decreased the volatility of the dollar-mark. Therefore, through the introduction of several dummy variables related to central bank interventions in the GARCH model, the author was able to argue how these interventions impacted the volatility of the exchange rates.

Another paper in which the same methodology is applied is the article “*Using GARCH in event studies*” written in 2017 by Miltiades Georgiou. The author of this article aims to examine if M&A announcements have an effect on the volatility of the share prices of several main US acquiring banks. In order to conduct his analysis, Miltiades Georgiou uses a GARCH (1,1) model and concerning the data, he uses daily data between 2000 and 2016. In this GARCH model, the author decides to add two additional variables that are a dummy variable related to a M&A announcement day and another dummy variable related to the global economic crisis.

[14] According to the author of the article, the secret interventions reflect the interventions that central banks choose not to make public.

Regarding the result among eight different banks analyzed, the author observed that the M&A announcement day dummy variable reveals itself to be a significant variable for only three banks.

To conclude this part related to the literature review, the research which studies foreign exchange volatility reaction to news announcement is quite scattered due to the fact that there exist several categories in the announcement effects on foreign exchange volatility. With the development of high frequency data, more and more research on the announcement effects are realized on an intra-day basis. However, this paper deals with daily data. In the category of the announcement effect on the volatility with daily data, the majority of the researchers use GARCH models. Thus, in order to analyze the impact of the Brexit announcement on the GBP, a GARCH model will be implemented in this research.

4. Data and Methodology

4.1. Data

Concerning the data related to this research, two daily nominal exchange rates are used to answer to the questions regarding the volatility of the GBP. These exchange rates are the EUR/GBP and the GBP/USD. Regarding the two questions, the change in the GBP volatility after the EU referendum and the effects of the Brexit announcements on the GBP volatility, the time series are different. For the first question, the time series starts on the 23rd May 2013 and ends the 24th May 2019 which constitutes a 6 years-time series with 1522 daily data. On the other hand, for the second question, the time series only focuses on the post-referendum period. Therefore, this time series starts on the announcement day of the EU referendum result, the 24th June 2016 and stops on the resignation day of the Prime Minister, Theresa May, the 24th May 2019. This second time series has 761 daily observations. All the data were extracted from the Bloomberg terminal. Consequently, four different time series are investigated in this research, the EUR/GBP and GBP/USD between 2013 and 2019, then, the EUR/GBP and the GBP/USD between 2016 and 2019. The evolutions of these exchange rates between 2013 and 2019 are available in the *appendices* 7 and 8. *Appendix* 9 delivers several comments on the evolution of these exchange rates.

The nominal values of the exchange rates constitute the foundation of this research. Nonetheless, in order to conduct the calculations which will deliver the answers, the returns of the exchange rates are required. These returns constitute the daily percentage change of an exchange rate. The general formula used in order to compute these returns is the following:

$$ln(ExchangeRate_t/ExchangeRate_{t-1}) = Return_t$$

Due to the fact that the time series related to the exchange rates have 1522 and 761 observations depending on the question, these returns constitute a database of 1521 observations regarding the time series for the first question that investigates on the GBP volatility change after the EU referendum result and 760 return observations related to the second question that analyzed the impact of the Brexit news on the GBP volatility. These returns are plotted in the graphs of the *appendices* 10 and 11.

Then, it is necessary to analyze several statistics concerning these returns in order to know if a GARCH model is a suitable model to implement regarding these statistics.

Table 1 – EUR/GBP summary statistics

EUR/GBP			
Exchange rate returns	2013-2019	2013-2016	2016-2019
Mean	0.005	-0.006	0.010
Standard deviation	0.509	0.500	0.475
Skewness	1.039	0.087	0.305
Kurtosis	11.264	0.923	2.578
Minimum	-2.123	-2.123	-2.037
Maximum	5.844	1.822	2.748
Jarque-Bera test	9141.3 [0.000]	34.003 [0.000]	224.72 [0.000]
Ljung-Box (r=10)	12.333 [0.264]	9.249 [0.509]	13.946 [0.175]
Augmented Dickey-Fuller test	-12.759 [0.01]	-9.883[0.01]	-8.877 [0.01]
Squared exchange rate returns			
Ljung-Box(r=10)	85.491 [0.000]	69.164 [0.000]	22.415 [0.01]
ARCH Lagrange Multiplier (q=4)	437596 [0.000]	5166 [0.000]	5420 [0.000]
ARCH Lagrange Multiplier (q=8)	197337 [0.000]	2091 [0.000]	3013 [0.000]

Source: Bloomberg – Own Calculations.

Table 1 delivers several statistics related to the EUR/GBP exchange rate returns. The time periods which are investigated in this paper are the first column, from 2013 to 2019 and the last column, from 2016 to 2019. A first observation is that for the three time series, the average of the daily returns is close to zero. Then, the normality of the time series could be approached through several statistics such as the Skewness and the Kurtosis. The time series of the first column shows nonsymmetrical results with a high Skewness that demonstrates heavy tail on the right-hand side and a high Kurtosis. The two other time series display more symmetrical characteristics. However, the normality of the time series is known through the Jarque-Bera test. Through the realization of this test, it is demonstrated that the three time series do not have a normal distribution.

For the next statistic analyses, the same approach as Rapach and Strauss (2008) is undertaken. Through the Ljung-Box test on the returns, it is reported that there is no evidence of autocorrelation between these returns at lag 10. Then, the stationarity of the time series is investigated with a unit root test that is the Augmented Dickey-Fuller test and according to the result of this test, the three time series are stationary with a p-value lower than 0.05. To conclude the analysis of the EUR/GBP time series, two last tests are realized on the squared exchange rate returns. The Ljung-Box statistic tests conducted show that there is a serial correlation for the squared EUR/GBP returns of each time series at lag 10 and that through the results of the ARCH-LM test, the ARCH effects are confirmed at lags 4 and 8 which gives an additional proof of the heteroskedasticity in the time series. The collection of these observations gives robustness for modelling the EUR/GBP exchange rate returns through GARCH processes.

Table 2 – GBP/USD summary statistics

	GBP/USD		
Exchange rate returns	2013-2019	2013-2016	2016-2019
Mean	-0.014	-0.010	-0.009
Standard deviation	0.549	0.473	0.558
Skewness	-1.821	0.473	-0.188
Kurtosis	27.466	1.789	3.153
Minimum	-7.944	-1.687	-3.456
Maximum	2.576	2.490	2.576
Jarque-Bera test	53463 [0.000]	125.32 [0.000]	322.69
Ljung-Box (r=10)	10.21 [0.422]	8.109 [0.618]	11.323 [0.3329]
Augmented Dickey-Fuller test	-12.601 [0.01]	-9.690 [0.01]	-9.758 [0.01]
Squared exchange rate returns	2013-2019	2013-2016	2016-2019
Ljung-Box(r=10)	70.383 [0.000]	22.968 [0.001]	22.39 [0.01]
ARCH Lagrange Multiplier (q=4)	558890 [0.000]	12191 [0.000]	6255 [0.000]
ARCH Lagrange Multiplier (q=8)	267477 [0.000]	5707 [0.000]	3002 [0.000]

Source: Bloomberg – Own Calculations.

The second table is related to the statistics on the GBP/USD exchange rate returns. The average of the daily returns is again close to zero for the three time series. Regarding the normality of the data, as it has been shown for the EUR/GBP returns, the observations of the first column display the least symmetrical distribution among the three. However, all these time series do not approach a normal distribution and this is demonstrated through the Jarque-Bera test.

Then, according to the Ljung Box test, there is no serial correlation between the GBP/USD daily returns at lag 10. Concerning the stationarity, the ADF test shows that the three time series are significantly stationary. The Ljung-Box test is again used and signals that the squared returns of the GBP/USD are serially correlated at lag 10 and finally, the ARCH LM test reveals the presence of ARCH effects in each time series at lags 4 and 8. These observations confirm that a GARCH model could be applied on these daily exchange rate returns in order to investigate on the volatility of the GBP/USD. Consequently, the same methodology as the one for the EUR/GBP returns will be applied for the GBP/USD returns.

In the matter of the first question, which is related to the change in the volatility structure of the exchange rates after the EU referendum result, one methodology is used in order to tackle the question and it requires an additional variable. This additional variable represents a dummy variable. Therefore, the time series will be divided up into two parts. In the first part, which is related to the period before the referendum, the value of this new variable is zero. On the other hand, concerning the date after the EU referendum result, the additional variable takes the value of one. Through this implementation, the purpose would be to observe if this dummy variable could explain a change in the volatility of the exchange rates.

After the first question, the second question deals with the impact of the Brexit announcements on the volatility of the exchange rates. For this analysis, an additional variable is also required. This additional variable constitutes a binary variable that focuses on the days for which an announcement or a news related to the Brexit has been released. If an announcement related to the Brexit was made public, then the variable takes the value of 1 and for the other days which do not have any news related to the Brexit, these days take the value of 0. Therefore, the purpose of this dummy variable is to capture the potential effect of these news on the exchange rates volatility.

In order to determine the day for which an announcement or a news on the Brexit has been released, several websites of British newspapers were used to know what happened during this post-Brexit period. The first date of this time series is the 24^{th} of June 2016. However, the day at which the EU referendum result was made public is the first observation of the exchange rates. Consequently, there is no return for this date and the start of the time series related to the exchange rate returns start on the 27^{th} of June 2016. The *appendix* 12 constitutes the table with the dates at which an important event related to the Brexit outcome occurred. For each date, a short explanation regarding what happened on that day is available. Furthermore, the daily variation of the exchange rates, EUR/GBP and GBP/USD are also present in the table.

4.2. Methodology

Concerning the methodology used in this paper, several volatility models are introduced. However, before developing these volatility models, a focus on the definition of the volatility itself is provided. According to the website, The Economic Times, the volatility is “a rate at which the price of a security increases or decreases for a given set of returns. Volatility is measured by calculating the standard deviation of the annualized returns over a given period of time. It shows the range to which the price of a security may increase or decrease.*"* The website concludes its definition of the volatility with a description which explains that the volatility provides the investors with an indication on the pricing behavior of the asset.

Therefore, a key element in the volatility computation is the return of the asset. The returns of an asset could be calculated by two different ways that are the arithmetic returns or the geometric returns (Jorion, 1997). Nonetheless, investors perceive the geometric formula as a more accurate method in order to compute the returns. The reason in the choice of this formula lies in the fact that the geometric formula takes into account the compounding which occurs from period to period (Aas, 2004). Therefore, the geometric formula is used in this research.

$$R_t = log(P_t) - log(P_{t-1}) \tag{1}$$

This formula delivers the return of the day t where P_t represents the price of the security at day t and P_{t-1} is the price of the security the day before day t.

Another important concept which is mentioned in the definition of the volatility here above is the standard deviation. This statistic metric is a frequent measure in order to determine the volatility of an asset or a market. Through the formula of the standard deviation, it is possible to measure the dispersion of returns (Daly, 2011). The computation of the standard deviation is realized through the following formula

$$\sigma = \sqrt{\sum_{1}^{T}(R_t - E(R))/(T-1)} \tag{2}$$

In this formula, the standard deviation of the returns calculated from a sample that contains T observations is the square root of the average deviations between the returns and the average of these returns, the expected return which is denoted $E(R)$ and $E(R)= \sum R_t/T$. The standard deviation is an easy method in order to compute the volatility and to get information on the probability of observing extreme values of return (Daly, 2011).

Therefore, investors are able to calculate the volatility which is related to the risk. However, volatility does not necessarily mean risk. The risk is perceived as the uncertainty or the probability of occurrence of a negative outcome related to the returns of an asset. On the other hand, the volatility captures the spread of the outcomes which includes the positive outcomes as well as the negative outcomes. In order to investigate on the risk of an asset with the standard deviation formula, the Value-at-Risk (VaR) is investigated (McNeil, 1999). The definition of this risk metric is "The maximum amount of money that may be lost in a portfolio over a given period of time, with a given level of confidence" (Best, 1998).

Nowadays, when it comes to investigate on the volatility, researchers mainly use another methodology than the standard deviation formula. In order to get a better understanding of the volatility, they use the GARCH model. Therefore, this model is used in order to answer to the two questions of this thesis. Before explaining the implementation of this model in the context of this study, an explanation of this volatility model is provided.

4.2.1. Foundation of the GARCH model

4.2.1.1. The Autoregressive model

The foundation of the GARCH model lies in the autoregressive (AR) time series model. In such a model, a return R_t is directly linked to the *z* previous returns. This statement could be written such as

$$R_t = \phi_1 R_{t-1} + \phi_2 R_{t-2} + \phi_3 R_{t-3} + ... + \phi_z R_{t-z} + \epsilon_t \quad (3)$$

This equation represents an Autoregressive series of order *z*, AR(*z*). Therefore, the *z* previous returns explain the return at the day t. The last term in this model, ε_t represents the error term. In the AR model, this error term is assumed to be white noise[15] (Weiss, 1984). The intuition of this model is that for a series of observations R_t, it is possible to show that the level of the current observation is related to the level of the lagged observations. For example, if the GDP increase is high for this quarter, an individual could expect that the GDP increase in the following quarters will be as good as the one for this quarter (de Jong, 2006).

[15] The error term is said to be white noise when these errors are independent, have a normal distribution that shows a mean equal to zero and a constant variance equals to σ_ε^2.

In the context of an Autoregressive series of order 1, AR(1), the observation of yesterday explains the return of today and therefore, the formula of such a model is

$$R_t = \phi_1 R_{t-1} + \epsilon_t \tag{4}$$

Furthermore, knowing that R_t is recursive from the previous returns, the Autoregressive model could be expressed as:

$$R_t = \epsilon_t + \phi_1 R_{t-1}$$
$$R_t = \epsilon_t + \phi_1(\epsilon_{t-1} + \phi_2 R_{t-2})$$
$$R_t = \epsilon_t + \phi_1 \epsilon_{t-1} + \phi_1^2 R_{t-2}$$
$$R_t = \epsilon_t + \phi_1 \epsilon_{t-1} + \phi_1^2(\epsilon_{t-2} + \phi_1 R_{t-3})$$
$$R_t = \epsilon_t + \phi_1 \epsilon_{t-1} + \phi_1^2 \epsilon_{t-2} + \phi_1^3 R_{t-3}$$
$$\vdots$$
$$R_t = \sum_{i=0}^{k} \phi_1^i \epsilon_{t-i} + \phi_1^{k+1} R_{t-k-1} \tag{5}$$

From this formula, $|\phi_1|$ is assumed to be lower than 1 and therefore, it enables k to go to infinity; which gives

$$R_t = \sum_{i=0}^{\infty} \phi_1^i \epsilon_{t-i} \tag{6}$$

Consequently, if the process $\{R_t\}$ is defined through this formula, then R_t is in line with the recursive behavior shows in the equation (5) and $\{R_t\}$ is said to be stationary (Lo, 2003).

4.2.1.2. The Moving Average model

Another model which is well known in the financial literature in order to explain the return at the day t is the Moving Average series of order z, MA(z), which is formulated by

$$R_t = \epsilon_t + \theta_1 \epsilon_{t-1} + \theta_2 \epsilon_{t-2} - ... + \theta_z \epsilon_{t-z} \tag{7}$$

Usually, the mean of the previous returns should have been added to this formula. However, because of the assumption of the zero mean of the returns, the mean term was removed (Weiss, 1984). Then, as it has been defined in the context of the Autoregressive model, ε_t represents the white noise error terms. θ_1 is the parameter of the model that establishes the relation between the white noise error term of the previous period and the observation at the period *t* (Weiss, 1984). The intuition concerning this model is that through this process, it is possible to model the fact that the observations of a random variable at time *t* are not only impacted by the shock at time *t*, but also the shocks that occurred in the past. For example, if a negative shock occurs to the stock price of a company because of a bad annual report, an investor could expect that this negative shock impacts not only at the announcement day but also for the near future (de Jong, 2006).

As it has been developed for the Autoregressive model, a Moving average series of order 1, MA (1) is formulated by

$$R_t = \epsilon_t + \theta_1 \epsilon_{t-1} \tag{8}$$

Through this formula of the Moving average process of order 1, the returns at day *t* are explained by the white noise error term of day *t* and the white noise error term of the day before that is multiplied by a parameter θ (Weiss, 1984).

4.2.1.3. The Autoregressive Moving Average model

After the investigation of the Autoregressive model and the Moving Average model, it is possible to extend these models through a combination of the Autoregressive process and the Moving Average process. This combination is called the Autoregressive Moving Average model, the ARMA process. Therefore, an ARMA (*p, q*) model is a consolidation of an AR(*p*) model and an MA(*q*) model. This process is well-known to be a suitable model for univariate time series modelling (Adhikari & Agrawal, 2013). The formula of an ARMA (*p, q*) model is the following

$$R_t = \phi_1 R_{t-1} + \phi_2 R_{t-2} + ... + \phi_p R_{t-p} + \theta_1 \epsilon_{t-1} + \theta_2 \epsilon_{t-2} + ... + \theta_q \epsilon_{t-q} + \epsilon_t \tag{9}$$

Through the equation (10), the return of period *t* is explained by the equation (3), the AR(*p*) model and the equation (7), the MA(*q*) model (Guidolin, 2018). In the compact form, the ARMA (p, q) model is formulated by

$$R_t = \sum_{i=1}^{p} \phi_i R_{t-i} + \sum_{i=1}^{q} \theta_i \epsilon_{t-i} \tag{10}$$

Then, if the ARMA model is formulated in an ARMA (1,1) process, this is given by the following expression

$$R_t = \phi_1 R_{t-1} + \theta_1 \epsilon_{t-1} + \epsilon_t \tag{11}$$

To conclude on the ARMA models, these processes are not commonly used in order to fit the data (Guidolin, 2018).

4.2.1.4. The Autoregressive Conditional Heteroskedasticity model

So far, several linear models have been investigated. Another category of time series is the nonlinear model that should also be considered in the context of time series analysis (Adhikari & Agrawal, 2013). According to Campbell, Lo and McKinley (1997) there exist two categories of nonlinear time series. The first category contains the models that are nonlinear in their mean and the other category includes models that does not show linearity in their variance. The lack of linearity in the variance of the error terms in a time series is characterized by the heteroskedasticity. In statistics, it is possible and quite common that the standard errors of a variable are non-constant and it represents the heteroskedasticity. Furthermore, researchers often talk about conditional heteroskedasticity (Hamilton & Susmel, 1994). This concept of conditional heteroskedasticity is represented by the volatility clustering for which large variations tend to follow large variations, and small variations tend to follow small variations. This phenomenon has been accepted in the financial time series researches and is modeled by several ARCH-type models (Wang, 2005).

The first ARCH model was developed by Engle in 1982. Through this model it is possible to investigate on the heteroskedasticity and the volatility clustering in the financial data. According to the ARCH formula, the conditional variance of the returns changes in function of an autoregressive-type process (Fryzlewicz, 2007). In his seminal paper, Engle (1982) suggests that one possibility for modeling σ^2 is to express σ^2 as a function of past squared values of the process. Therefore, the ARCH formula is the following

$$R_t = \mu_t + \epsilon_t \tag{12}$$

$$\epsilon_t = z_t \sigma_t \tag{13}$$

$$\sigma_t^2 = \omega + \sum_{i=1}^{q} \alpha_i \epsilon_{t-i}^2 \tag{14}$$

The equation (12) explains that the return of an asset is equal to the sum of its expected value and a white noise error term which corresponds to a shock. In the context of a data set of observations that shows a mean equal to zero, the return is equal to the error term. Furthermore, in such a situation, the ARCH model would be a stationary process, which is often assumed. Concerning the equation (13), it states that the error term depends on σ_t, which describes a volatility process and z_t that represents an innovative process (Chen, 2013). This innovation term is assumed to have mean zero and a variance equal to one. Furthermore, this term is often supposed to be normally distributed (Sorensen, 2005). Then, equation (14) delivers the ARCH formula of order *q*.

Concerning the parameters of the ARCH model in equation (14), the parameter ω is greater than zero and the parameter α_i is greater or equal to zero. Then, ω corresponds to a long-term variance term and α provides with the information on the importance of the returns of the previous days versus the other parameter, the long-term average. Therefore, the more the series is autocorrelated, the more the value of α is important (Murphi, 2008). This ARCH process which is called a linear ARCH (*q*) model is able to capture the tendency for volatility clustering which means that a large change in the price is supposed to be followed by other large change in the price and small change in the price is supposed to be followed by other small change in the price. However, the sign related to the change in the price is unknown (Engle, 1982). Regarding the estimation of the parameters of the model, the estimation strategy implemented is the Maximum Likelihood (Sorensen, 2005).

Then, if the ARCH model is formulated in an ARCH (1) process, the ARCH formula is

$$\sigma_t^2 = \omega + \alpha_i \epsilon_{t-1}^2 \quad (15)$$

Therefore, in this formula, the α captures the effect of the returns of yesterday on the volatility of today (Chen, 2013).

The ARCH model is considered as an intuitive model which is easily applicable and allows the researchers to investigate on the volatility of the time series. Engle, who developed the ARCH methodology, applied the formula in order to study the inflation rate (1983). Nonetheless, in the context of the ARCH model, it is complicated to determine the number of lags q and moreover, there exists no standardized approach in order to decide on the number of lags. Another problem is the application of the non-negativity constraints which is imposed on the parameters of the model and with an important number of lags, it is possible that one of the parameters would violate the constraint(Asghar & Abid, 2007). However, some of these problems are solved through an extension of the ARCH model, the GARCH model which is universally used in the empirical studies related to the volatility of time series (Asghar & Abid, 2007).

4.2.2. The Generalized Autoregressive Conditional Heteroskedasticity models

4.2.2.1. The Generalized Autoregressive Conditional Heteroskedasticity model

In 1986, Bollerslev proposed an extension to the ARCH model, the GARCH model in his paper "Generalized Autoregressive Conditional Heteroskedasticity". In his research, he developed a generalization of the ARCH model by computing the formula with an additional term which is the previous variances of the time series, σ^2. Therefore, the formula of the GARCH (*p*, *q*), with *p* lags of the conditional variance in the linear ARCH(*q*), is the following

$$R_t = \mu_t + \epsilon_t \quad (16)$$

$$\epsilon_t = z_t \sigma_t \quad (17)$$

$$\sigma_t^2 = \omega + \sum_{i=1}^{q} \alpha_i \epsilon_{t-i}^2 + \sum_{i=1}^{p} \beta_i \sigma_{t-i}^2 \tag{18}$$

Equations (16) and (17) are the same as the equations (12) and (13) and the principle which linked them to the GARCH model is the same as the one explained for the ARCH formula. Therefore, the equation (18) is investigated. In the ARCH model, the model has a constraint of non-negativity on the parameters. This constraint is repeated in the context of the GARCH model. The parameter ω is greater than zero and the parameter α_i is greater or equal to zero. In addition to these parameters that are also present in the ARCH model, β, which is the new parameter in this model, is also greater or equal to 0 (Bollerslev, 1986). Through the parameters, it is possible to calculate the unconditional variance which is

$$\sigma^2 = \omega/(1 - \alpha - \beta) \tag{19}$$

Therefore, another constraint in the GARCH formula is that $\alpha+\beta$ is lower than 1 in order to have a bounded volatility. If $\alpha+\beta$ is greater than 1, the variance will not be defined and consequently, would be non-stationary in variance (Akigiray, 1989). In the GARCH model, the interpretations of the two first parameters are the same as the ARCH model. The presence of β in the equation means that the variance depends not just on the past returns, but also on the past variances (Murphi, 2008). Concerning the estimation of the parameters, as it has been used for the ARCH process, the maximum likelihood is applied (Engle, 2001).

The GARCH model enables the researchers to have a more flexible lag structure and at the same time a longer memory (Bollerslev, 1986). After the publication of Bollerslev related to this volatility model, many researchers used this new methodology in order to investigate the volatility of the time series. It has been noticed that the time series of daily asset returns shows a significant level of dependence and then, among the different class of conditional heteroskedasticity processes, the GARCH (1,1) model has proved to deliver the best fit in the data (Akgiray, 1989). Therefore, the problem related to the lag order in the ARCH model is not present in the context of the GARCH model and most of the researchers use the GARCH (1,1) process. This formula of a GARCH (1,1) is given by

$$\sigma_t^2 = \omega + \alpha_1 \epsilon_{t-1}^2 + \beta_1 \sigma_{t-1}^2 \quad (20)$$

Therefore, this model is able to explain the volatility of a time series according to its parameters that are, the long-term average of the variance which is the constant of the model, the effect of the volatility shock from yesterday and the level of volatility from yesterday (Campbell, 1996). Nonetheless, despite the popularity of this model, there are several drawbacks in the model. One of the most important problems is related to the fact that the GARCH model is not capable of reacting differently at the occurrence of positive and negative innovations. This constitutes a problem because in the financial literature, researchers have demonstrated that volatility are likely to increase more after the occurrence of a large negative shock than an equally positive shock. This is defined as the leverage effect and a solution to counter this problem lies in the extensions of the GARCH model (Engle & Ng, 1993).

After the introduction of the GARCH model in 1986, several extensions of the GARCH model were presented in the financial literature with the purpose to counter the problems related to the original GARCH model (Terasvirta, 2006). One of the first extensions is the GJR-GARCH model (Glosten, Jagannathan & Runkle, 1993) which is a GARCH model able to capture the leverage effect defined here above. Then, another extension is the EGARCH model (Nelson, 1991) which, in addition to being able to capture the leverage effect, has the property to cancel out the constraint of the non-negativity of the parameters. Nonetheless, although these extensions in the GARCH model seem to overcome its drawbacks, it does not necessarily mean that these models fit better the data related to the volatility. In order to compare the performance of these GARCH models, researchers use several information criteria (Javed & Mantalos, 2011).

4.2.2.2. Extension of the Generalized Autoregressive Conditional Heteroskedasticity model

The GARCH extensions mentioned here above are investigated later as well as the information criteria methodology which enables to compare the performance of the GARCH models. Now that the GARCH model has been explained and that it has been demonstrated as a popular model in order to model the volatility of a time series, the questions of this paper are partly tackled through the utilization of a GARCH model. Nonetheless, there exists several GARCH models and the three GARCH mentioned in this paper, the GARCH, GJR-GARCH and EGARCH are used in order to model the volatility of the exchange rate time series. The purpose of implementing several GARCH models is to find out which GARCH process has the better fit to the data and this will be shown through the information criteria.

4.2.2.2.1. Exponential Generalized Autoregressive Conditional Heteroskedasticity model

Therefore, the GARCH (1,1), which has been already explained and whose the formula is represented by the equation (20), is implemented to the EUR/GBP and GBP/USD returns of the time period during 2013 and 2019. Then, the EGARCH (1,1) is also implemented in the same time series. The formula of the EGARCH (1,1) is the following

$$ln(\sigma_t^2) = \omega + \alpha_1 \left[\frac{|\epsilon_{t-1}|}{\sigma_{t-1}} - \sqrt{\frac{2}{\pi}} \right] + \beta_1 ln(\sigma_{t-1}^2) + \lambda \left[\frac{\epsilon_{t-1}}{\sigma_{t-1}} \right] \tag{21}$$

Therefore, in this model, the EGARCH (1,1) process allows for the asymmetric behavior of shocks through the parameter λ. If λ is lower than zero, then negative innovations will increase the volatility more than the positive innovations. On the other hand, if λ is greater than zero, the positive innovations will increase the volatility more than the negative innovations (Nelson, 1991). Concerning the other parameters, their interpretations are the same as the interpretations for the GARCH model. In addition to account for the leverage effect, the EGARCH model specifies the logarithm of the conditional volatility and consequently, the model enable to cancel out the parametric constraint which imposes the non-negativity of the GARCH parameters (Chang, 2017). However, there is empirical evidence that the variability of the logarithmic conditional variance implied by the EGARCH model is too high (Engle & Ng, 1993). This last statement is supported through the *appendix* 13 where the graph of the news impact curve of different GARCH models is displayed (Caporin & Costola, 2019).

4.2.2.2.2. GJR - Generalized Autoregressive Conditional Heteroskedasticity model

Concerning the third GARCH model mentioned, the GJR-GARCH is also implemented to the EUR/GBP and GBP/USD returns of the period between 2013 and 2019. Therefore, the GJR-GARCH (1,1) process is formulated by

$$\sigma_t^2 = \omega + \alpha_1 \epsilon_{t-1}^2 + \gamma_1 \epsilon_{t-1}^2 I(\epsilon_{t-1} < 0) + \beta_1 \sigma_{t-1}^2 \tag{22}$$

In this GARCH model, the GJR-GARCH process enables the conditional variance to react differently to negative and positive innovations, shocks in the volatility from the past. Therefore, as the EGARCH process, the leverage effect is taken into account. The leverage effect is captured by the parameter γ in the GJR-GARCH equation. The positive innovation will have an impact of α, while the negative innovation will have an impact of $(\alpha+\gamma)$ (Bollerslev, 2009).

Furthermore, *I(•)* represents the indicator function which allows the model to differentiate the sign of the innovations in the volatility. This parameter could be perceived as a dummy variable which takes the value of 1 if the previous shock is negative (Glosten, Jagannathan & Runkle, 1993). Then, the parametric constraint related to the non-negativity of the parameters are applied in the context of the GJR-GARCH (Dutta, 2014). However, the advantage of this model in comparison with the EGARCH model, which is the other model that captures the asymmetric volatility, is that the conditional variance is directly computed and is not modeled through the natural logarithm. Therefore, the GJR-GARCH is easier to implement and more intuitive than the EGARCH in practice (Hayashi, 2000).

4.2.3. Information criterions

After the explanations related to the different GARCH models that are used in order to understand the volatility on the time series of the exchange rates, the methodologies in order to compare the performance of these GARCH models are introduced. The reason behind this investigation on the performance is linked to the fact that the evaluation of real-life data depends on the specification of the model. Selecting the most appropriate model constitutes the essence of data analysis. Consequently, this explains the importance of model selection criteria in order to assess the goodness of a model (Javed & Mantalos, 2011).

Akaike (1973) proposed a method in order to evaluate the model in terms of Kullback-Leibler information which is a method that is based on the principle of closeness between the generic distribution *g(x)* generated by the model and the real-life distribution *f(x)*. The Kullback-Leibler information *I (f, g)* constitutes the information lost when the model *g(x)* is implemented in order to approximate *f(x)*. The formula of this information criteria is

$$I(f,g) = \int f(x)ln\left[\frac{f(x)}{g(x\mid\theta)}\right]dx \qquad (23)$$

However, the most popular method to evaluate a model is the Akaike Information Criterion, AIC. This model was designed with the objective to be an asymptotically unbiased estimate of the Kullback-Leibler index. The formula of the AIC is the following

$$AIC = -2lnL + 2k \qquad (24)$$

In this formula, the *L* represents the maximized value of the likelihood function. The other parameter, *k*, represents the number of parameters used in this model. This Akaike criterion is perceived as a measure of goodness of fit for an estimated statistical model. Nonetheless, a pitfall arises in this information criteria due to the fact that there is a compromise between the log maximized likelihood and *k* that increases with the number of parameters in the model. Furthermore, it has been demonstrated through empirical evidences that AIC tends to choose models that are over-parameterized (Shibata, 1976). Therefore, a solution proposed by the researchers would be to penalize the likelihood which increases by adding parameters (Javed & Mantalos, 2011).

Schwarz (1978) introduced another criterion in order to evaluate the model which is defined in function of their posterior probability and therefore, is implemented through a Bayesian approach. The formula of this information criteria which is called the Bayesian Information Criterion, BIC, is

$$BIC = -2lnL + klnT \qquad (25)$$

In this formula, the parameters *L* and *k* have the same interpretation as the one in the AIC formula. The extension of this model lies in the new variable *T*. This variable represents the number of observations and therefore, the penalty term is larger in the equation (25) than in equation (24) (Kuha, 2010). Nonetheless, some studies have demonstrated several arguments in favor of AIC over BIC (Burnham & Anderson, 2004).

Therefore, the two information criterions mentioned here above are used on the GARCH models and according to their result, it will determine the most appropriate model to use in the context of this research. The model that displays the lowest information criteria index is considered as the most appropriate GARCH model (Bulteel et al., 2013). Nonetheless, it should be highlighted that the three GARCH models analyzed do not have the same number of parameters. The GARCH (1,1) process has 3 parameters and on the other hand, the EGARCH and GJR-GARCH have 4 parameters. Then, the BIC seems to be the best information criteria in order to compare these models due to the fact that they have different number of parameters and the BIC penalizes the most the number of parameters (Kuha, 2010).

4.2.4. Specification test

Another information which delivers insights on the GARCH model is the Ljung-Box test which is a specification test related to the model. Through this test, it is possible to inquire about the validity of the model. The principle is that the model should capture the dynamics of the data which means that the squared standardized residuals should be independently distributed (Burns, 2002). The formula of this test is the following

$$Q = n(n+2)\sum_{k=1}^{h} \frac{\rho_k^2}{n-k} \tag{26}$$

In this formula, *n* is the number of observations, *h* represents the number of lags that is implemented in this test and ρ constitutes the sample autocorrelation at lag *k*. Then, the level of significance is determined on the basis of a chi-squared distribution with *h* degree of freedom. Nonetheless, this test is not used in order to compare the quality of the GARCH models but instead, is used in order to guarantee that the squared standardized residuals of the model are independently distributed. If this assumption is met, this constitutes a proof that the model delivers a good fit of the data (Burns, 2002).

The determination of the most appropriate model in this paper is important due to the fact that the most appropriate GARCH model is used in order to answer to the questions of this thesis. In the context of the first question, related to a change in the volatility after the Brexit announcement, the best GARCH model is extended through the use of a dummy variable in the model. The approach of introducing a dummy variable is perceived as the most popular methodology in order to investigate on the event-study (Binder, 1998). This GARCH extension could be perceived as a GARCH-X process in which an additional parameter is added in the model (Apegix, 1998). In this case, the additional parameter is a dummy variable that takes the value of 1 for the dates after the Brexit announcement and 0 otherwise.

4.2.5. Methodology used to detect a change in the volatility structure

4.2.5.1. GARCH model with dummy variable

In order to get an idea about the different GARCH models with the implementation of a dummy variable, here is the different GARCH (1,1) models for which an additional variable is added.

The GARCH (1,1) model with dummy variable

$$\sigma_t^2 = \omega + \alpha_1 \epsilon_{t-1}^2 + \beta_1 \sigma_{t-1}^2 + \phi D_t \tag{27}$$

The EGARCH (1,1) model with dummy variable

$$ln(\sigma_t^2) = \omega + \alpha_1 \left[\frac{|\epsilon_{t-1}|}{\sigma_{t-1}} - \sqrt{\frac{2}{\pi}} \right] + \beta_1 ln(\sigma_{t-1}^2) + \lambda \left[\frac{\epsilon_{t-1}}{\sigma_{t-1}} \right] + \phi D_t \tag{28}$$

The GJR-GARCH (1,1) model with dummy variable

$$\sigma_t^2 = \omega + \alpha_1 \epsilon_{t-1}^2 + \gamma_1 \epsilon_{t-1}^2 I(\epsilon_{t-1} < 0) + \beta_1 \sigma_{t-1}^2 + \phi D_t \tag{29}$$

The constraints and interpretations related to the parameters in the GARCH models are the same as explained before. Concerning the new parameter, ϕ, there is no constraint on this parameter.

Then, as explained previously, one of these GARCH models is used in order to observe if the volatility has changed after the Brexit announcement. This observation is possible through the sign of the additional parameter, ϕ. If the sign of ϕ is positive then, the volatility is supposed to have increased during the post-referendum period. If the sign of ϕ is negative then, the volatility is supposed to have decrease during the post-Brexit period. However, the most important characteristic in the determination of the volatility change is the level of significance of the parameter ϕ. If this parameter reveals itself to be not significant, the methodology of the GARCH model with a dummy variable will not be able to deliver the required information in order to answer to the first question.

Nonetheless, two other methodologies are used in order to investigate more on the change in the GBP volatility structure after the result of the EU referendum. These methodologies are the CUSUM test and the bootstrapping process. Through these three different approaches, the volatility change of the GBP is covered.

4.2.5.2. The CUSUM test

Concerning the CUSUM test, as it has been explained in the literature review part, this type of test is mainly used in order to detect structural breaks in the volatility. There exist several types of CUSUM test, nonetheless, the one that is implemented in the context of this research is the CUSUM test developed by Inclàn and Tiao (1992). The formula of this test is the following

$$IT = \sqrt{T/2} \max_k \left| \sum_{j=1}^{k} X_j / \sum_{j=1}^{T} X_j - \frac{k}{T} \right| \tag{30}$$

In this formula, $X_t = e_t^2$ and it represents the squared standardized residuals of the GARCH model (de Pooter & van Dijk, 2004). Then, under the null hypothesis which states that there is no structural break, the *IT* CUSUM test has a Kolmogorov-Smirnov distribution. Therefore, if the maximum value among the sums calculated through the IT CUSUM test is higher than 1.36, which represents the 5% critical value of a Kolmogorov-Smirnov distribution, there is a structural break in the unconditional level of volatility (Smith, 2008). If there is no structural break in the series, the model is said to be well specified due to the fact that it seems to capture the dynamic of the model (Rapach & Strauss, 2008).

In the context of the first question, the IT CUSUM test exposed here above is implemented in the GARCH model which performs the best in terms of goodness of fit and therefore, which demonstrates the lowest value for the AIC and BIC index. The principle of choice related to the GARCH model for this methodology is the same as the choice for the previous methodology, the GARCH process with a dummy variable. Furthermore, if a structural break is found out by the IT CUSUM test and that the dummy variable shows significant result, then the application of the IT CUSUM test on the GARCH model with the dummy variable would lead to a different result and there could be no more structural break due to the fact that the GARCH model including the dummy variable captures better the dynamic of the model (Lee, 2000).

4.2.5.3. The Bootstrap methodology

The last approach which allows to investigate on the volatility change after the Brexit announcement is the bootstrapping method. This methodology examines the change in the parameters of the GARCH model in order to observe if the differences of the GARCH parameters between the two periods, before and after the Brexit announcement, are significant. The bootstrap techniques are very useful tools in the field of statistical inference (Wickramarachchi, 2008). The fundament of bootstrapping is that the real-world data generated from a specific observation are randomly resample. Through this data resample technique, the random resample process could be realized with replacement or without replacement[16]. According to the purpose of bootstrap technique, the observations are randomly resampled several times. One popular purpose of the bootstrap method is the construction of confidence intervals (Ho, 2019).

Therefore, researchers resample several times the original dataset in order to observe a specific statistic metric or a specific statistic parameter in an equation for each resampled dataset. Through the several resampling, it is possible to observe the distribution of this specific statistic metric or this specific statistic parameter. Furthermore, the distribution of the parameters or the statistics generated through the resampling follows a normal distribution. This is explained due to the Central Limit Theorem which states that a large number of independent random samples will approach a normal distribution even if the underlying population used for the resampling does not have a normal distribution. Then, through the confidence interval generated by the

[16] Without replacement means that no observation can be selected more than once in the sample. With replacement is the fact that the observation could appear multiple times in one sample.

resampling distribution, it is possible to see if the statistic metric or the statistic parameter of the original dataset lies in the 95% of the confidence interval (Ho, 2019).

Concerning this research, the first step of this technique is to separate the two samples of the exchange rate returns, the EUR/GBP and the GBP/USD in sub-samples that constitute additional time series. The first time series is the time series before the Brexit announcement and the second time series is the one after the Brexit announcement. Secondly, the GARCH model which has demonstrated to be the most efficient in term of goodness of fit is implemented to each time series. Then, the difference in the parameters of the two GARCH models, before the Brexit and after the Brexit, are calculated. At this point, the process looks like this

$$TS = R_{i,1}, R_{i,2}, ...R_{i,759}, R_{i,760}, R_{i,761}, ...R_{i,1520}, R_{i,1521}$$

$$TS_{i,2013-2016} = R_{i,1}, R_{i,2}, ...R_{i,760}$$

$$TS_{i,2016-2019} = R_{i,761}, ...R_{i,1520}, R_{i,1521}$$

This first part constitutes the division of the time series of the returns during 2013 and 2019. *R* represents the daily returns. Therefore, the two sub-sample have each 760 observations which are the returns. After the division, a GARCH model is implemented in each of these sub-sample, in a case of a GARCH (1,1) process,

$$\sigma_t^2 = \omega + \alpha_1 \epsilon_{t-1}^2 + \beta_1 \sigma_{t-1}^2$$

$$TS_{2013-2016} = (\omega_1; \alpha_1; \beta_1)$$
$$TS_{2016-2019} = (\omega_2; \alpha_2; \beta_2)$$

The GARCH implementations produce different estimations of GARCH parameters for each time series and the differences of these parameter estimations are

$$\omega_1 - \omega_2$$
$$\alpha_1 - \alpha_2$$
$$\beta_1 - \beta_2$$

Consequently, the hypothesis which states that the difference of these GARCH parameters is equal to zero is formulated by

$$\left.\begin{aligned} \omega_1 &= \omega_2 \\ \alpha_1 &= \alpha_2 \\ \beta_1 &= \beta_2 \end{aligned}\right\} \qquad \begin{aligned} \omega_1 - \omega_2 &= 0 \\ \alpha_1 - \alpha_2 &= 0 \\ \beta_1 - \beta_2 &= 0 \end{aligned}$$

In order to inquire about the level of significance of these differences, the bootstrap method is introduced. The following step is to resample several times the original dataset of returns of the exchange rates which is

$$TS_i = R_{i,1}, R_{i,2}, ...R_{i,1520}, R_{i,1521}$$

The original dataset is resampled N times which deliver N new time series

$$TS_1^* = R_{1,1}^*, R_{1,2}^*, ...R_{1,1520}^*, R_{1,1521}^*$$

$$TS_2^* = R_{2,1}^*, R_{2,2}^*, ...R_{2,1520}^*, R_{2,1521}^*$$

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$$TS_N^* = R_{N,1}^*, R_{N,2}^*, ...R_{N,1520}^*, R_{N,1521}^*$$

As it has been done with the original dataset of returns, these resampled time series are divided up into two sub-samples of each 760 observations. After, a GARCH model is implemented for each sub-sample and the estimation of the GARCH parameters are generated.

$$\sigma_t^2 = \omega + \alpha_1 \epsilon_{t-1}^2 + \beta_1 \sigma_{t-1}^2$$

$$TS_{1,1}^* = (\omega_{1,1}^*; \alpha_{1,1}^*; \beta_{1,1}^*)$$
$$TS_{1,2}^* = (\omega_{1,2}^*; \alpha_{1,2}^*; \beta_{1,2}^*)$$

$$TS_{2,1}^* = (\omega_{2,1}^*; \alpha_{2,1}^*; \beta_{2,1}^*)$$
$$TS_{2,2}^* = (\omega_{2,2}^*; \alpha_{2,2}^*; \beta_{2,2}^*)$$

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$$TS^*_{N,1} = (\omega^*_{N,1}; \alpha^*_{N,1}; \beta^*_{N,1})$$
$$TS^*_{N,2} = (\omega^*_{N,2}; \alpha^*_{N,2}; \beta^*_{N,2})$$

After the generation of the estimation of the GARCH parameters, the following step is the calculation of the differences of these parameters for each resampled dataset. These calculations are

$$\omega^*_{1,1} - \omega^*_{1,2}$$
$$\alpha^*_{1,1} - \alpha^*_{1,2}$$
$$\beta^*_{1,1} - \beta^*_{1,2}$$
$$\vdots$$
$$\omega^*_{N,1} - \omega^*_{N,2}$$
$$\alpha^*_{N,1} - \alpha^*_{N,2}$$
$$\beta^*_{N,1} - \beta^*_{N,2}$$

Then, three cumulative distribution functions are established for each difference of GARCH parameters. As stated previously, these cumulative distribution functions are expected to approach a normal distribution. The final step of this procedure is to observe if the differences of the GARCH parameters generated by the original observations lie in the 95% confidence interval of the cumulative distribution functions. If the difference of one of the GARCH parameters is situated in the confidence interval, the change in the parameter of the GARCH is said to be not significant. On the other hand, if the difference of the GARCH parameters is not situated in the confidence interval, then, the change in the GARCH parameter is said to be significant.

4.2.6. Methodology used to measure the impact of the announcements on the volatility

After covering the first question in this paper, the second question which is related to the impact of the Brexit news on the GBP volatility is tackled. In order to investigate on the significance of the Brexit news, a GARCH model with dummy variable is implemented on the exchange rate returns that occurred during the post-referendum period. The procedure is the same as the one explained for the implementation of a GARCH model including binary variable in order to answer to the first question. Regarding the dummy variable, the value takes the value of 1 if a

Brexit announcement has been made during the day and 0 otherwise. Therefore, if the dummy variable is demonstrated as a significant parameter, this will constitute a proof that the Brexit announcement has an impact on the volatility of the EUR/GBP and/or the GBP/USD.

In addition to the level of significance of the dummy variable in the GARCH model, a further analysis is undertaken and it is related to several information criterion comparisons between the GARCH model without the dummy variable and the GARCH model with the dummy variable. Through this analysis, it is possible to observe if the GARCH model, including the dummy variable, performs better than the original model in term of goodness of fit. This analysis is conducted through the Akaike Information Criteria and the Bayesian Information Criteria. The two information criterions are explained in the part here above.

Then, in order to develop a better understanding regarding the impact of the Brexit news on the GBP volatility, the post-referendum time period is divided up into three different time series that are, the period between 2016 and 2017, the period between 2017 and 2018 and finally, the last period which is between, 2018 and 2019. Through these 3 different time series analyses, it is possible to observe the significance of the Brexit news on the volatility for each year after the Brexit announcement. Furthermore, as explained here above, the comparison of several information criteria of the GARCH models with the dummy variable and without the dummy variable provides with the ability to observe if the GARCH models, including the dummy variable, explain better the dynamics of the model.

Therefore, the methodologies explained here above are expected to deliver the answers to the questions that are, does the volatility structure of the GBP has changed after the Brexit announcement and how the announcements related to the Brexit have impacted the volatility of the GBP.

5. Empirical result

5.1. Change in the volatility structure

5.1.1. Selection of the GARCH model

The first purpose in this paper is to know if the volatility structure of the GBP/EUR and GBP/USD have changed after the announcement of the Brexit. As explained previously, there exist several GARCH models that are able to model the volatility of a time series. Nonetheless, among the three GARCH models mentioned in the methodology part, only one is used for the rest of the investigation due to the fact that this GARCH model will be perceived as the one which best captures the dynamic of the model. Therefore, the three GARCH models are implemented to the exchange rate returns and according to the information criterion, a GARCH model will be used for the following step.

Table 3 – GARCH MODELS EUR/GBP (2013 - 2019)

EUR/GBP (2013-2019)

GARCH (1,1)	Coefficient	Std.Error	t Value	Prob
ω	0.001	0.000	1.932	0.053
α	0.048	0.011	4.522	0.000
β	0.946	0.011	79.886	0.000
	Statistic	p-value		
Ljung-Box (r=5)	2.449	0.517		
Ljung-Box (r=9)	3.969	0.594		
AIC	1.3883			
BIC	1.3988			
EGARCH (1,1)	Coefficient	Std.Error	t Value	Prob
ω	-0.003	0.003	-1..064	0.287
α	-0.0112	0.010	-1.117	0.264
β	0.994	0.003	299.62	0.000
γ	0.092	0.013	7.060	0.000
	Statistic	p-value		
Ljung-Box (r=5)	6.816	0.057		
Ljung-Box (r=9)	8.306	0.112		
AIC	1.3888			
BIC	1.4028			
GJR-GARCH (1,1)	Coefficient	Std.Error	t Value	Prob
ω	0.001	0.000	1.587	0.112
α	0.021	0.006	3.347	0.000
β	0.961	0.004	218.67	0.000
γ	0.033	0.011	3.069	0.021
	Statistic	p-value		
Ljung-Box (r=5)	4.489	0.199		
Ljung-Box (r=9)	6.088	0.288		
AIC	1.3886			
BIC	1.3996			

Source: Bloomberg – Own Calculations.

In table 3, the GARCH model that delivers the lowest AIC and BIC index for the EUR/GBP exchange rate returns is the GARCH (1,1) model. This means that the GARCH (1,1) is the volatility model that captures the best the dynamic of the model. This result is in line with the findings in the empirical literature related to the volatility of the exchange rate. It has been proved that when it comes to model the exchange rate volatility, symmetric GARCH models perform better than asymmetric GARCH models (Arachchi, 2018). Furthermore, this symmetric characteristic is also explained through the fact that exchange rate returns can be perceived as a zero-sum game. Therefore, a negative innovation for the EUR/GBP, which is expected to increase more the volatility than a positive innovation, constitutes a positive innovation for the GBP/EUR and in this case, the expectation is the opposite. Consequently, this explains why the symmetric GARCH model suits better in the exercise of modelling the exchange rate volatility (Yam, 2017).

Furthermore, the Ljung-Box test applied on the squared standardized residuals of the GARCH (1,1) model shows a high p-value and consequently, the test fails to reject the null hypothesis which states that the squared standardized residuals are not autocorrelated. Therefore, the GARCH (1,1) model of the EUR/GBP between 2013 and 2019 is the following

$$\sigma_t^2 = 0.001 + 0.048\epsilon_{t-1}^2 + 0.946\sigma_{t-1}^2$$

According to the GARCH (1,1) equation for the EUR/GBP, the volatility of yesterday is an important component in the explanation for the current volatility. Then, the innovation from yesterday also has a role in the explanation of the volatility at day t. Consequently, through the estimation of these parameters, the EUR/GBP exchange rate could be perceived as a relatively stable exchange rate over that time period[17].

In table 4 the three different GARCH models are applied on the GBP/USD exchange rate returns. According to the results related to the information criterions, the observation related to the performance of the symmetric GARCH is the same as the observation for the other exchange

[17] "For daily data the GARCH reaction α usually range between about 0.05 (for a market that is relatively stable) and about 0.1 (for a market that is jumpy or nervous)."
(Alexander, 2008).

rate, the EUR/GBP. Therefore, it confirms that the GARCH (1,1) performs better than the asymmetric GARCH models in order to capture the dynamic of the model. Furthermore, the Ljung-Box test fails to reject the null hypothesis according to which there is no autocorrelation between the squared standardized residuals of the GARCH model. In the case of this exchange rate, the GARCH (1,1) model of the GBP/USD between 2013 and 2019 is the following

$$\sigma_t^2 = 0.006 + 0.085\epsilon_{t-1}^2 + 0.900\sigma_{t-1}^2$$

In comparison with the EUR/GBP, the GBP/USD is a more nervous exchange rate due to the fact that the α parameter is greater than the one for the EUR/GBP and that this exchange rate depends less on the previous level of volatility.

Table 4 – GARCH models GBP/USD (2013-2019)

GBP/USD (2013-2019)

GARCH (1,1)	Coefficient	Std.Error	t Value	Prob
ω	0.006	0.002	2.275	0.022
α	0.085	0.014	5.760	0.000
β	0.900	0.019	45.508	0.000
	Statistic	p-value		
Ljung-Box (r=5)	2.251	0.560		
Ljung-Box (r=9)	3.808	0.621		
AIC	1.5121			
BIC	1.5226			
EGARCH (1,1)	Coefficient	Std.Error	t Value	Prob
ω	-0.018	0.011	-1.634	0.102
α	0.027	0.014	1.873	0.061
β	0.977	0.008	112.63	0.000
γ	0.179	0.025	6.985	0.000
	Statistic	p-value		
Ljung-Box (r=5)	3.119	0.385		
Ljung-Box (r=9)	5.073	0.418		
AIC	1.5123			
BIC	1.5263			
GJR-GARCH (1,1)	Coefficient	Std.Error	t Value	Prob
ω	0.007	0.003	2.363	0.018
α	0.105	0.020	5.244	0.000
β	0.898	0.021	42.636	0.000
γ	-0.046	0.020	-2.253	0.024
	Statistic	p-value		
Ljung-Box (r=5)	2.114	0.591		
Ljung-Box (r=9)	3.723	0.636		
AIC	1.5129			
BIC	1.5239			

Source: Bloomberg – Own Calculations.

Because of the previous observations that demonstrate that the symmetric GARCH model is the best volatility model in order to describe the volatility of the exchange rates return, this GARCH model is used for the rest of this research.

5.1.2. GARCH model with dummy variable

The first question which is investigated concerns the change in the GBP volatility after the Brexit announcement. Three methodologies that could answer to this question were mentioned in the methodology part and the first is through the utilization of a GARCH (1,1) including a dummy variable for the date after the Brexit announcement. This dummy variable is supposed to deliver information on the change in the volatility of the exchange rate through its sign but mainly through its level of significance.

Table 5 – GARCH (1,1) including dummy variable after EU referendum

EUR/GBP (2013-2019) with Dummy (After EU Referendum)

GARCH-X (1,1)	Coefficient	Std.Error	t Value	Prob
ω	0.002	0.001	1.884	0.059
α	0.048	0.011	4.316	0.000
β	0.946	0.012	76.474	0.000
ϕ	0.000	0.001	0.000	0.999
	Statistic	p-value		
Ljung-Box (r=5)	2.448	0.517		
Ljung-Box (r=9)	3.969	0.594		

GBP/USD (2013-2019) with Dummy (After EU Referendum)

GARCH-X (1,1)	Coefficient	Std.Error	t Value	Prob
ω	0.006	0.002	2.452	0.014
α	0.089	0.015	5.913	0.000
β	0.890	0.021	41.341	0.000
ϕ	0.003	0.002	1.282	0.199
	Statistic	p-value		
Ljung-Box (r=5)	2.457	0.515		
Ljung-Box (r=9)	4.159	0.562		

Source: Bloomberg – Own Calculations.

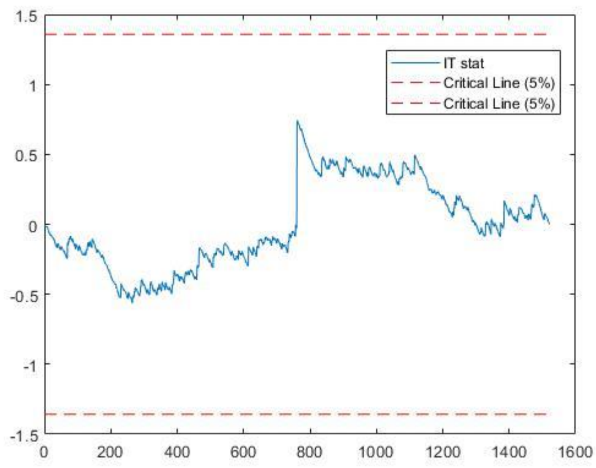
According to the result in table 5, the dummy variable, which is represented by the parameter ϕ, does not show any effect in the case of the EUR/GBP. Furthermore, the other parameters keep the same values as the ones in the GARCH model without the dummy variable.

Nonetheless, the p-value of this parameter displays a high number and therefore, it is not possible to deliver a conclusion with this methodology regarding to the volatility change for the EUR/GBP after the Brexit referendum. Concerning the GBP/USD exchange rate, the introduction of the dummy variable in the GARCH model shows a small positive effect. However, this variable does not show a p-value lower than 5%. Consequently, it is also not possible to conclude for the volatility change regarding the GBP/USD exchange rate after the Brexit referendum.

5.1.3. The IT CUSUM test

The second possibility in order to investigate on a change in the volatility of the EUR/GBP and the GBP/USD is through the IT CUSUM test. As it has been explained in the methodology part, the IT CUSUM test provides with the information on a structural break in the volatility structure. Therefore, if this test notices a break in the volatility structure of the exchange rates, this would constitute a proof of a change in the volatility structure. In order to produce this test, the standardized residuals of the GARCH (1,1) model are required.

Figure 1 – IT statistic EUR/GBP (2013 - 2019)

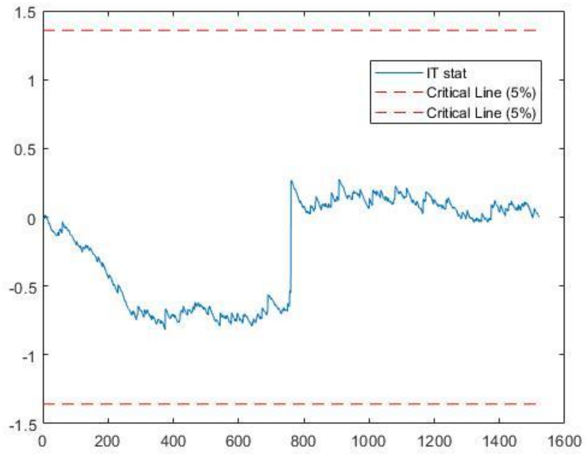


Source: Bloomberg – Own calculations.

The figure 1 is related to the IT CUSUM calculation based on the standardized residuals of the GARCH (1,1) for the EUR/GBP exchange rate. As it has been explained in the methodology part, the IT CUSUM test has a Kolmogorov-Smirnov distribution and a structural break is said to occur when the IT statistic reaches a critical line which represent the 5% critical value of the

Kolmogorov-Smirnov distribution. However, according to the IT CUSUM test, there is no structural break in the EUR/GBP volatility between 2013 and 2019. During this time period, the blue line that represents the IT statistic never reached the critical line and therefore, the model, GARCH (1,1) is said to be well specified over the time period analyzed. Nonetheless, an interesting observation that could be made with the graph is the jump in the IT CUSUM statistic that occurred at the moment of the result announcement of the EU referendum.

Figure 2 – IT statistic GBP/USD (2013 – 2019)



Source: Bloomberg – Own calculations.

The figure 2 represents the IT CUSUM calculations based on the standardized residuals of the GARCH (1,1) for the GBP/USD exchange rate. In the context of this exchange rate, the IT statistic line does not reach the critical lines. Therefore, such as for the EUR/GBP exchange rate, there is no structural break observed regarding the volatility of this exchange rate during the time period of 2013 to 2019. Another similarity with the IT CUSUM test on the EUR/GBP exchange rate is the jump of the IT CUSUM statistic on the day of the announcement of the Brexit, the 24th of June 2016.

In the *appendices* 14 and 15, the figures of the IT CUSUM test based on the standardized residuals of the GARCH (1,1) models including the dummy variable are available. Despite the introduction of the dummy variable in the GARCH models, the IT statistic lines do not show important differences with the ones here above. The reason is that the dummy variables introduced in the GARCH (1,1) models are not enough relevant in order to explain the conditional volatility and the other GARCH parameters remain the same.

Regarding the comparison of the CUSUM test results of this research and these from the financial literature, an important remark is that when researchers aim to test for structural breaks in GARCH models, among the different classes of asset returns, the exchange rate returns are usually the ones that show the lowest evidence of structural break in the volatility level (Smith, 2008).

5.1.4. Bootstrap method

The last option covered in order to observe a change in the GBP volatility structure after the Brexit announcement is through the bootstrap methodology. The first step, as explained in the methodology part, is to observe the GARCH (1,1) for the period before the Brexit and the post-referendum period. Afterwards, it will be possible to analyze the differences of the GARCH parameters.

Table 6 – GARCH (1,1) models EUR/GBP

EUR/GBP (2013-2016)

GARCH (1,1)	Coefficient	Std.Error	t Value	Prob
ω	0.000675	0.00017	0.950	0.341
α	0.030497	0.00829	3.677	0.000
β	0.968503	0.00893	107.81	0.000

	Statistic	p-value
Ljung-Box (r=5)	1.244	0.802
Ljung-Box (r=9)	3.721	0.636

EUR/GBP (2016-2019)

GARCH (1,1)	Coefficient	Std.Error	t Value	Prob
ω	0.002021	0.00145	1.391	0.164
α	0.023527	0.01009	2.331	0.019
β	0.965693	0.01521	63.455	0.000

	Statistic	p-value
Ljung-Box (r=5)	1.253	0.800
Ljung-Box (r=9)	1.614	0.946

Source: Bloomberg – Own calculations

Table 7 – GARCH (1,1) models GBP/USD

GBP/USD (2013-2016)

GARCH (1,1)	Coefficient	Std.Error	t Value	Prob
ω	0.000779	0.00069	1.128	0.259
α	0.031489	0.00770	4.089	0.000
β	0.966901	0.00827	116.896	0.000
	Statistic	p-value		
Ljung-Box (r=5)	0.422	0.969		
Ljung-Box (r=9)	0.654	0.996		

GBP/USD (2016-2019)

GARCH (1,1)	Coefficient	Std.Error	t Value	Prob
ω	0.003635	0.00104	2.026	0.000
α	0.016427	0.00249	2.647	0.000
β	0.969766	0.00883	109.856	0.000
	Statistic	p-value		
Ljung-Box (r=5)	1.531	0.732		
Ljung-Box (r=9)	3.308	0.707		

Source: Bloomberg – Own calculations

According to the result in the table 6, the GARCH parameters, related to the EUR/GBP, change between the two periods of time. After the Brexit announcement, ω increased and the parameters α and β decreased.

Concerning the GBP/USD GARCH parameters, the coefficients are available in table 7 and a change for each of the parameters is observed during the two periods of time. After the Brexit announcement, ω and β increased and the α decreased. Then, before interpreting the change in the parameters of the GARCH models, it would be more efficient to investigate first on the level of significance of these changes.

In order to proceed to this investigation, the bootstrap methodology, as explained in the methodology part, is implemented. Consequently, the bootstrap produces several distributions related to the differences of the GARCH parameters that were generated by the resampling of the original data. In the *appendices* 16, 17 and 18, the distributions of the differences of the EUR/GBP GARCH parameters are available. Then, the *appendices* 19, 20 and 21 show the distributions of the differences of the GBP/USD GARCH parameter.

According to the graphs related to the distribution of the GARCH parameters differences, all the distributions are centralized around zero and consequently, these distributions could deliver information on the significance level of the difference in the GARCH parameters. In order to investigate if the parameters differences are significant or not, a 95% confidence interval is introduced for each distribution. Through the confidence interval of 95%, it is possible to investigate on the significance level of the parameter differences generated by the real data. If the difference of the parameters lies in the confidence interval, therefore, the change in the GARCH parameter is said to be not significant. *Appendices* 22, 23 and 24 provide the distributions with confidence interval for the differences of the EUR/GBP GARCH parameters. Then, the *appendices* 25, 26 and 27 are related to the distributions with confidence interval for the differences of the GBP/USD GARCH parameters.

The results display in table 8 summarize the distributions and also highlight if the differences in the GARCH parameters generated by the real market observations lie or not in the 95% confidence intervals that have been generated by the bootstrap methodology.

Table 8 – Bootstrap for the significance of the GARCH parameters differences

Bootstrap EURGBP

GARCH (1,1)	Mean	Standard Deviation	IC (0.025)	IC (0.975)	Value
ω	0.00098	0.02226	-0.00096	0.002935	-0.00135
α	0.00004	0.01259	-0.00105	0.00115	0.00697
β	-0.00266	0.10162	-0.01157	0.00624	0.00281

Bootstrap GBPUSD

GARCH (1,1)	Mean	Standard Deviation	IC (0.025)	IC (0.975)	Value
ω	-0.00092	0.02005	-0.00268	0.00083	-0.00286
α	0.00027	0.01121	-0.00071	0.00125	0.0151
β	-0.00012	0.07836	-0.00699	0.00674	-0.00286

Sources: Bloomberg – Own calculations.

The only GARCH parameter that does not change significantly for both exchange rates is β. It has been observed that the real β difference for both exchange rates are situated in the 95% confidence interval of the β differences distribution. Then, the differences of the ω in the two exchange rates are significant. This is due to the fact that the differences of ω between the two periods do not lie in the 95% confidence interval of the distributions of the ω differences and therefore, the change in these parameters is significant in the context of both exchange rates. Then, regarding the differences for the α parameter, for both exchange rates these differences are significant due to the fact that they are not in the 95% confidence interval.

In order to interpret these results, it should be reminded what the role of the GARCH parameters is. The ω represents the long-run average variance term and constitutes the intercept of the GARCH model. The α shows how a volatility shock from yesterday explains the current level of volatility and the β explains the relationship between the level of volatility from yesterday and the volatility that occurs today (Alexander 2008). Therefore, for both exchange rates, the impact of the volatility from the past on the current level of volatility does not change significantly. However, for the EUR/GBP and GBP/USD, it is demonstrated that the parameter related to the volatility shocks has significantly decreased which means that during the post-referendum period, the EUR/GBP and the GBP/USD exchange rates were less sensitive to market events compared to the period before the Brexit announcement. Regarding the long-run average variance parameter, for both exchange rates, these parameters increased significantly. Therefore, according to these estimates, the unconditional variance for both exchange rates could be calculated through the equation (19). These computations demonstrate that the unconditional variance for the EUR/GBP and the GBP/USD have decreased for the period after the EU referendum.

Unconditional Variance

EUR/GBP	GBP/USD
Unconditional Variance (2013-2016) = 0.675	Unconditional Variance (2013-2016) = 0.484
Unconditional Variance (2016-2019) = 0.187	Unconditional Variance (2016-2019) = 0.218

Consequently, the main observation related to the change in the volatility structure lies in the fact that the volatility innovations had less importance in the post-referendum period than the time period before the Brexit announcement. This difference is more important for the

GBP/USD than the EUR/GBP. This could be explained through the fact that the dollar is perceived as a central currency and many events could affect the movement of the USD (Groux et al., 2011). Consequently, it could be assumed that more events with volatility innovations impacted the GBP/USD between 2013 and 2016 than during the post-EU referendum period. Concerning the EUR/GBP, it should be emphasized that in 2013, the eurozone just went out from the European debt crisis (Ehrman et al., 2013). Consequently, after this eurozone crisis, the European Central Bank had to make several decisions in order to keep proceeding with the recovery of the eurozone. Nonetheless, these decisions had an impact on the volatility of the Euro (Gambetti & Musso, 2017). For that reason, these monetary policy decisions could be one of the reasons that explains why the volatility innovation term was more important between 2013 and 2016 than during the post-EU referendum period for the EUR/GBP.

5.2. Impact of the Brexit announcements on the GBP volatility

5.2.1. Impact of the Brexit announcements on the GBP volatility (2016-2019)

After addressing the question related to the volatility change before and after the EU referendum, the rest of this paper investigates on the volatility during the post-EU referendum period. The purpose of this second part is to find out how the Brexit announcements or news related to the Brexit impacted the EUR/GBP and the GBP/USD. As it has been described in the methodology part, in order to answer to this question a GARCH model including a dummy variable is implemented for the time period between 2016 and 2019. The dummy variable represents a day for which a Brexit announcement has been made public. Therefore, the sign and the level of significance of the dummy variable will deliver the answer on the impact of these political news on the GBP volatility. Furthermore, comparisons with normal GARCH models are also included in order to observe if the GARCH models including the dummy variable explain better the volatility or not.

Table 9 – GARCH (1,1) EUR/GBP (2016 – 2019)

EUR/GBP(2016-2019)

GARCH (1,1)	Coefficient	Std.Error	t Value	Prob
ω	0.002	0.001	1.391	0.164
α	0.023	0.010	2.331	0.019
β	0.965	0.015	63.455	0.000
	Statistic	p-value		
Ljung-Box (r=5)	1.253	0.800		
Ljung-Box (r=9)	1.614	0.950		

EUR/GBP (2016-2019) Information Criteria	
Akaike Information Criteria	1.2302
Bayes Information Criteria	1.2488

Sources: Bloomberg – Own calculations.

In table 9, the GARCH (1,1) model is displayed for the EUR/GBP returns on the post-EU referendum period. According to the result of the Ljung-Box test, the model does not show serial autocorrelation between the squared standardized residual. Then, the GARCH equation is

$$\sigma_t^2 = 0.002 + 0.023\epsilon_{t-1}^2 + 0.965\sigma_{t-1}^2$$

Table 10 – GARCH (1,1) including dummy variable EUR/GBP (2016 – 2019)

EUR/GBP(2016-2019) with Dummy Variable

GARCH-X (1,1)	Coefficient	Std.Error	t Value	Prob
ω	0.000	0.002	0.000	0.999
α	0.026	0.008	3.302	0.000
β	0.969	0.009	104.87	0.000
ϕ	0.022	0.002	9.397	0.000
	Statistic	p-value		
Ljung-Box (r=5)	2.414	0.525		
Ljung-Box (r=9)	3.518	0.671		

EUR/GBP with dummy variable (2016-2019) Information Criteria	
Akaike Information Criteria	1.2257
Bayes Information Criteria	1.2505

Sources: Bloomberg – Own calculations.

The results of the GARCH (1,1) model including a dummy variable are available in table 10. According to the model, the dummy variable is highly significant and has a positive effect. This means that over the time period between 2016 and 2019, the announcements related to the Brexit increased the volatility of the EUR/GBP exchange rate. Furthermore, through the Ljung-Box test, the squared standardized residuals of the model are not serially autocorrelated. In this case, the equation of the GARCH (1,1) including the dummy variable is

$$\sigma_t^2 = 0.000 + 0.026\epsilon_{t-1}^2 + 0.969\sigma_{t-1}^2 + 0.022\phi_t$$

If the comparison is realized between the original GARCH model and the GARCH model including the dummy variable related to the Brexit news, the Akaike information criterion of the original GARCH model demonstrates a higher level than the GARCH model with the dummy variable. However, the Bayesian Information Criteria displays a lower value for the original GARCH model. As it has been explained in the methodology part, the BIC possesses a higher punishment term for including additional variables in a model. Therefore, the original GARCH model is supposed to constitute a better model in order to model the volatility of the EUR/GBP over the post-Brexit period. Regardless this last observation, the Brexit news that have been selected in order to compute the dummy variable demonstrate a positive effect on the volatility of the EUR/GBP.

Table 11 – GARCH (1,1) GBP/USD (2016 – 2019)

GBP/USD(2016-2019)

GARCH (1,1)	Coefficient	Std.Error	t Value	Prob
ω	0.003	0.001	3.490	0.000
α	0.016	0.002	6.603	0.000
β	0.969	0.008	109.856	0.000
	Statistic	p-value		
Ljung-Box (r=5)	1.531	0.732		
Ljung-Box (r=9)	3.308	0.707		

GBP/USD (2016-2019) Information Criteria	
Akaike Information Criteria	1.5645
Bayes Information Criteria	1.5831

Sources: Bloomberg – Own calculations.

The same process is applied for the GBP/USD exchange rate and in table 11, the results of the implementation of a GARCH (1,1) model are available. Through the Ljung-Box test, the squared standardized residuals of the model are demonstrated to be independently distributed and therefore, are not serially autocorrelated. The GARCH equation in this case is

$$\sigma_t^2 = 0.003 + 0.016\epsilon_{t-1}^2 + 0.969\sigma_{t-1}^2$$

Concerning the implementation of the Brexit dummy variable in the GARCH model, the results are available in the table 12. According to the estimate of the dummy variable, the Brexit news had no impact on the volatility of the GBP/USD. However, the p-value of this parameter is high and therefore, from this observation it is not possible to deliver a conclusion on how the Brexit announcements has impacted the volatility of this exchange rate. Furthermore, the other parameters of the GARCH model including the binary variable display the same value than the parameters for the GARCH model and the Ljung-Box test gives the same value. Then, all the information criterions of the original GARCH model are lower than the information criterions of the GARCH model including the dummy variable. Then, the GARCH equation for the GBP/USD including the dummy variable is

$$\sigma_t^2 = 0.003 + 0.016\epsilon_{t-1}^2 + 0.969\sigma_{t-1}^2 + 0.022 + 0.000\phi_t$$

Table 12 – GARCH (1,1) including dummy variable GBP/USD (2016 – 2019)

GBP/USD (2016-2019) with Dummy Variable

GARCH (1,1)	Coefficient	Std.Error	t Value	Prob
ω	0.003	0.001	3.489	0.000
α	0.016	0.002	6.603	0.000
β	0.969	0.008	109.856	0.000
ϕ	0.000	0.012	0.000	0.999

	Statistic	p-value
Ljung-Box (r=5)	1.531	0.732
Ljung-Box (r=9)	3.308	0.707

GBP/USD with dummy variable (2016-2019) Information Criteria	
Akaike Information Criteria	1.5670
Bayes Information Criteria	1.5920

Sources: Bloomberg – Own calculations.

Regarding these GARCH models, the IT CUSUM test is applied for each of these models in order to observe if a structural break occurs. The figures related to these CUSUM test are available in the *appendices* 28, 29, 30 and 31. They show that there was no structural break in the GARCH models. The IT statistic line does not reach the 5% critical lines for each test and consequently, it could be said that all the GARCH models are well-specified. Nonetheless, there is no significant difference between the IT test of the original GARCH model and the GARCH model including a binary variable related to the GBP/USD exchange rate. This is explained by the fact that, as observed in table 11 and 12, the values of the parameters are the same and the dummy variable, which is the only different parameter between the two models, is equal to zero.

A last inquiry on this time period is realized through the introduction of an additional independent variable in the GARCH (1,1) models. This additional independent variable is the VIX. The reason of the VIX implementation in the GARCH model is an attempt to capture more explanation concerning the volatility of the exchange rates.

Table 13 – GARCH (1,1) models with VIX (2016 – 2019)

EUR/GBP(2016-2019) with Dummy Variable and VIX

GARCH-X (1,1)	Coefficient	Std.Error	t Value	Prob
ω	0.000	0.000	0.000	1.000
α	0.027	0.005	5.254	0.000
β	0.969	0.008	118.211	0.000
ϕ	0.022	0.010	2.128	0.033
ψ	0.000	0.000	0.001	0.999

	Statistic	p-value
Ljung-Box (r=5)	2.419	0.523
Ljung-Box (r=9)	3.523	0.670

GBP/USD(2016-2019) with Dummy Variable and VIX

GARCH-X (1,1)	Coefficient	Std.Error	t Value	Prob
ω	0.003	16.989	0.000	0.999
α	0.016	0.004	3.298	0.000
β	0.969	0.007	132.91	0.000
ϕ	0.000	0.013	0.004	0.999
ψ	0.000	16.991	0.000	1.000

	Statistic	p-value
Ljung-Box (r=5)	1.531	0.732
Ljung-Box (r=9)	3.308	0.707

Sources: Bloomberg – Own calculations.

In the table 13, the two GARCH (1,1) models of the EUR/GBP and GBP/USD exchange rate are observable. The VIX data is implemented through the parameter ψ and in both GARCH models including the dummy variable, the VIX parameter shows itself to not be a relevant parameter in order to explain the volatility. Furthermore, in comparison with the values of the parameters of the previous GARCH models, the estimates of the parameters of this GARCH models are the same.

So far, the impact of the Brexit announcements on the GBP volatility has been analyzed on a three year-time period that starts on the 24th June 2016 and ends on the 24th May 2019. Nonetheless, as it could be observed in the *appendix* 12, the number of dates for which a Brexit announcement has been made public is different for each year. Therefore, the next task is to implement a GARCH model including the Brexit news as a dummy variable for each year between 2016 and 2019.

5.2.2. Impact of the Brexit announcements on the GBP volatility (2016-2017)

Table 14 – GARCH (1,1) with dummy variable EUR/GBP (2016 – 2017)

27/06/2016 – 23/05/2017

GARCH-X (1,1)	Coefficient	Std.Error	t Value	Prob
ω	0.000	0.002	0.000	0.999
α	0.001	0.000	1.660	0.096
β	0.997	0.000	2.328e+03	0.000
ϕ	0.000	0.009	0.000	1.000
	Statistic	p-value		
Ljung-Box (r=5)	0.796	0.901		
Ljung-Box (r=9)	1.855	0.922		

EUR/GBP with dummy variable (2016-2017) Information Criteria	
Akaike Information Criteria	1.7250
Bayes Information Criteria	1.7764

Sources: Bloomberg – Own calculations.

According to the results in table 14, the dummy variable that represents the Brexit announcements shows no effect on the EUR/GBP volatility in the first year after the announcement of the Brexit. In the *appendix* 32, the figure related to the squared of the EUR/GBP returns over this period of time is available. Furthermore, the GARCH (1,1) model is also applied to this time series and the basic GARCH parameters are the same than the GARCH parameters which includes the dummy variable. Nonetheless, the information criterions of the GARCH (1,1) model show lower values than the information criterions of the GARCH model with the binary variable. These information are also available in table 15.

Table 15 – GARCH (1,1) EUR/GBP (2016 – 2017)

27/06/2016 – 23/05/2017

GARCH (1,1)	Coefficient	Std.Error	t Value	Prob
ω	0.000	0.000	0.000	0.999
α	0.001	0.000	1.556	0.119
β	0.997	0.000	2.135e+03	0.000
	Statistic	p-value		
Ljung-Box (r=5)	0.796	0.901		
Ljung-Box (r=9)	1.855	0.922		

EUR/GBP (2016-2017) Information Criteria	
Akaike Information Criteria	1.7186
Bayes Information Criteria	1.7565

Sources: Bloomberg – Own calculations.

Table 16 – GARCH (1,1) with dummy variable GBP/USD (2016 – 2017)

27/06/2016 – 23/05/2017

GARCH-X (1,1)	Coefficient	Std.Error	t Value	Prob
ω	0.000	0.001	0.000	0.999
α	0.005	0.001	4.733	0.000
β	0.991	0.002	525.17	0.000
ϕ	0.000	0.006	0.000	0.999
	Statistic	p-value		
Ljung-Box (r=5)	0.972	0.866		
Ljung-Box (r=9)	2.246	0.874		

GBP/USD with dummy variable (2016-2017) Information Criteria	
Akaike Information Criteria	1.9324
Bayes Information Criteria	1.9838

Sources: Bloomberg – Own calculations.

The table 16 is related to the GARCH model that includes the dummy variable of the Brexit announcement for the GBP/USD exchange rate for the first year after the result of the EU referendum. According to this dummy variable, the Brexit announcements had no effect on the volatility of the exchange rate and furthermore, the p-value of this parameter shows that the dummy variable is not significant in order to explain the volatility of the GBP/USD over this time period. Another observation is that according to the Ljung-Box test, the squared residuals of the model are not serially autocorrelated. In the *appendix* 33, the figure of the squared GBP/USD returns is available. The table 17 is the result of a GARCH (1,1) on this time series without the dummy variable. As it was the case for the EUR/GBP, the value of the basic parameters of the GARCH model are the same than the value of these parameters in the case of the GARCH model including the binary variable. Then, the information criterions of the GARCH (1,1) model display lower value than the information criterion of the GARCH (1,1) model which takes into account the Brexit announcements and therefore, it demonstrates that the GARCH (1,1) is a better model in terms of goodness of fit.

Table 17 – GARCH (1,1) GBP/USD (2016 – 2017)

27/06/2016 – 23/05/2017

GARCH (1,1)	Coefficient	Std.Error	t Value	Prob
ω	0.000	0.000	0.000	0.999
α	0.005	0.002	2.125	0.033
β	0.991	0.003	328.99	0.000
	Statistic	p-value		
Ljung-Box (r=5)	0.972	0.866		
Ljung-Box (r=9)	2.246	0.874		

GBP/USD (2016-2017) Information Criteria	
Akaike Information Criteria	1.9253
Bayes Information Criteria	1.9639

Sources: Bloomberg – Own calculations.

5.2.3. Impact of the Brexit announcements on the GBP volatility (2017-2018)

Table 18 – GARCH (1,1) with dummy variable EUR/GBP (2017 – 2018)

24/05/2017 – 23/05/2018

GARCH-X (1,1)	Coefficient	Std.Error	t Value	Prob
ω	0.08	0.007	1.169	0.242
α	0.064	0.046	1.404	0.160
β	0.887	0.075	11.673	0.000
ϕ	0.000	0.04	0.000	1.000
	Statistic	p-value		
Ljung-Box (r=5)	1.443	0.754		
Ljung-Box (r=9)	2.914	0.773		

EUR/GBP with dummy variable (2017-2018) Information Criteria	
Akaike Information Criteria	1.0347
Bayes Information Criteria	1.0978

Sources: Bloomberg – Own calculations.

The table 18 displays the result of the GARCH (1,1) model with the binary variable for the second year after the Brexit announcement. According to the results, the announcements on the Brexit of this year were not a relevant factor of the EUR/GBP volatility. Another observation that could be made on the basis of this table is that according to the Ljung-Box test, the squared residuals are not serially autocorrelated. The graph of the squared returns of the EURGBP over that time period is available in the *appendix* 34. Then, a GARCH (1,1) for this time series is available in the table 19. The information criterions of this GARCH (1,1) are also lower than the information criterions of the GARCH (1,1) with the dummy variable and consequently, here again the GARCH (1,1) seems to be a better model than the GARCH (1,1) which takes into account the announcements related to the Brexit.

Table 19 – GARCH (1,1) EUR/GBP (2017 – 2018)

24/05/2017 – 23/05/2018

GARCH (1,1)	Coefficient	Std.Error	t Value	Prob
ω	0.008	0.007	1.139	0.254
α	0.064	0.039	1.631	0.102
β	0.887	0.065	13.562	0.000
	Statistic	p-value		
Ljung-Box (r=5)	1.443	0.754		
Ljung-Box (r=9)	2.914	0.773		

EUR/GBP (2017-2018) Information Criteria	
Akaike Information Criteria	1.0253
Bayes Information Criteria	1.0727

Sources: Bloomberg – Own calculations.

Table 20 – GARCH (1,1) with dummy variable GBP/USD (2017 – 2018)

24/05/2017 – 23/05/2018

GARCH-X (1,1)	Coefficient	Std.Error	t Value	Prob
ω	0.000	0.001	0.000	0.999
α	0.000	0.002	0.000	1.000
β	0.999	0.000	9.18e+05	0.000
ϕ	0.000	0.007	0.000	1.000
	Statistic	p-value		
Ljung-Box (r=5)	2.494	0.507		
Ljung-Box (r=9)	3.974	0.610		

GBP/USD with dummy (2017-2018) Information Criteria	
Akaike Information Criteria	1.4151
Bayes Information Criteria	1.4783

Sources: Bloomberg – Own calculations.

The table 20 is related to the GARCH (1,1) with the binary variable on the GBP/USD of the time period which represents the second year after the Brexit referendum. The dummy variable, ϕ, which is the Brexit announcements parameter does not show a relevant relationship toward the GBP/USD volatility over that period of time. Furthermore, according to this GARCH model, the volatility of today is mainly explained by the volatility of yesterday. Therefore, the graph that plots the squared returns of the GBP/USD over that period of time is important in order to observe the volatility clustering. Despite the fact that this GARCH model puts a lot of importance on the β parameter, the model seems to fit the data due to the fact that the Ljung-Box test fails to reject the null hypothesis which states that the squared standardized residuals are not serially autocorrelated. In the table 21, the GARCH (1,1) results over this time period are also available. The basic GARCH parameters are the same which confirms the volatility clustering that could be observed in *appendix 35*. However, the information criterions of the GARCH (1,1) model are lower than the information criterions of the GARCH (1,1) model including the dummy variable and this shows that the GARCH (1,1) fits better the data than the other GARCH model.

Table 21 – GARCH (1,1) GBP/USD (2017 -2018)

24/05/2017 – 23/05/2018

GARCH (1,1)	Coefficient	Std.Error	t Value	Prob
ω	0.000	0.000	0.204	0.838
α	0.000	0.003	2.125	1.000
β	0.999	0.000	6.9061e+03	0.000
	Statistic	p-value		
Ljung-Box (r=5)	2.498	0.506		
Ljung-Box (r=9)	3.877	0.610		

GBP/USD (2017-2018) Information Criteria	
Akaike Information Criteria	1.4088
Bayes Information Criteria	1.4531

Sources: Bloomberg – Own calculations.

5.2.4. Impact of the Brexit announcements on the GBP volatility (2018-2019)

Table 22 – GARCH (1,1) with dummy variable EUR/GBP (2018 – 2019)

24/05/2018 – 24/05/2019

GARCH-X (1,1)	Coefficient	Std.Error	t Value	Prob
ω	0.098	0.029	3.387	0.000
α	0.072	0.060	1.197	0.231
β	0.055	0.305	0.304	0.760
ϕ	0.589	0.229	2.567	0.010
	Statistic	p-value		
Ljung-Box (r=5)	1.728	0.684		
Ljung-Box (r=9)	4.681	0.477		

EUR/GBP with dummy variable (2018-2019) Information Criteria	
Akaike Information Criteria	0.8732
Bayes Information Criteria	0.9279

Sources: Bloomberg – Own calculations.

The third year after the Brexit referendum which represents the time period between the 24th May 2018 and the 24th of May 2019 constitutes the year with the more dates for which a Brexit announcement has been released. Therefore, this time period would be the most interesting to investigate. On table 22, the GARCH (1,1) model including the dummy variable related to the Brexit announcements is developed. According to the parameters of this GARCH model, the news related to the Brexit is a significant variable due to the fact that the dummy variable has a p-value lower than 5%. Furthermore, the sign of this binary variable is positive which means that the relationship between the Brexit announcements and the volatility of the EUR/GBP is positive. The equation of this GARCH is

$$\sigma_t^2 = 0.098 + 0.072\epsilon_{t-1}^2 + 0.055\sigma_{t-1}^2 + 0.589D_t$$

Concerning the other parameters of the GARCH model, the innovation term is higher than 0.05 and therefore, the exchange rate could be assumed to have been more nervous than the two previous years. Then, regarding the persistence of the volatility, this parameter is quiet low which means that the level of the volatility from yesterday was not that important in order to determine the current level of volatility. However, the p-value of these parameters is high.

Another observation is that according to the Ljung-Box test, the squared standardized residuals are not serially autocorrelated and therefore the model over this time period fits well the data.

The graph of the squared returns of the EUR/GBP is displayed in the *appendix* 36. Table 23 provides with the development of a GARCH (1,1) model over this period of time. The values of the parameters of this GARCH (1,1) model are interesting to interpret due to the fact that the parameters show different value than what is usually reported by GARCH models. In this model, the β is low and consequently, is associated with a higher α. According to these parameters, the volatility of the EURGBP could be perceived as a "spiky" volatility and this term is confirmed by looking at the graph of the squared returns of the EUR/GBP. Consequently, several shocks occurred during this period and it impacted the volatility of the exchange rate. Then through the comparison of the information criterions of the GARCH models, the GARCH model including the binary variable shows lower value for each information criterions. It means that the model that incorporates the dummy variable related to the Brexit news is a better model due to the fact that it explains better the data and consequently, it could be stated that the Brexit announcements that occurred during this period of time could explain the volatility of the EUR/GBP. The GARCH (1,1) equation without the dummy variable is

$$\sigma_t^2 = 0.076 + 0.183\epsilon_{t-1}^2 + 0.379\sigma_{t-1}^2$$

Table 23 – GARCH (1,1) EUR/GBP (2018 – 2019)

24/05/2018 – 24/05/2019

GARCH (1,1)	Coefficient	Std.Error	t Value	Prob
ω	0.076	0.035	2.122	0.033
α	0.183	0.084	2.163	0.030
β	0.379	0.241	1.574	0.115
	Statistic	p-value		
Ljung-Box (r=5)	1.020	0.854		
Ljung-Box (r=9)	1.731	0.934		

EUR/GBP (2018-2019) Information Criteria	
Akaike Information Criteria	1.0486
Bayes Information Criteria	1.0896

Sources: Bloomberg – Own calculations.

Table 24 – GARCH (1,1) with dummy variable GBP/USD (2018 – 2019)

24/05/2018 – 24/05/2019

GARCH-X (1,1)	Coefficient	Std.Error	t Value	Prob
ω	0.201	0.043	4.671	0.000
α	0.000	0.083	0.000	1.00
β	0.062	0.160	0.386	0.699
ϕ	0.586	0.244	2.393	0.017
	Statistic	p-value		
Ljung-Box (r=5)	4.289	0.220		
Ljung-Box (r=9)	9.208	0.073		

GBP/USD with dummy variable (2018-2019) Information Criteria	
Akaike Information Criteria	1.4548
Bayes Information Criteria	1.5094

Sources: Bloomberg – Own calculations.

The tables 24 shows the result of the GARCH (1,1) model with the binary variable for the GBP/USD returns over the time period between 2018 and 2019. The dummy variable in this model is significant with a p-value lower than 5%. Furthermore, the relationship between this parameter and the volatility is positive. Therefore, the interpretation of this binary variable in the GARCH model is that the Brexit announcements over that period of time had a positive impact on the volatility of the GBP/USD. The Ljung-Box test fails to reject the null hypothesis that the squared standardized residuals are serially autocorrelated. Nonetheless, the Ljung-Box test with a lag of 9 shows a little p-value and the hypothesis stated just before would be rejected at the 10% level of significance. The intercept of this GARCH model is high and the innovation term shows no effect on the volatility. Furthermore, the p-values of the parameters α and β demonstrate that these estimations are not relevant. Consequently, because of these last observations it is difficult to deliver a clear statement on this GARCH model including the dummy variable. In this context, the GARCH equation is

$$\sigma_t^2 = 0.201 + 0.000\epsilon_{t-1}^2 + 0.062\sigma_{t-1}^2 + 0.586D_t$$

Regarding the table 25 with the implementation of a GARCH (1,1) model on this time series, the information criterions generated by this GARCH (1,1) model deliver higher value than the values of the information criterions of the other GARCH (1,1) model. Consequently, the GARCH (1,1) including the binary variable explains better the volatility of this time period and this is due to the presence of the dummy variable that is related to the Brexit announcements. In the *appendix* 37, the graph of the squared returns of the GBP/USD over this time period is available. Regarding the estimations of the GARCH (1,1) parameters, they display an important relationship between the volatility from the past and the current level of volatility. Moreover, the innovation term is lower than 0.05 which means that this exchange rate could be perceived as stable over this time period. Then, the Ljung-Box test on this GARCH model fails to reject the hypothesis according to which the standardized residuals are independently distributed. The GARCH equation in this case is

$$\sigma_t^2 = 0.009 + 0.027\epsilon_{t-1}^2 + 0.937\sigma_{t-1}^2$$

Table 25 – GARCH (1,1) GBP/USD (2018 – 2019)

24/05/2018 – 24/05/2019

GARCH (1,1)	Coefficient	Std.Error	t Value	Prob
ω	0.009	0.013	0.696	0.486
α	0.027	0.024	1.111	0.266
β	0.937	0.065	14.282	0.000
	Statistic	p-value		
Ljung-Box (r=5)	2.220	0.566		
Ljung-Box (r=9)	3.830	0.617		

GBP/USD (2018-2019) Information Criteria	
Akaike Information Criteria	1.5314
Bayes Information Criteria	1.5724

Sources: Bloomberg – Own calculations.

To conclude on these GARCH models implemented for each year after the EU referendum, it has been demonstrated that Brexit news only had a real impact on the volatility of the exchange rates during the third year which corresponds to the time period between the 24th May 2018 and the 24th May 2019. The GARCH model including the dummy variable generated by the GBP/USD returns displays a low p-value for the Ljung-Box test. On the other hand, the GARCH model with the binary variable generated on the basis of the EUR/GBP returns does not show this feature that could be perceived as a problem in term of interpretation. Therefore, only the volatility of the EUR/GBP over the third year is analyzed.

5.2.5. EUR/GBP exchange rate analysis (2018 – 2019)

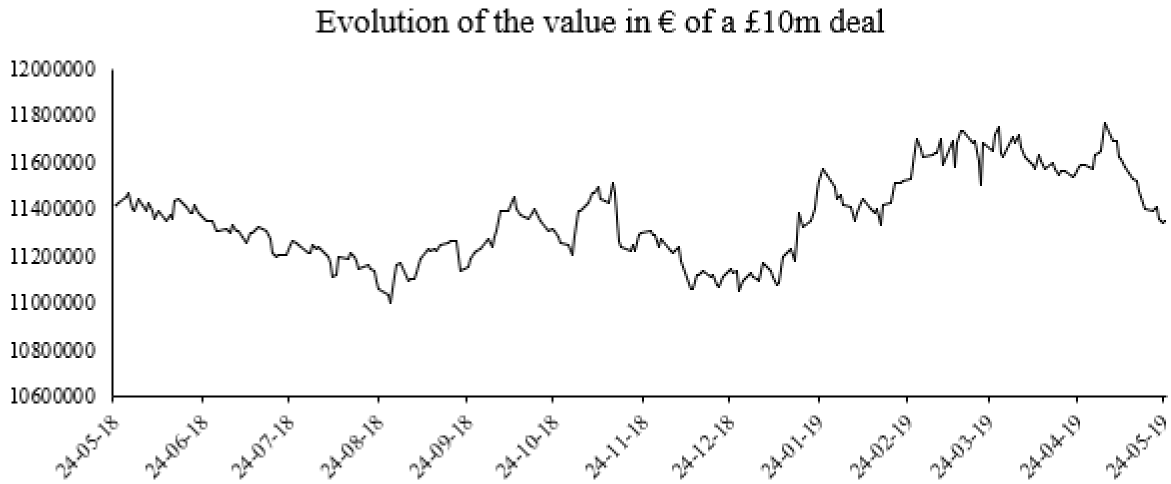
As it has been explained in the background part, the international trade between the EU and the UK is important. Therefore, it would be interesting to observe how the movements of the EUR/GBP exchange rate could have impacted several European companies between May 2018 and May 2019 which is the year for which the Brexit announcements impacted the most the volatility of the EUR/GBP.

If European companies trade with British companies, these firms will face an additional risk in their operational business which is the exchange rate risk. However, the risk from these exchange rate movements is different among the importers and exporters (Hull, 2008). The risk for the European exporters lies in the potential increase of the EUR/GBP due to the fact that they receive the payment for their goods or services in pound sterling. Therefore, a depreciation of the pound sterling constitutes a threat for their revenue. On the other hand, the risk for the European importers lies in the potential decrease of the EUR/GBP due to the fact that they need to convert their euro in pound sterling in order to proceed to their payment transactions. Consequently, the appreciation of the pound sterling is a threat for the importers.

This level of risk could be interpreted through the operational business of a European exporter. The context assumed is that during the year, the European company delivers several times goods to a UK-based company and they both agree on the price related to the transactions and this price should be paid at one moment during the year. This price is expressed in pound sterling and the EU-based company will receive the payment in pound. Consequently, the European firm will have to convert this pound sterling in Euro and this will generate the revenue of the company. This payment is equal to £10.000.000. Then, this deal was agreed on the 24th of May 2018. As it is demonstrated in figure 3, the EUR/GBP exchange rate movements impacted the converted value in euro of this payment in British pound.

Because of these changes in the exchange rate, the revenue generated from this deal was uncertain. The European exporter, who received the payment in British pound during this year, could have make a loss in comparison of what the European firm would have received if the payment occurred on the 24th of May 2018. This is the reason why, the exporter should have use currency options such as a call option on the EUR/GBP which would have ensured to the company the certainty of the value in € of this deal.

Figure 3 – Evolution of the value in € of a £10m deal.



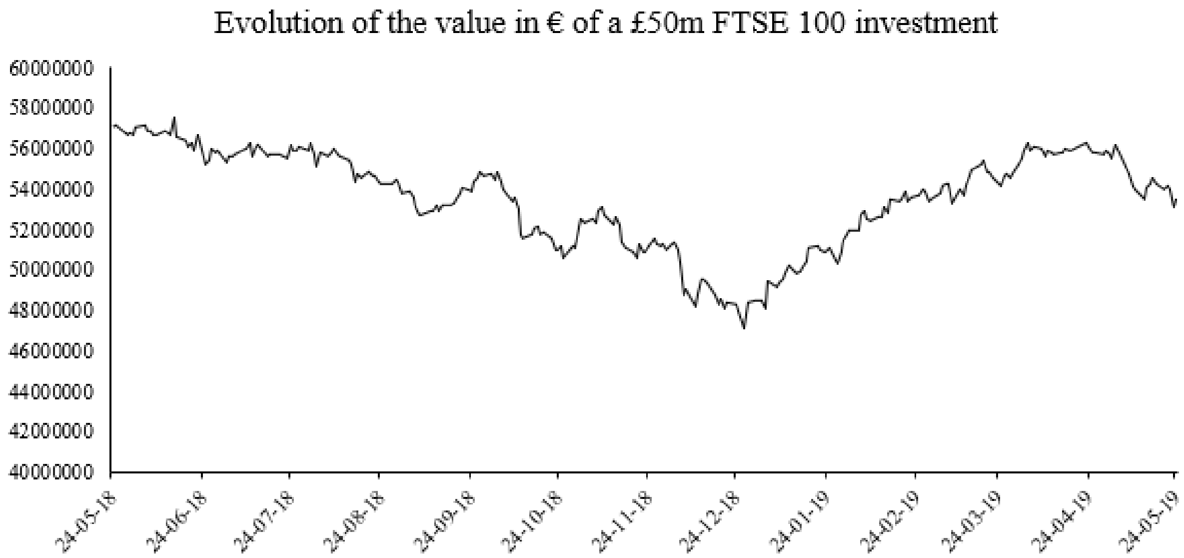
Sources: Bloomberg – Own calculations

Another example that illustrates the impact of the movements of the EUR/GBP exchange rate between May 2018 and May 2019 is the situation of a European pension fund. It is assumed that this fund has decided to allocate a certain amount of their resources in British stocks, or in a British index such as the FTSE 100. In addition to the performance of the British stocks, the fund should also consider the evolution of the exchange rate due to the fact that the fund could sell its position during the year. In the context in which the European pension fund decided to purchase ETFs of the FTSE 100 for a value of £50m on the 24th May 2018, its profit generation over the year would have depended on the movement of the FTSE 100 index but also on the EUR/GBP exchange rate movements.

In the case of this fund, it is more difficult to predict the revenue generation. Nonetheless, the exchange rate risk could be eliminated or reduced through the use of currency options. As it has been explained in the situation of the European exporter, by purchasing a call option on the EUR/GBP, the fund is able to fix the exchange rate that will be used in order to convert to

British pound, that are obtained through the sale of its ETFs, in Euro which constitute its home currency.

Figure 4 – Evolution of the value in € of a 50£m FTSE 100 investment



Sources: Bloomberg – Own calculations

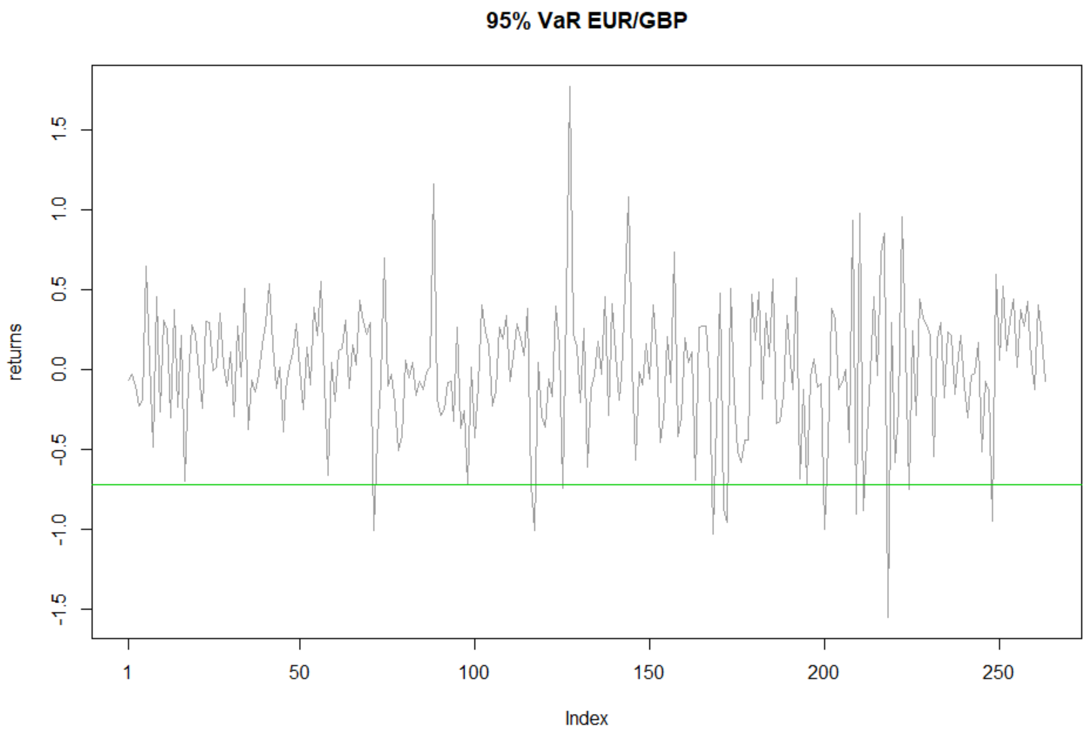
Therefore, in both cases explained here above, the use of a call option would have been beneficial to the companies due to the fact that this hedging tool is able to eliminate or to reduce the exchange rate risk. The holder of a currency call option will benefit from the right to purchase a currency at a price that has been determined within a specific time frame (Hull, 2012). This does not represent an obligation. Therefore, if the exchange rate movements affect positively the position of the European company, this firm will not exercise its right to buy the currency at the price specified in the contract. However, the company bought the contract and consequently, this option price would constitute an expense for the company (Hull, 2012).

The implementation of a hedging strategy depends on the level of risk of the position of an individual or a company. This level of risk is related to the volatility of the markets. The more the markets are perceived as volatile, the more the probability of negative outcome occurrences arise. Consequently, hedging should be highly considered when the markets show a certain level of volatility (Coleman et al., 2001). A tool that could be used in order to determine the risk of an investment is the Value at Risk[18] (Best, 1998).

Through the computation of the VaR formula, it is possible to determine with a certain level of confidence that the worst daily loss will not exceed a certain level (Hu, 2016). Therefore, it would be interesting to investigate on the VaR of the EUR/GBP for this last year.

According to the VaR result on the basis of the daily returns that occurred between May 2018 and May 2019, with 95% confidence, it is expected that the worst daily loss will not exceed 0.72%. This figure represents a likely loss for the European companies that are exposed to the EUR/GBP exchange rate risk. Figure 5 shows this level of Value at Risk.

Figure 5 – 95% Value at Risk EUR/GBP (2018 – 2019).



Sources: Bloomberg – Own calculations.

[18] "The VaR is a statistic that measures and quantifies the level of financial risk within a firm, portfolio or position over a specific time frame. This metric is most commonly used by investment and commercial banks to determine the extent and occurrence ratio of potential losses in their institutional portfolios." (Investopedia): https://www.investopedia.com/terms/v/var.asp

Therefore, through the purchase of currency options, it is possible to eliminate or to reduce this currency risk which is demonstrated by the VaR (Papaioannou, 2006). Nonetheless, as it has been explained here above, the purchase of an option contract requires an expense that the company would prefer to avoid if the volatility of the financial markets is low. One possibility to deliver a judgement on the level of volatility is to compare with previous years (Papaioannou, 2006). Consequently, when the VaR is calculated for the previous year for which the time series is situated between May 2017 and May 2018, with 95% confidence, it would have been expected that the worst daily loss would have not exceeded 0.58%. Therefore, through this comparison, the Value at Risk of the EUR/GBP has increased this last year and this could be partly explained through the volatility that had been impacted by the Brexit announcements as it is demonstrated in this research.

For that reason, hedging strategies should be implemented in order to eliminate or to reduce the currency risk of the EUR/GBP which has increased because of the Brexit announcements that occurred between May 2018 and May 2019. Moreover, Brexit negotiations is not over yet and the uncertainty related to the outcome of an agreement between the EU and the UK is still important (Elliott, 2019). Because of this political context, it is possible that the risk for the international companies that trades with UK firms keep increasing in a near future which is an additional incentive to adopt a hedging strategy related to the exchange rate risk.

6. Conclusion

The Brexit constitutes an important decision from the UK that will have many impacts on the British economy but also on the European economy (Partington, 2019). However, a deal has to be agreed between the EU and the UK and without this deal, the uncertainty related to the future economic relationship between the two economic area will remain uncertain (Elliott, 2019). In several economic reports or interviews, experts affirm that this uncertainty is responsible for the volatility of the British pound (Chatterjee & Rao, 2019). Nonetheless, there is no empirical evidence of this statement. Therefore, this paper sheds light on the change in the volatility structure of the British pound after the EU referendum and how the Brexit announcements impacted the volatility during this post-EU referendum period.

The first investigation on the volatility structures of the pre-EU referendum period and post-EU referendum period is tackled through several methodologies that are the GARCH models including a dummy variable, the CUSUM test and the Bootstrap process. Nonetheless, the two first approaches do not deliver enough information in order to answer to the question. On the other hand, the bootstrap process provides with insights on the fact that the GBP volatility were less impacted by the shocks during the post-EU referendum period. Concerning the volatility clustering term, which is the most important term in the GARCH model, it has been proved that the change in this parameter is not significant between the two period of time. Then, through the calculation of the unconditional variance, it has been observed that the volatility is lower between 2016 and 2019 than the volatility before the EU referendum for both exchanges rates.

Then, during the time period after the EU referendum, the volatility of the GBP has been analyzed in order to observe if the Brexit announcements impacted the volatility of the British pound. This second part of the research has been conducted through the implementation of several GARCH models including a dummy variable. The first observation related to this question is that on a 3 year-time period study, the Brexit announcements impacted the volatility of the EUR/GBP but not the volatility of the GBP/USD. However, when this 3 year-time period is decomposed in three different one year-time series, it demonstrates that only the Brexit announcements that occurred between May 2018 and May 2019 impacted the volatility of the exchange rates.

Therefore, a conclusion on this work is that the more the announcements related to the Brexit is closed to the settlement day, the more impact this announcement will have on the GBP volatility. By looking at the events selected as Brexit announcements, it could be observed that during this last year, the political climate between the British politicians was not at its best with several resignations from the government or several motions of no confidence towards Theresa May (Coakley, 2019). Furthermore, in the course of the month of March, which was the month at which the Brexit should have occurred, the uncertainty related to a possible no deal was increasing and therefore any news that contained information on the Brexit at that time impacted the GBP volatility (Tappe, 2019).

This research stops at the announcement of the resignation of Theresa May as PM of the UK. Nowadays, Boris Johnson has been recently appointed as new PM of the UK and this politician is well known to be a Eurosceptic (Rayner, 2019). Furthermore, the negotiations with the EU are expected to be difficult because on one hand the EU does not want to modify the previous agreement negotiated with Theresa May and on the other hand, Boris Johnson does not want to meet the EU leaders before they accept several concessions in the deal (Mason, Brooks & Rankin, 2019). In addition to these difficulties, Mr. Johnson has promised that the UK will leave the EU on the 31st October 2019 with or without a deal (Mason, 2019). Consequently, with his admission at the position of new PM, the probability of a no deal has increased (Hamilton, 2019) and this is the reason why the UK government has started to prepare to face a no deal situation (Sodha, 2019).

Therefore, according to the observations of this empirical research, the level of volatility of the British pound is expected to increase due to the fact that the uncertainty and the risk related to a no deal is becoming more and more important for the reason mentioned here above. If a no deal occurs on the 31st October or if before this date, the market will not perceive any other solution possible, the British pound is expected to lose value against the other currencies. Moreover, according to several economists, the BoE is ready to increase its interest rate in case of a no deal in order to strengthen the British currency (Hopps, 2019).

Consequently, if one risk-averse individual wants to proceed to a transaction operation including GBP, this transaction should not take place on a day at which a Brexit announcement is expected. According to this research, the volatility could increase due to the Brexit news and it could be harmful for the position of the individual. However, for European corporations that export and receive their payment in GBP, it would be necessary for them to hedge these future receivables in order to ensure the stability of their financial account that could also suffer from the movement of the GBP and its volatility. The necessity of the hedging policy application is also applicable for the European pension fund that are investing in the British stock markets. Through the purchase of the currency options, the companies are able to lower the uncertainty. Therefore, in the current context and with an increasing probability related to the no deal outcome, bankers should advice their client to hedge their future transactions in order to ensure the stability of their revenue in these uncertain times.

This research analyzes the volatility of the GBP and how this volatility has been affected by the Brexit announcements. An important component of this research in order to generate the results is the selection of the dates that constitute the dummy variable in the volatility models. There is no standardized method in order to select these different dates which contained a Brexit release. Consequently, by implementing another method of date selection such as focus on other newspapers or use more newspapers, it could be possible to deliver different results than in this research.

Finally, although this paper provides with insights on the GBP volatility related to the Brexit and its political announcements, there is still room for future researches related to this subject. For example, it could be interesting to undertake the same research through the use of intraday data. Moreover, this research demonstrates that only the Brexit announcements that occurred during this last year had an impact on the volatility of the British pound. Consequently, the research with intraday data should only cover the period between May 2018 and May 2019. Another study that could also be undertaken is the study of these announcements through three different categories of announcements. One of these categories would be related to the Brexit news that are perceived as good for the realization of a soft Brexit. Another category would be related to the news that are increasing the probability for a hard Brexit and then, a category for news which are linked to a no-deal scenario. This would be possible through the introduction of three dummy variables in a GARCH model as it has been implemented in this research.

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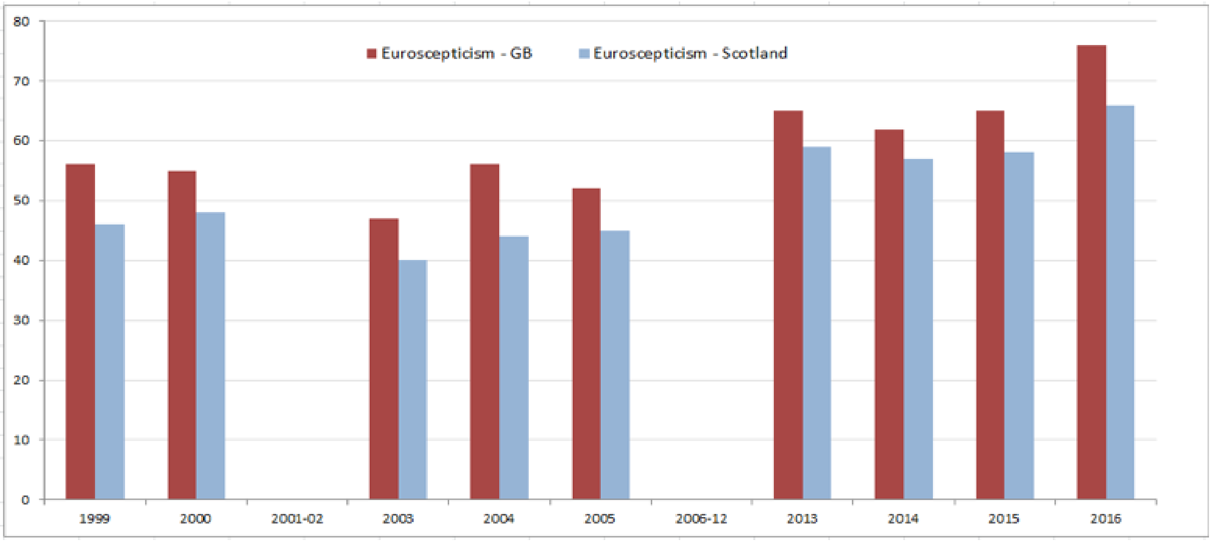
APPENDICES

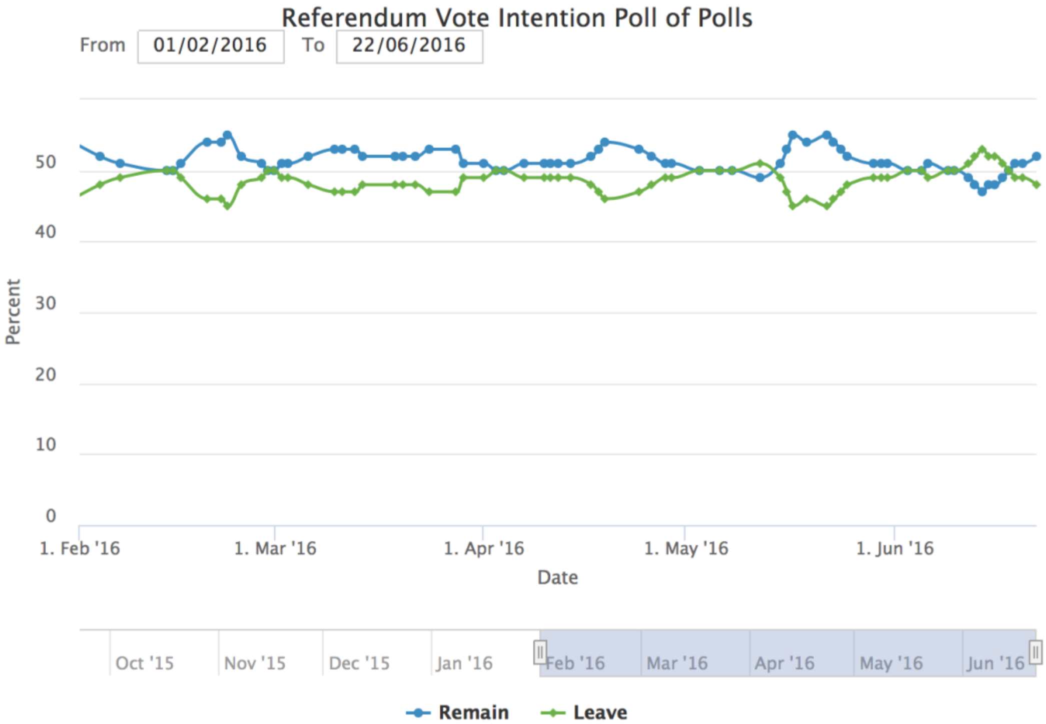
Appendix 1 – Increase of the Euroscepticism in the UK



Source: British Social Attitudes 1999-2016; Scottish Social

Figure 6 – Increase of the Euroscepticism in the UK

Appendix 2 – EU Referendum vote intention

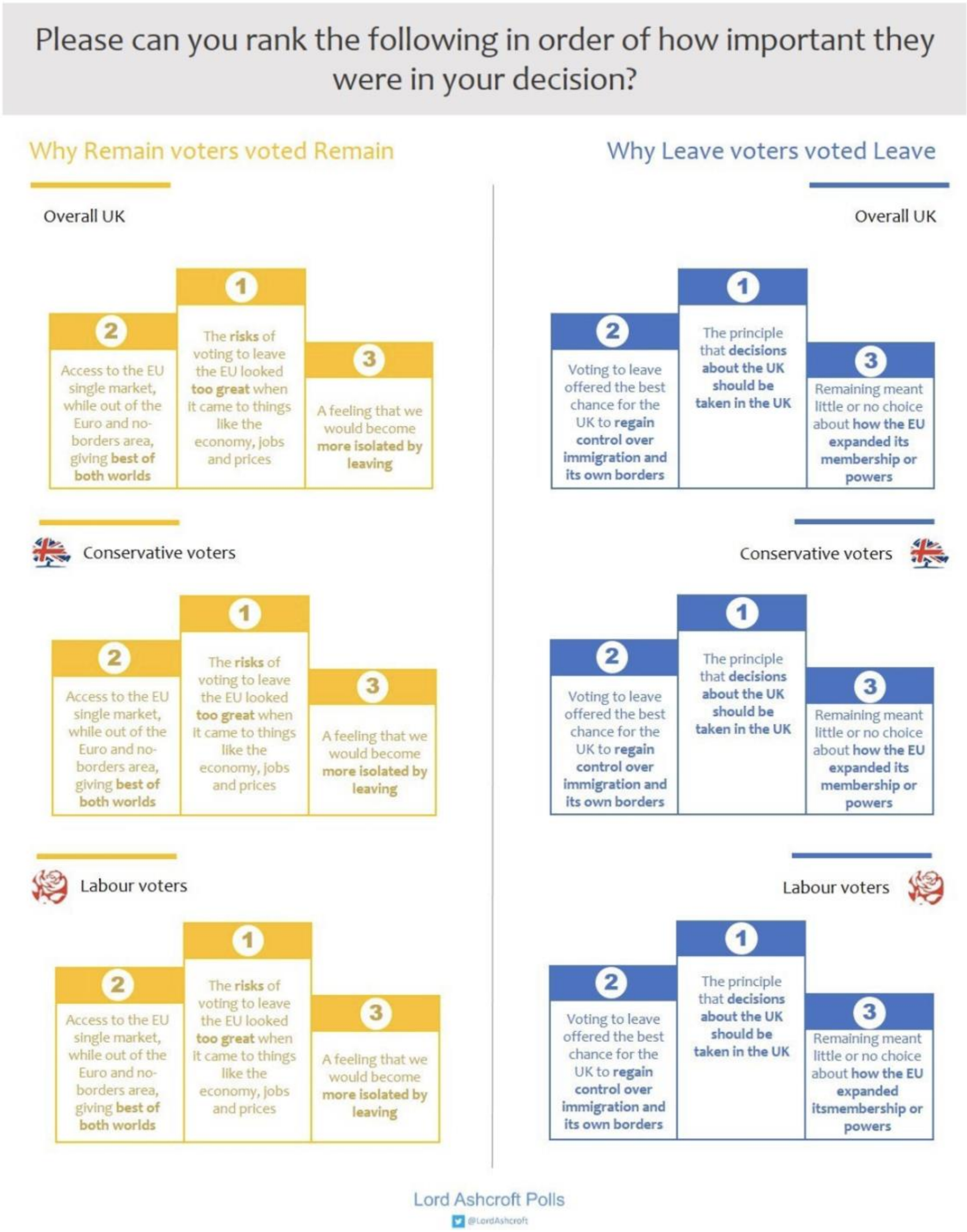


Sources : WhatUThink.org

Figure 7 – EU Referendum vote intention

Appendix 3 – EU Referendum. The reasons to leave and reasons to remain

Reasons to leave, reasons to remain



Sources: Lord Ashcroft polls

Table 26 – EU Referendum. The reasons to leave and reasons to remain

Appendix 4 – 12 points of the Chequers plan

OUR BREXIT DEAL FOR BRITAIN

THE PRIME MINISTER **7TH JULY 2018**

1 Leaving the EU on 29th March 2019

2 Ending free movement and taking back control of our borders

3 No more sending vast sums of money each year to the EU

4 A new business friendly customs model with freedom to strike new trade deals around the world

5 UK-EU free trade area with a common rulebook for industrial goods and agricultural products which will be good for jobs

6 Commitment to maintain high standards on consumer and employment rights and the environment

7 Parliamentary lock on all new rules and regulations

8 Leaving the Common Agricultural Policy and Common Fisheries Policy

9 Restoring the supremacy of British courts by ending the jurisdiction of the ECJ in the UK

10 No hard border between NI and Ireland or between NI and GB

11 Continued close cooperation on security to keep our people safe

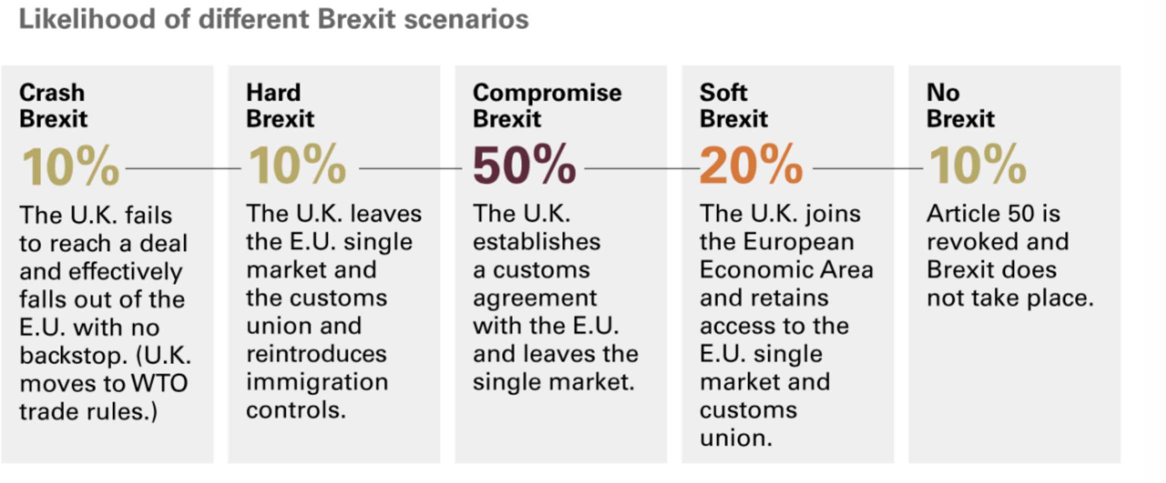
12 An independent foreign and defence policy working closely with the EU and other allies

10 DOWNING STREET
LONDON SW1A 2AA

Sources: The Sun

Table 27 – 12 points of the Chequers plan

Appendix 5 – Probabilities of the different Brexit scenarios (May 2018)

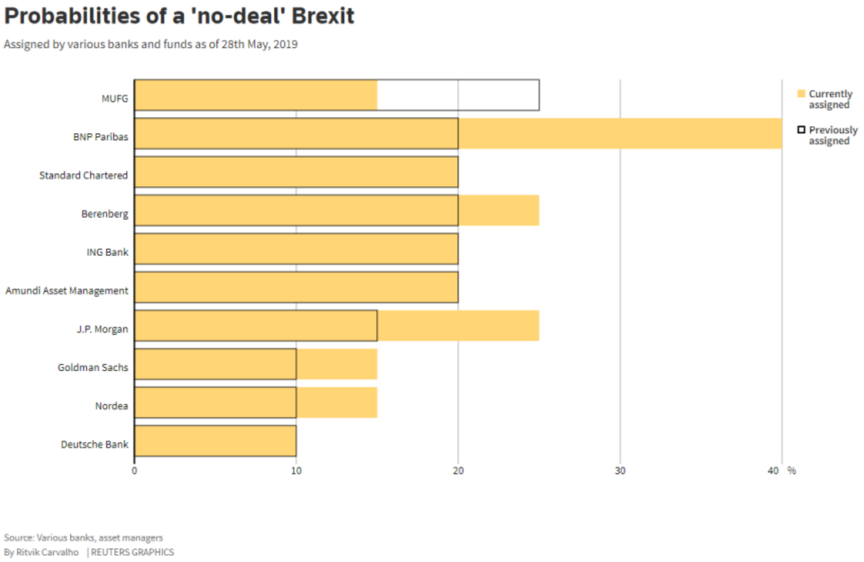

Likelihood of different Brexit scenarios

Crash Brexit	Hard Brexit	Compromise Brexit	Soft Brexit	No Brexit
10%	10%	50%	20%	10%
The U.K. fails to reach a deal and effectively falls out of the E.U. with no backstop. (U.K. moves to WTO trade rules.)	The U.K. leaves the E.U. single market and the customs union and reintroduces immigration controls.	The U.K. establishes a customs agreement with the E.U. and leaves the single market.	The U.K. joins the European Economic Area and retains access to the E.U. single market and customs union.	Article 50 is revoked and Brexit does not take place.

Source: Vanguard

Table 28 – Probabilities of the different Brexit scenarios (May 2018)

Appendix 6 – Probabilities evolution of a no-deal Brexit (May 2019)



Sources: Reuters

Figure 8 – Probabilities evolution of a no-deal Brexit (May 2019)

Appendix 7 – EUR/GBP exchange rate (2013-2019)

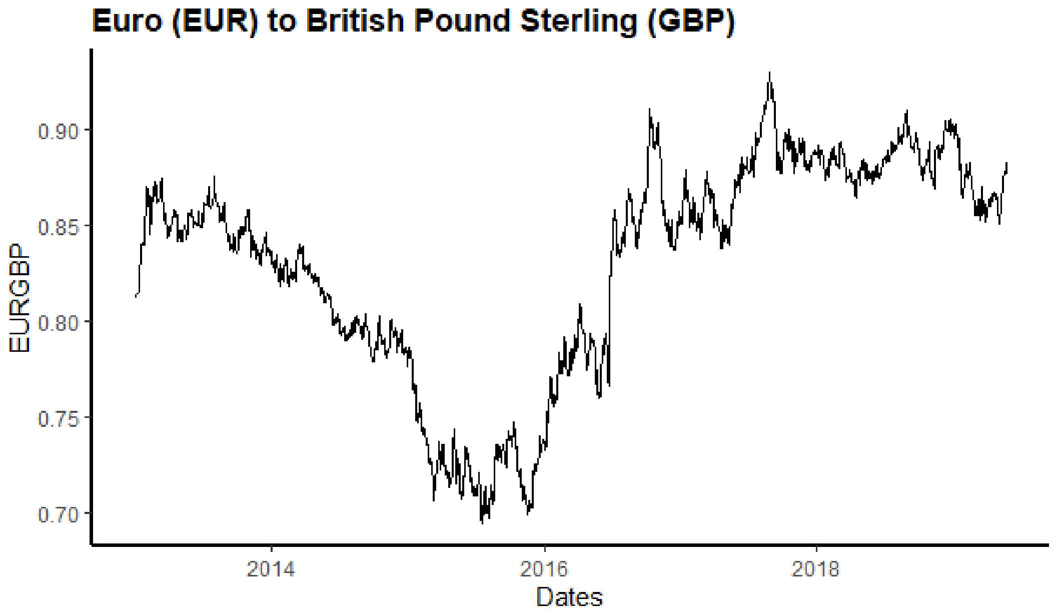


Figure 9 – Graph of the EUR/GBP exchange rate between 2013 and 2019.
Source: Bloomberg – Own calculations

Appendix 8 – GBP/USD exchange rate (2013-2019)

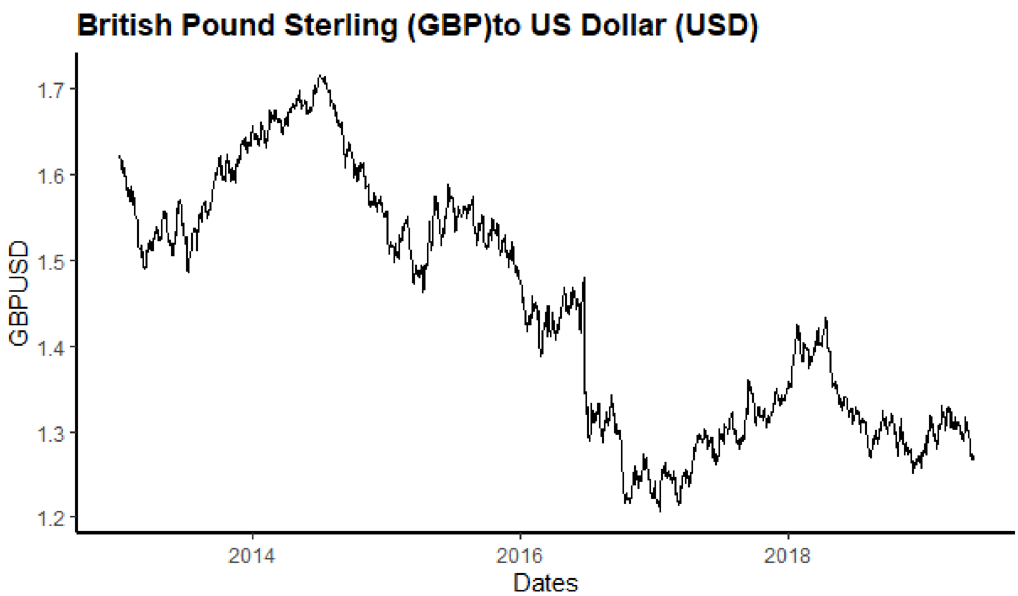


Figure 10 – Graph of the GBP/USD exchange rate between 2013 and 2019.
Source: Bloomberg – Own calculations

Appendix 9 – Comments on the exchange rates evolution (2013-2019)

Several facts that could be observed in the graphs related to the time period between 2013 and 2019 are that for both exchange rates, an important change of the price occurred in June 2016. These significant jumps are related to the result announcement of the EU referendum which was made public on the 24th of June 2016. Furthermore, according to the direction of the change of the exchange rates, the decision of the UK to leave the EU weakened the GBP currency against the currency of two main trading partners of the British economy. It means that with one euro, the individuals could get more GBP than previously and with one GBP the individuals would have less USD than previously. After this symbolic date which constitute the beginning of the UK departure from the EU, the EUR/GBP has significantly increased and the GBP/USD has significantly decreased. These exchange rate movement could be originated from the uncertainty linked to the decision to leave the EU. The EURGBP and GBPUSD exchange rates never reached their previous level after the EU referendum.

Table 29 – Comments on the exchange rates evolution (2013-2019)

Appendix 10 – EUR/GBP exchange rate daily returns (2013-2019)

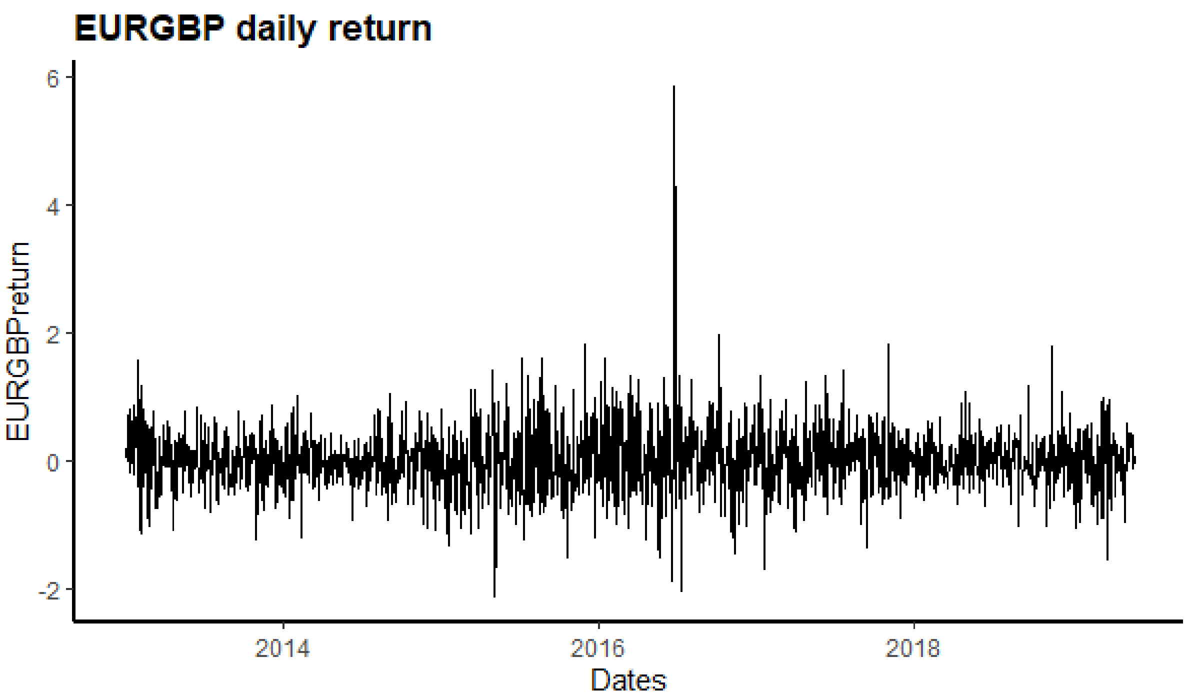


Figure 11 – Graph of the EUR/GBP exchange rate daily returns between 2013 and 2019.
Source: Bloomberg – Own calculations

Appendix 11 – GBP/USD exchange rate daily returns (2013-2019)

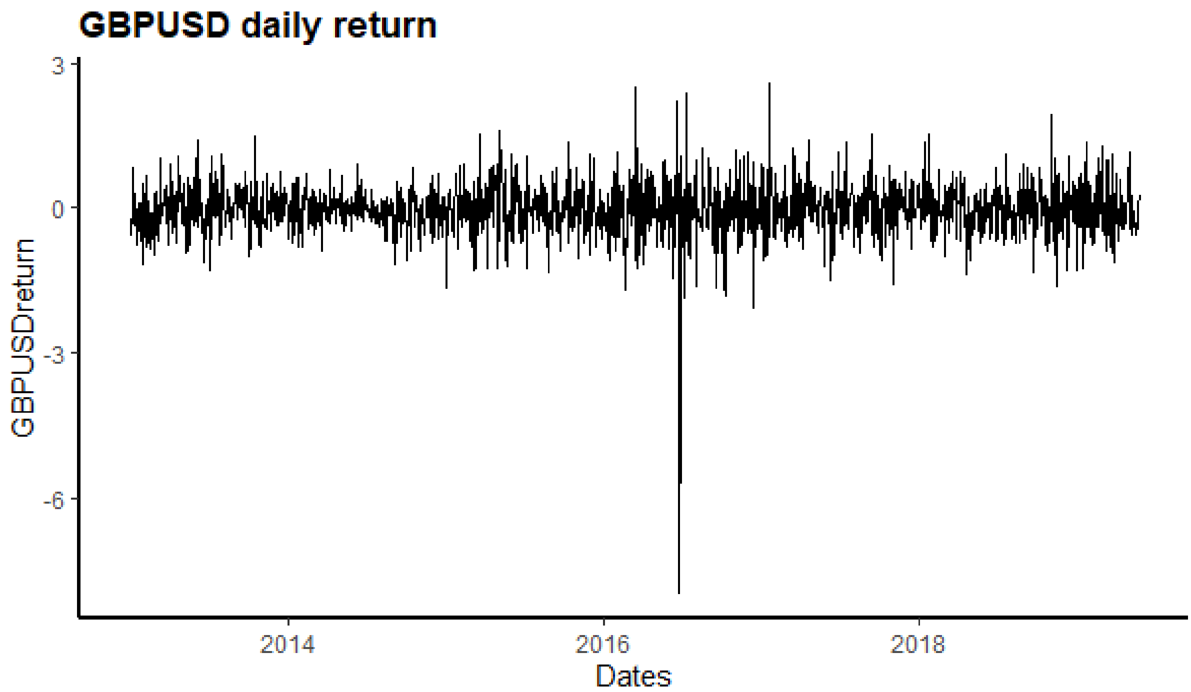


Figure 12 – Graph of the GBP/USD exchange rate daily returns between 2013 and 2019.
Source: Bloomberg – Own calculations

Appendix 12 – Brexit announcements and dates

Dates	Brexit events	EURGBP variation	GBPUSD variation
27/06/16	The Prime Minister David Cameron delivered a statement in the House of Commons concerning the result on the EU referendum and what should come next in term of processes.	2,75%	-3,46%
13/07/16	Theresa May was appointed as new Prime Minister. In her government, she appointed David Davis, a strong supporter of the Brexit, as the minister responsible for managing the negotiation of the Brexit.	0,82%	-0,66%
7/12/16	The House of Commons voted in order to trigger Article 50 by the end of March 2017	0,83%	-0,52%
9/01/17	During an interview, Theresa May announced that the United Kingdom would certainly leave the Single Market when Brexit will take place. This announcement showed the intention of Theresa May to not deliver a "soft Brexit"	1,31%	-0,96%
24/01/17	The UK Supreme Court decided to rule that the Parliament must pass legislation to authorize the triggering of Article 50	-0,12%	0,33%

16/03/17	The bill receives the Royal Assent	-0,39%	1,25%
29/03/17	Theresa May delivered a letter to the European Council in order to invoke Article 50 which represented the beginning of a two years process during which the UK would have to leave the EU at the end of this period of time	-0,96%	0,52%
8/06/17	General election is held in the UK. The purpose of these anticipated general election was to give more weight to the Conservative party for the Brexit negotiation. However, after this election, the Tories lost their majority.	1,33%	-1,49%
19/06/17	Start of the Brexit negotiations	-0,04%	-0,30%
18/07/17	Beginning of the second round of the negotiations. These negotiations were related to the Northern Irish border concern.	0,89%	-0,10%
23/08/17	Theresa May declared that the United Kingdom would leave the direct jurisdiction of the EU court of Justice when the Article 50 would end which meant in March 2019.	0,71%	-0,39%
28/08/17	Beginning of the third round of the negotiation and first tension around the negotiations. According to the European Commission President, the negotiations were not satisfactory and no trade negotiations would start until the bill that the UK must pay was settled.	0.06%	0.40%
22/09/17	Theresa May made public the details of her Brexit proposal. This speech which concerned the future relationship between the EU and the UK is perceived as a willingness to reach a soft Brexit.	0.67%	-0,52%
16/10/17	Theresa May and Jean Claude Juncker announced in a statement that Brexit negotiations should accelerate in the coming months.	0,25%	-0,80%
8/12/17	Publication of a draft agreement concerning three points for the Brexit: The protection of the rights of Union citizens in the UK and the UK citizens in the EU. The framework concerning the circumstances of Northern Ireland and the financial settlement.	0,05%	-0,26%
29/01/18	The European Council made public a report relating to the negotiating directives. According to this report, the rights and obligations binding on all European member states would continue to apply to the UK until the end of the Article 50 and the UK would keep being part of the customs unions and the single market. However, the UK would no longer participate in the EU decision making.	0,15%	-0,64%

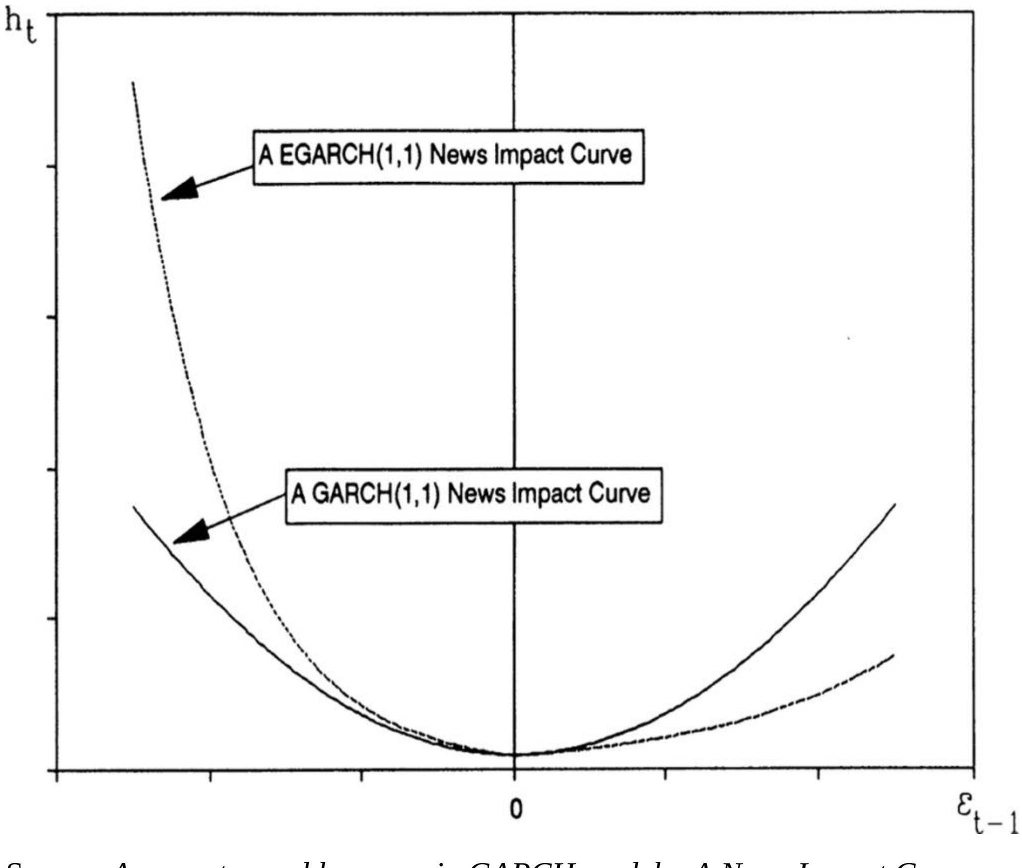
8/03/18	The United Kingdom rejected the European proposition concerning the customs and regulatory border down the Irish Sea, the EU single market and the customs union. Because of this issue, Donald Tusk announced that it would not be possible to progress further on the negotiation until the UK came with a solution	-0,35%	0,25%
19/03/18	On that day, a joint withdrawal deal report was published. According to this report, 75% was agreed nonetheless, there was a lack of clarity relating to the Northern Ireland border. The senior members of the Conservative party criticized the concessions given to Brussels in this deal agreement.	-0,29%	0,75%
6/07/18	The Minister Cabinet agreed (not unanimously) to deliver a proposition of a UK-EU free trade agreement relating to the industrial, goods and agricultural products. This does not concern the services.	0,52%	-0,51%
8/07/18	Not satisfied by the UK White Paper realized by the Minister Cabinet, Davis resigned as Secretary of State for Exiting the European Union. His resignation will be followed by the resignation of the minister Boris Johnson.	-0,37%	0,27%
2/08/18	Barnier stated that the EU was open to improve their proposition relating to the Ireland border. This point is the main concern in the negotiations for the Brexit. Furthermore, he also announced that the White Paper of the UK had several problems such as the customs proposal.	0,14%	-0,64%
29/08/18	Michel Barnier, the President of the European Comission stated that the EU would offer a trade deal which would guarantee a close relationship between the two economic area after the Brexit negotiations.	-1,01%	0.90%
21/09/18	European Union rejected the UK White Paper concerning the Brexit deal. After this rejection, Theresa May announced that a no deal is better than a bad deal for the United Kingdom.	1,16%	-1,31%
14/11/18	Theresa May announced that the Minister Cabinet agreed on the draft agreement developed by the European Commission.	0,40%	-0,26%
15/11/18	Raab resigned as Secretary of State for Exiting the European Union	1,77%	-1,59%
25/11/18	All the EU27 leaders endorsed the withdrawal agreement concerning the Brexit.	NA	NA

10/12/18	With the several concerns from the House of Commons relating to the withdrawal agreement, Theresa May decided to postpone Brexit deal vote in order to gain time and to convince the member of the House of Commons that this represented a good deal.	1,09%	-1,28%
14/12/18	After the decision of postponing the Brexit vote, Theresa May tried to re-negociate the deal with the European Union. Nonetheless, the European Council announced that there could be no further negotiations relating to the Brexit.	-0,10%	-0,37%
15/01/19	The Brexit deal was voted down by the House of Commons. Thereafter, Jeremy Corbyn, the Leader of the Labor party, tabled for a motion of no confidence towards Theresa May. A vote for which, Theresay May survived.	0,48%	-1,24%
17/01/19	Corbyn asked to the Prime Minister to rule out the "No Deal" option for the following propositions that would be delivered to the House of Commons but Theresa May rejected this demand.	-0,96%	0,84%
26/02/19	Jeremy Corbyn and his Labour party had backed for the organization of a new referendum.	-0,99%	1,28%
12/03/19	The House of Commons again rejected the Brexit deal proposal.	0,98%	-0,56%
13/03/19	The House of Commons refused the proposition to leave the EU in a no deal context	-0,88%	0,99%
14/03/19	The House of Commons approved on the extension of the Article 50 in order to have more time to negotiate the Brexit	-0,44%	0,40%
21/03/19	The European Council accepted to extend the Article 50 until May 2019	0,85%	-0,90%
27/03/19	Eight propositions concerning the Brexit concern were given to the House of Commons and each of these propositions were rejected.	0,96%	-1,13%
29/03/19	Third vote relating to the Brexit deal is realized at the House of Commons and the withdrawal agreement is again rejected.	-0,13%	-0,28%
1/04/19	Second round of indicative votes, John Bercow, the speaker of the House took back four propositions which had been made on the 27th March. However, these four propositions were again rejected by the House of Commons.	-0,75%	0,64%

10/04/19	The European Council decided to extend the Article 50 related to the Brexit until 31 October 2019. In this new agreement, there is the option of an earlier withdrawal from the EU.	-0,55%	0,58%
3/05/19	Local election in the United Kingdom during which the Conservatives lost several seats and the Liberal Democrats which is a party composed of Pro-EU gained 145 seats.	-0,95%	1,14%
24/05/19	Theresa May announced her resignation from her position of Prime Minister. The reason of her resignation is due to the fact that she was not able to convince the Parliament to pass her Brexit deal agreement.	-0,08%	0,28%

Table 30 – Brexit announcements and dates.

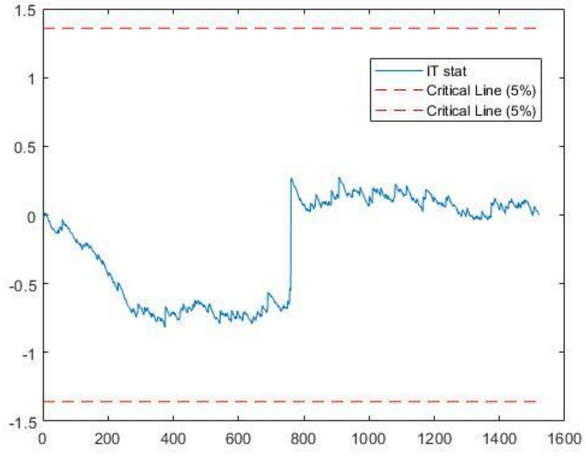
Appendix 13 – GARCH and EGARCH news impact curve



Source: *Asymmetry and leverage in GARCH models: A News Impact Curve perspective*

Figure 13 – GARCH and EGARCH news impact curve

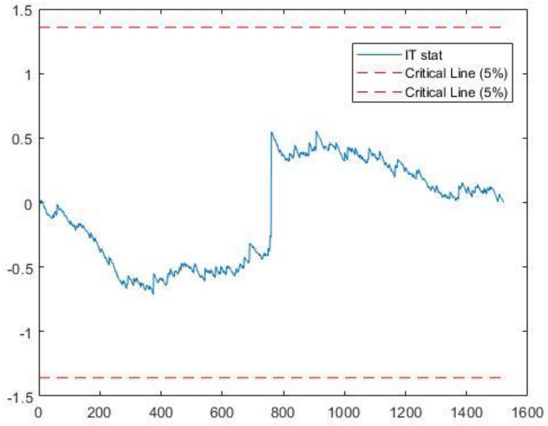
Appendix 14 – IT statistic EUR/GBP (2013 – 2019) GARCH with dummy variable



Source: Bloomberg – Own calculations.

Figure 14 – IT statistic EUR/GBP (2013 – 2019) GARCH with dummy variable

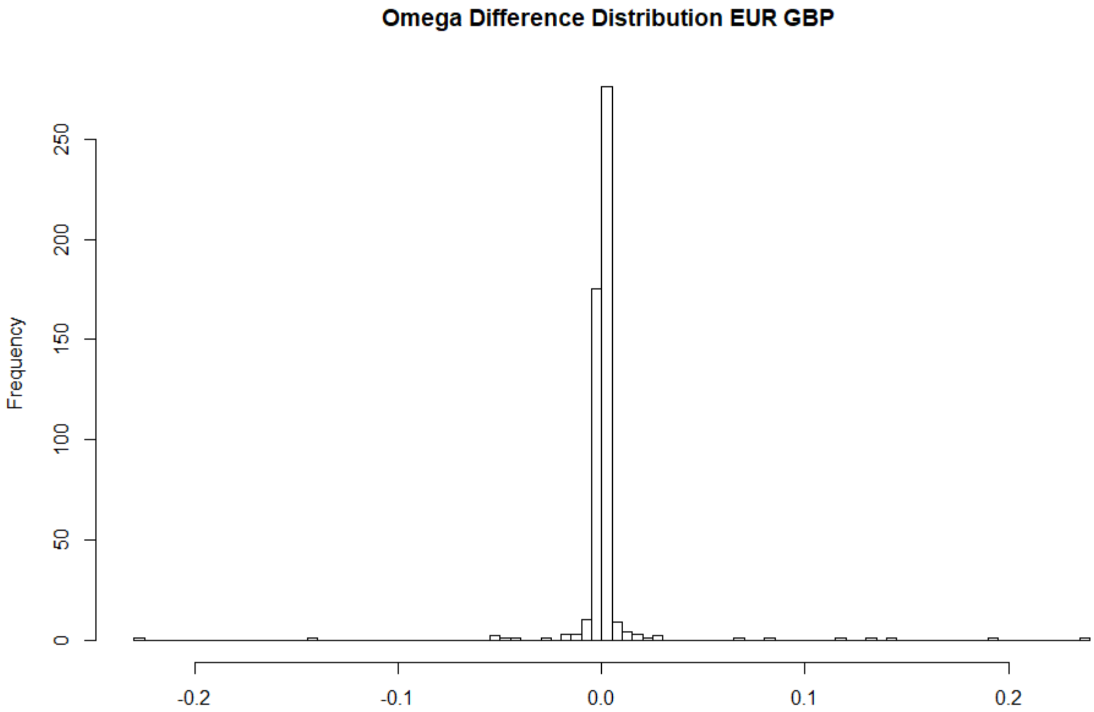
Appendix 15 – IT statistic GBP/USD (2013 – 2019) GARCH with dummy variable



Source: Bloomberg – Own calculations.

Figure 15 – IT statistic GBP/USD (2013 – 2019) GARCH with dummy variable

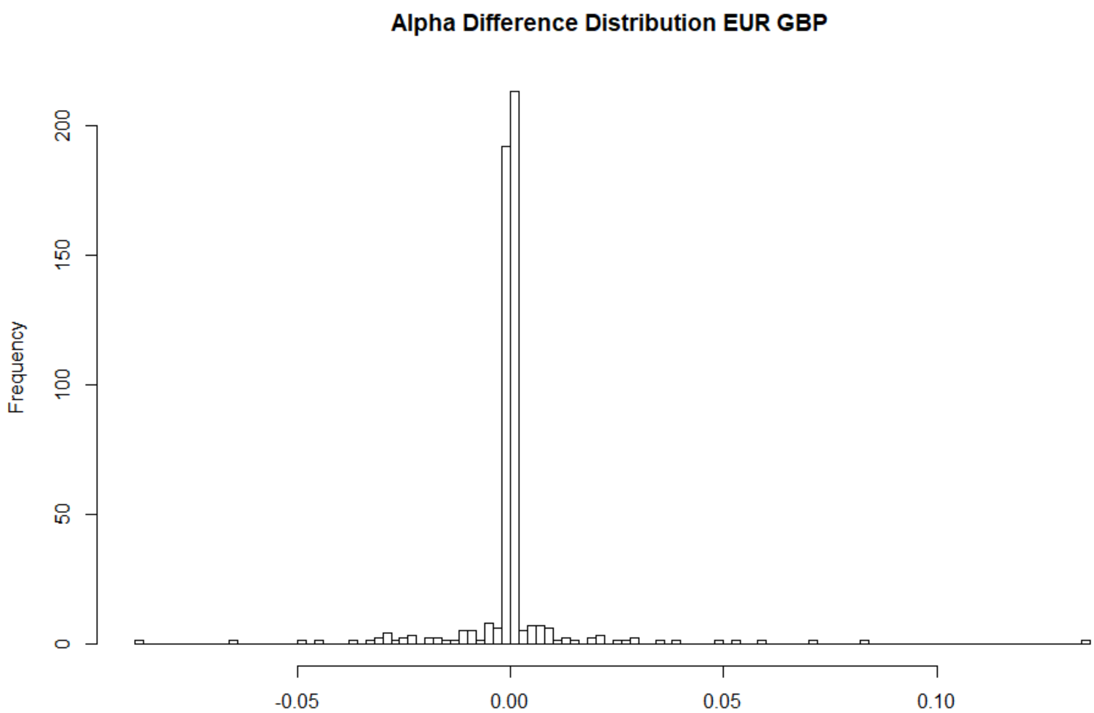
Appendix 16 – Omega Differences Distribution EUR/GBP



Sources: Bloomberg – Own calculations.

Figure 16 – Omega Differences Distribution EUR/GBP

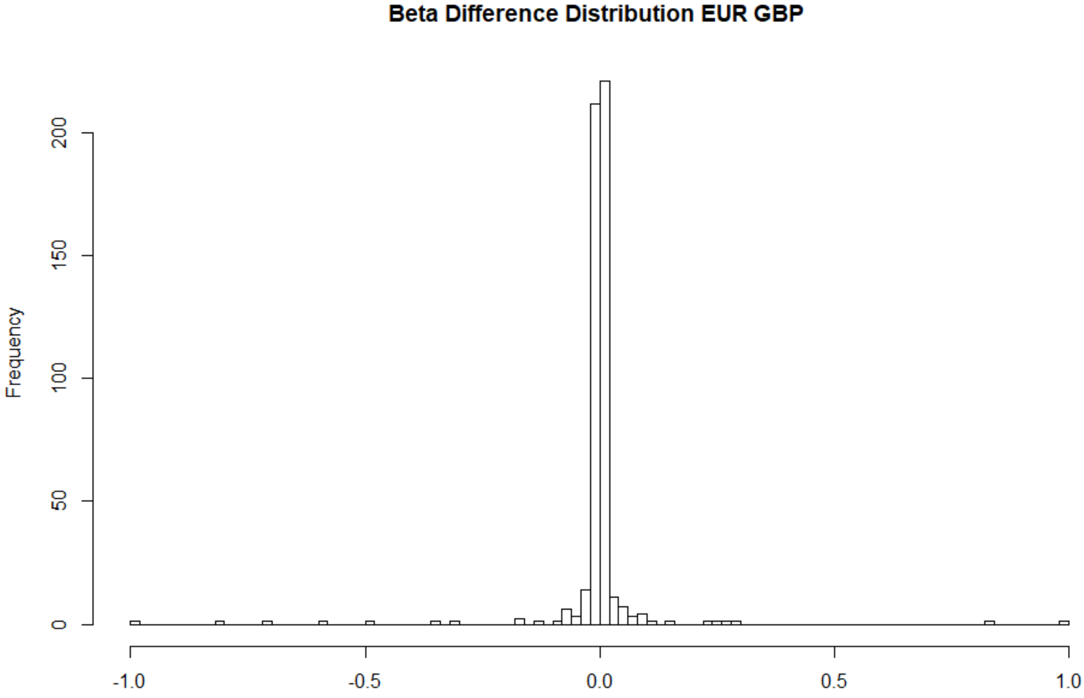
Appendix 17 – Alpha Differences Distribution EUR/GBP



Sources: Bloomberg – Own calculations.

Figure 17 – Alpha Differences Distribution EUR/GBP

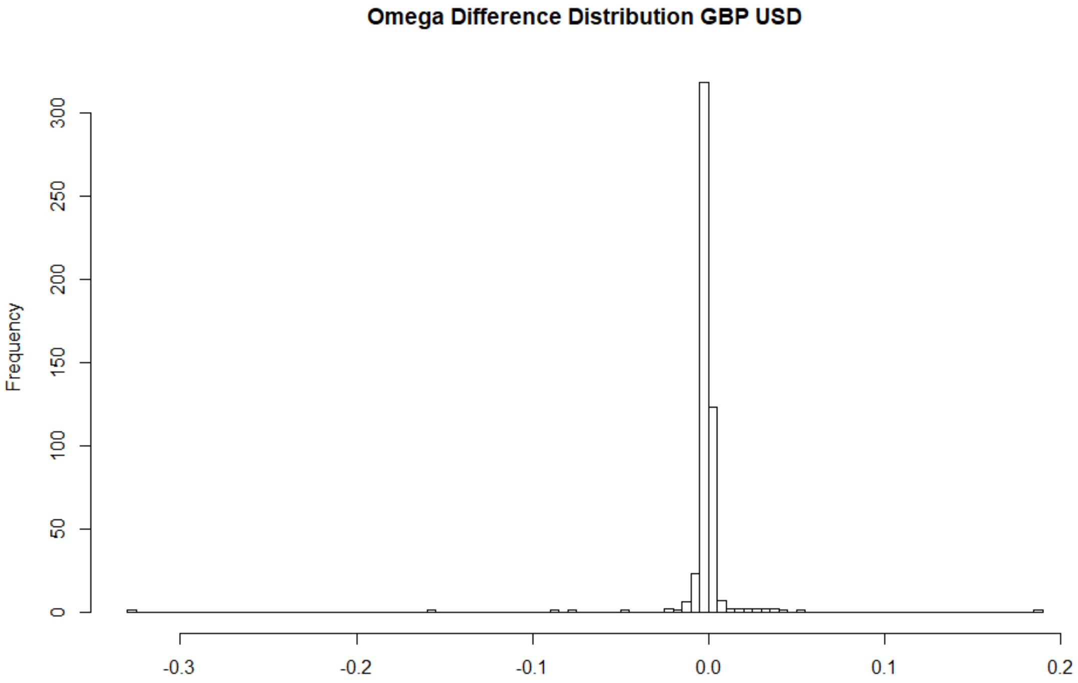
Appendix 18 – Beta Differences Distribution EUR/GBP



Sources: Bloomberg – Own calculations.

Figure 18 – Beta Differences Distribution EUR/GBP

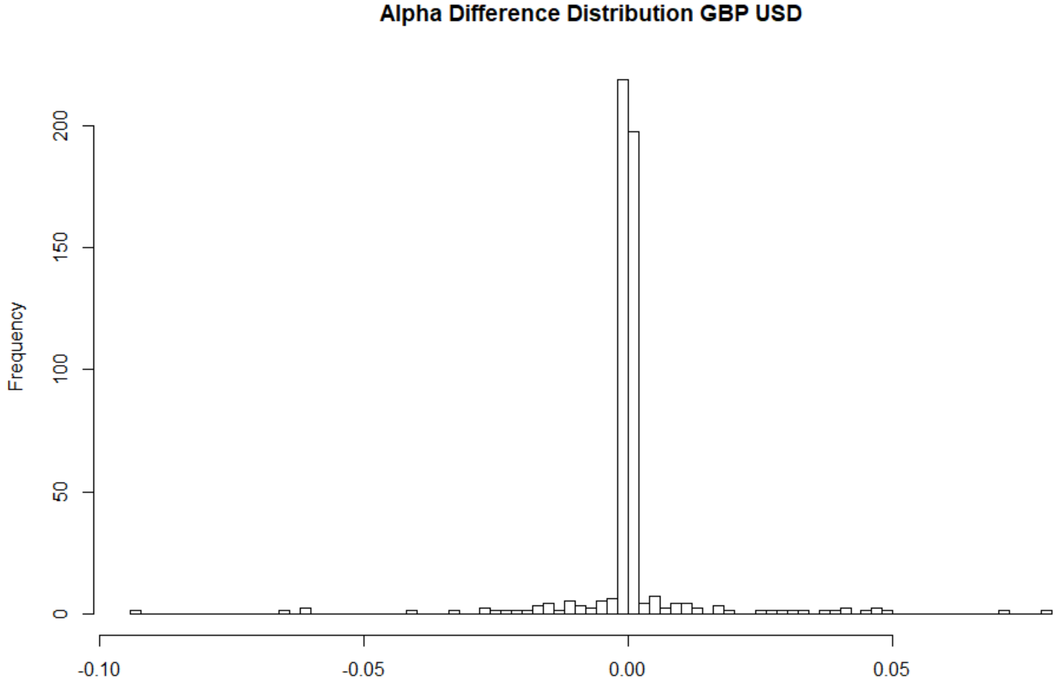
Appendix 19 – Omega Difference Distribution GBP/USD



Sources: Bloomberg – Own calculations.

Figure 19 – Omega Differences Distribution EUR/GBP

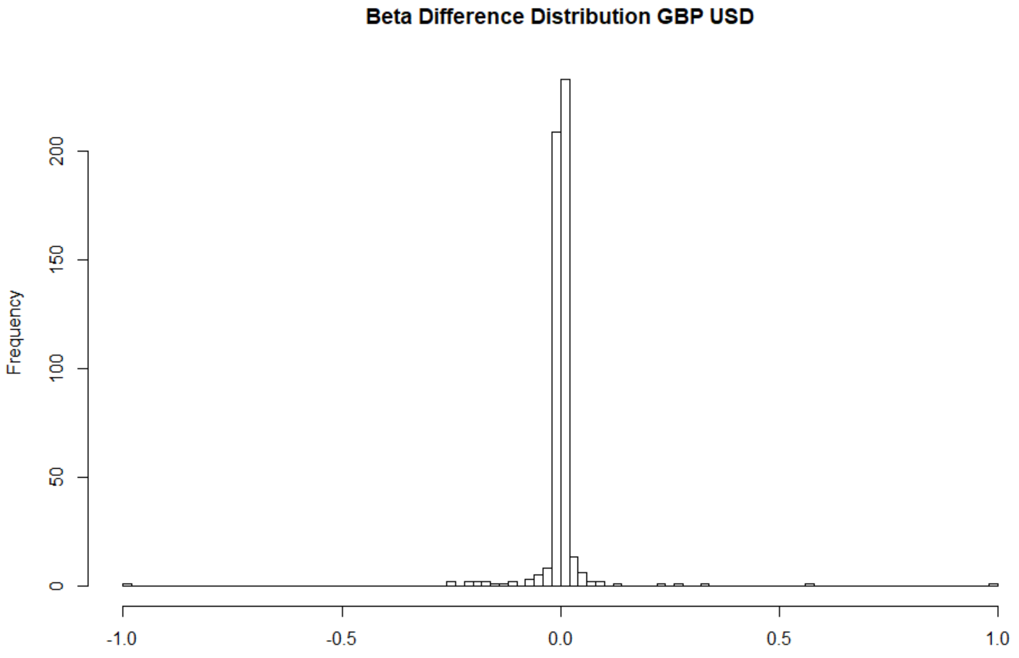
Appendix 20 – Alpha Differences Distribution GBP/USD



Sources: Bloomberg – Own calculations.

Figure 20 – Alpha Differences Distribution GBP/USD

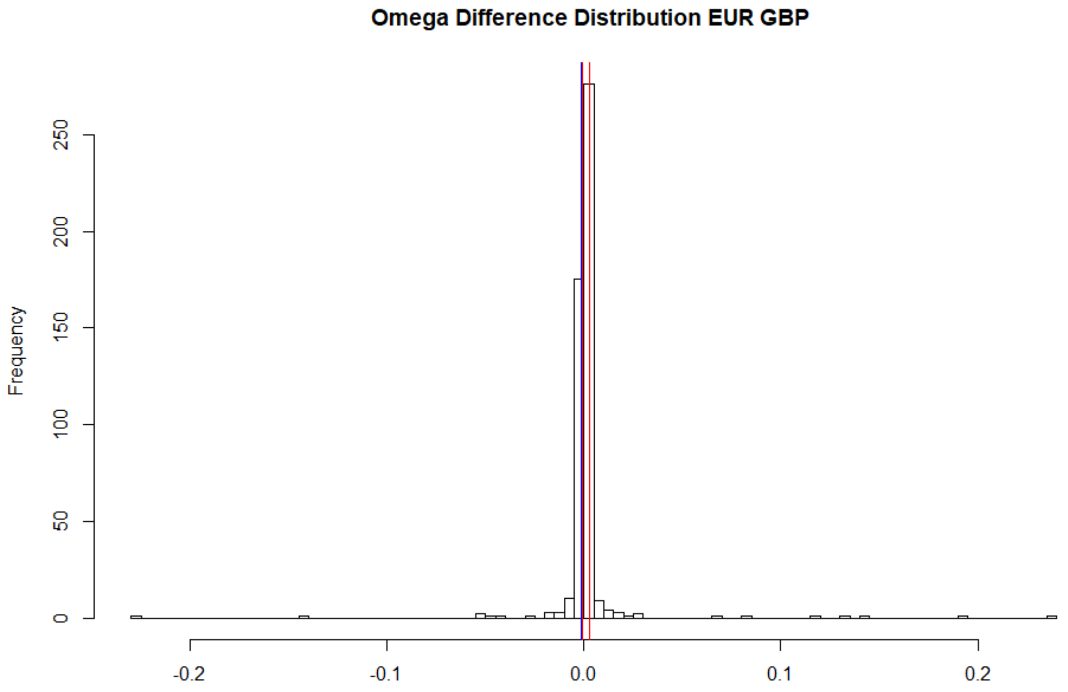
Appendix 21 – Beta Differences Distribution GBP/USD



Sources: Bloomberg – Own calculations.

Figure 21 – Beta Differences Distribution GBP/USD

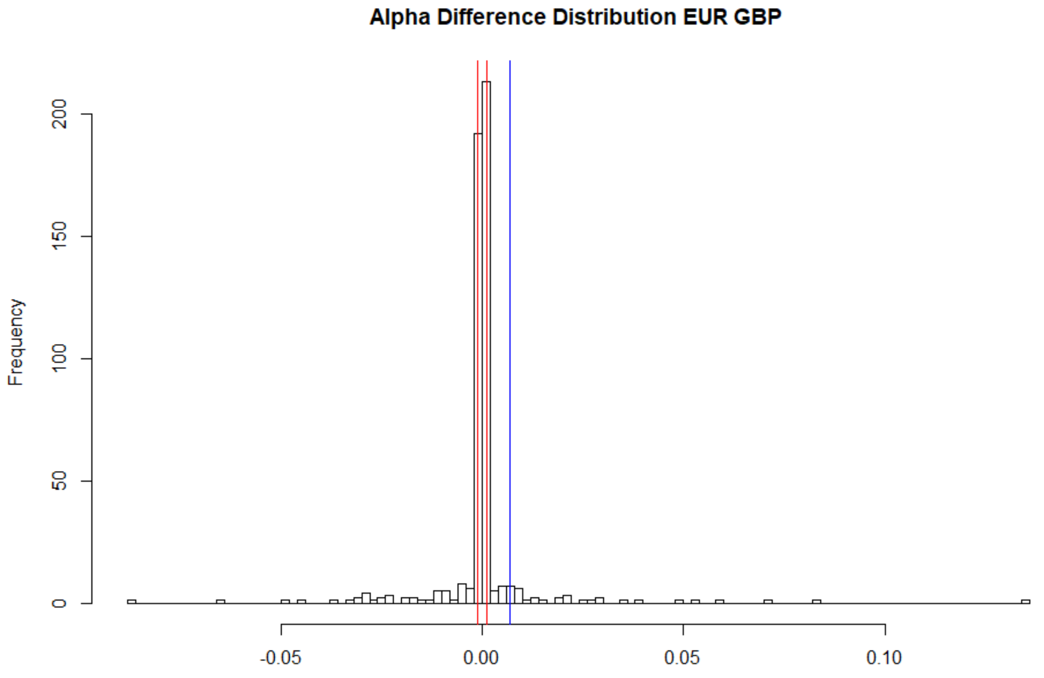
Appendix 22 – Omega Differences Distribution EUR/GBP with IC



Sources: Bloomberg – Own calculations.

Figure 22 – Omega Differences Distribution EUR/GBP with IC

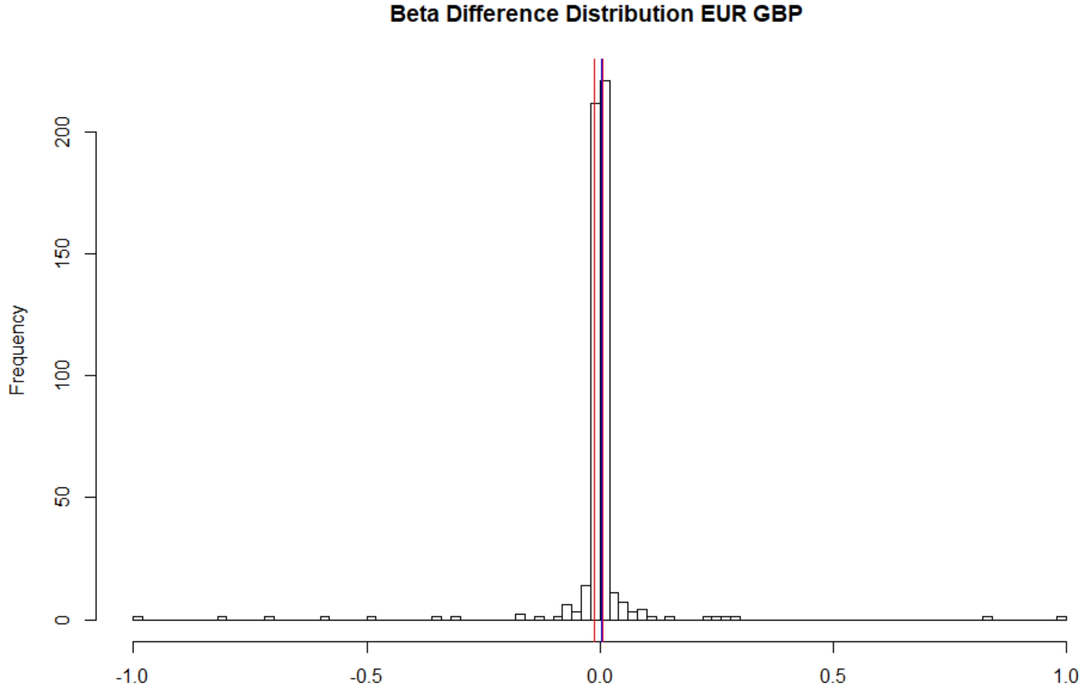
Appendix 23 – Alpha Differences Distribution EUR/GBP with IC



Sources: Bloomberg – Own calculations.

Figure 23 – Alpha Differences Distribution EUR/GBP with IC

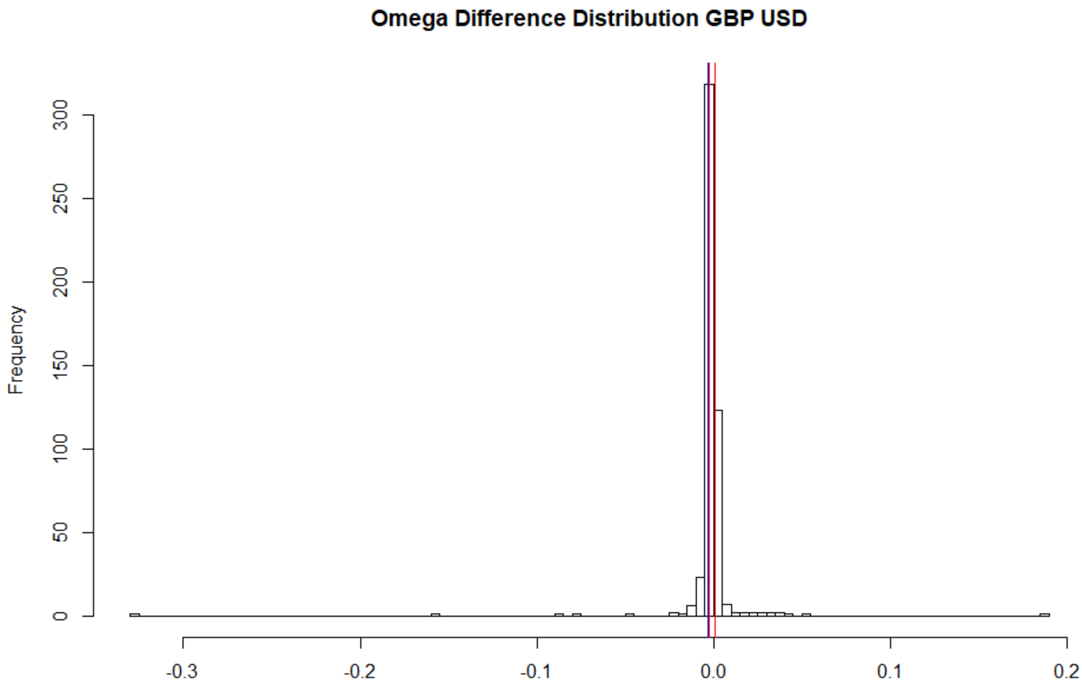
Appendix 24 – Beta Differences Distribution EUR/GBP with IC



Sources: Bloomberg – Own calculations.

Figure 24 – Beta Differences Distribution EUR/GBP with IC

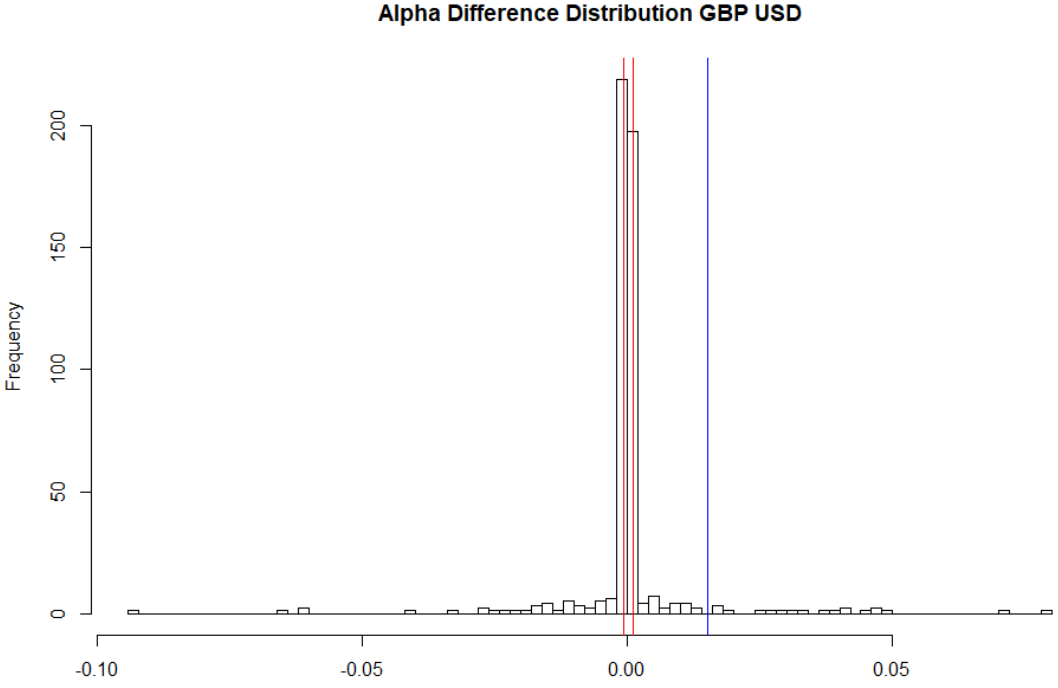
Appendix 25 – Omega Differences Distribution GBP/USD with IC



Sources: Bloomberg – Own calculations.

Figure 25 – Omega Differences Distribution GBP/USD with IC

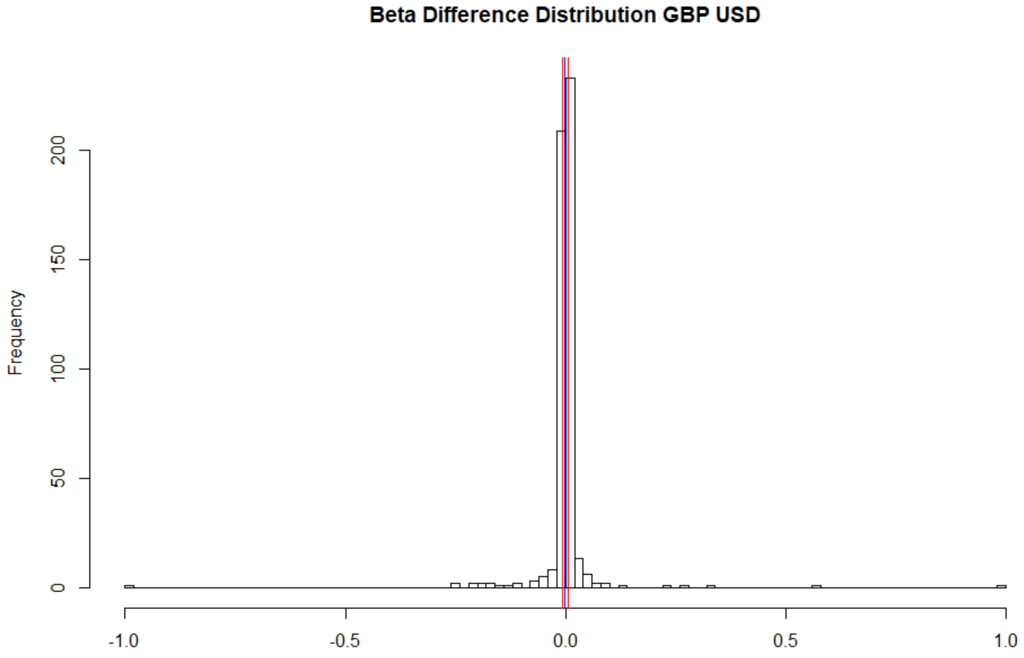
Appendix 26 – Alpha Differences Distribution GBP/USD with IC



Sources: Bloomberg – Own calculations.

Figure 26 – Alpha Differences Distribution GBP/USD with IC

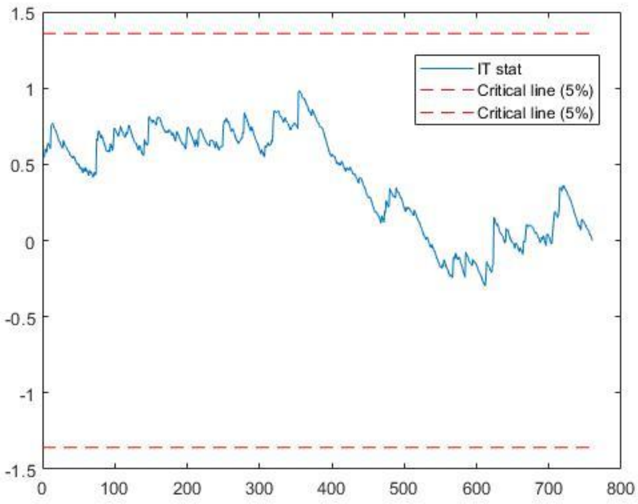
Appendix 27 – Beta Differences Distribution GBP/USD with IC



Sources: Bloomberg – Own calculations.

Figure 27 – Beta Differences Distribution GBP/USD with IC

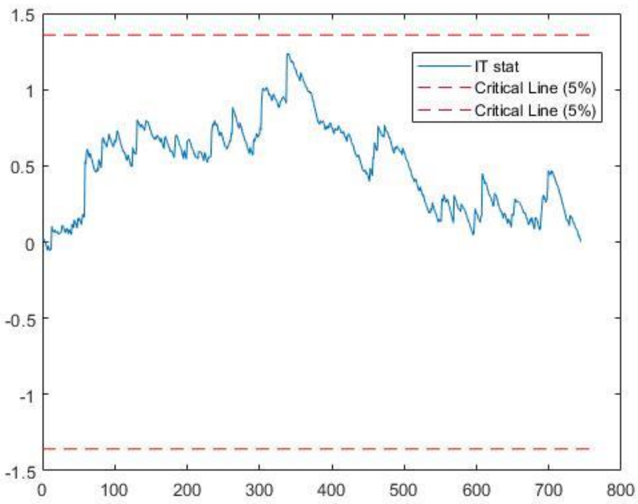
Appendix 28 – IT statistic EUR/GBP (2016 – 2019) GARCH



Sources: Bloomberg – Own calculations.

Figure 28 – IT statistic EUR/GBP (2016 – 2019) GARCH

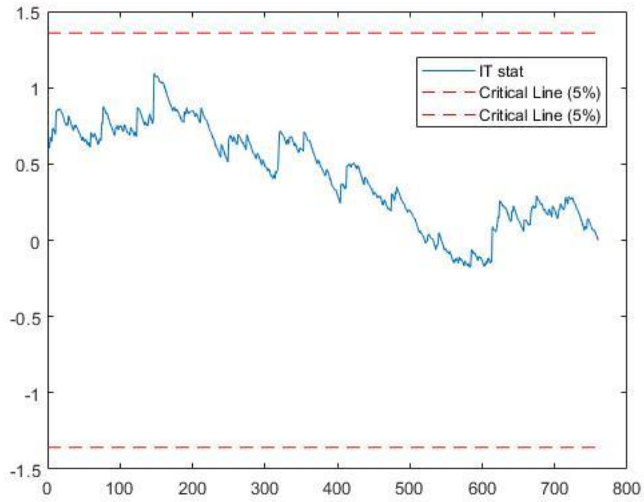
Appendix 29 – IT statistic EUR/GBP (2016 – 2019) GARCH with dummy variable



Sources: Bloomberg – Own calculations.

Figure 29 – IT statistic EUR/GBP (2016 – 2019) GARCH with dummy variable

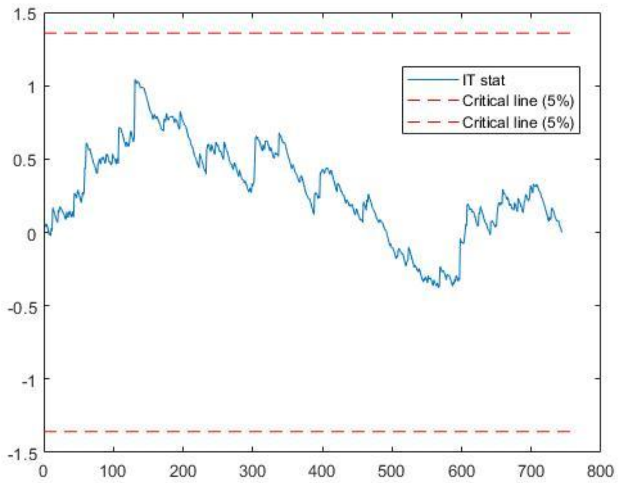
Appendix 30 – IT statistic GBP/USD (2016 – 2019) GARCH



Sources: Bloomberg – Own calculations.

Figure 30 – IT statistic GBP/USD (2016 – 2019) GARCH

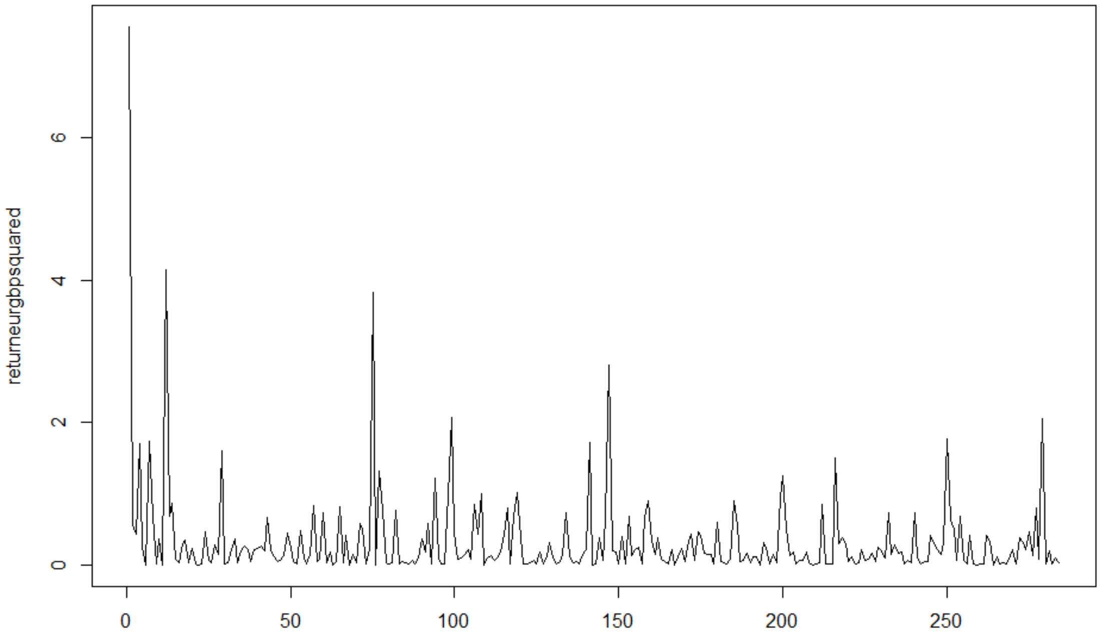
Appendix 31 – IT statistic EUR/GBP (2016 – 2019) GARCH with dummy variable



Sources: Bloomberg – Own calculations.

Figure 31 – IT statistic EUR/GBP (2016 – 2019) GARCH with dummy variable

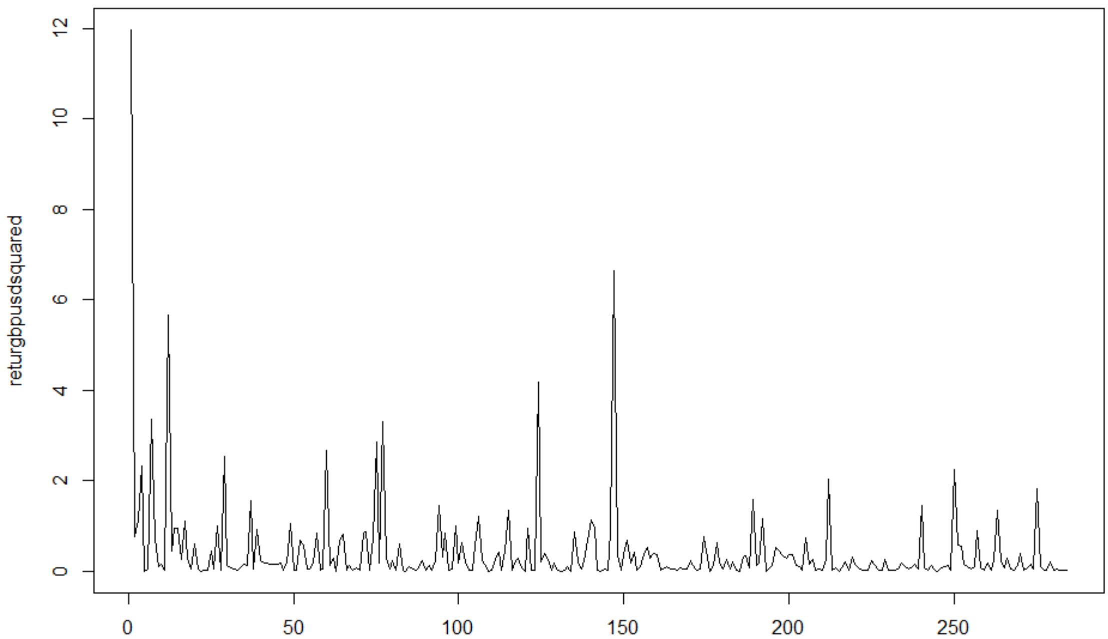
Appendix 32 – Squared of the EUR/GBP returns (2016 – 2017)



Sources: Bloomberg – Own calculations.

Figure 32 – Squared of the EUR/GBP returns (2016 – 2017)

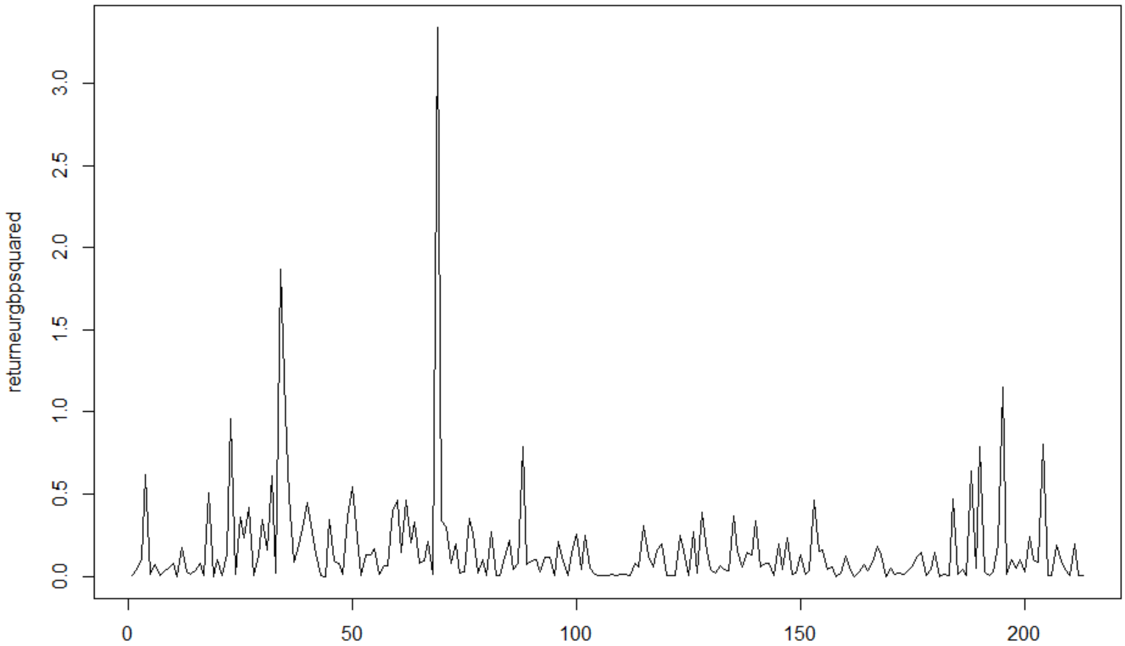
Appendix 33 – Squared of the GBP/USD returns (2016 – 2017)



Sources: Bloomberg – Own calculations.

Figure 33 – Squared of the GBP/USD returns (2016 – 2017)

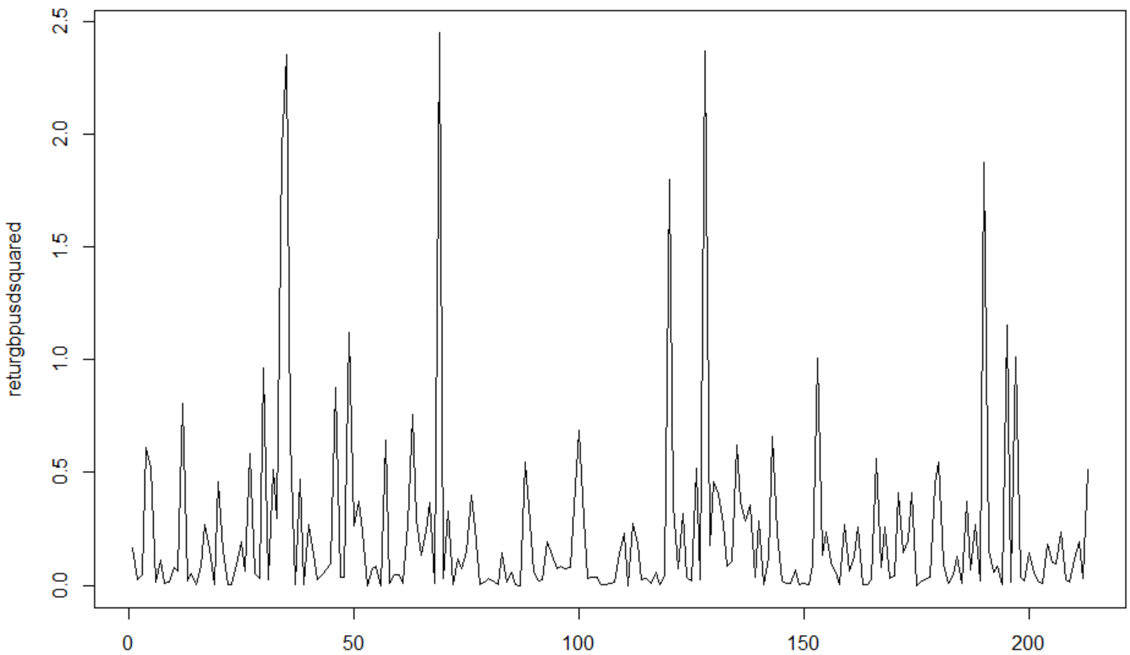
Appendix 34 – Squared of the EUR/GBP returns (2017 – 2018)



Sources: Bloomberg – Own calculations.

Figure 34 – Squared of the EUR/GBP returns (2017 – 2018)

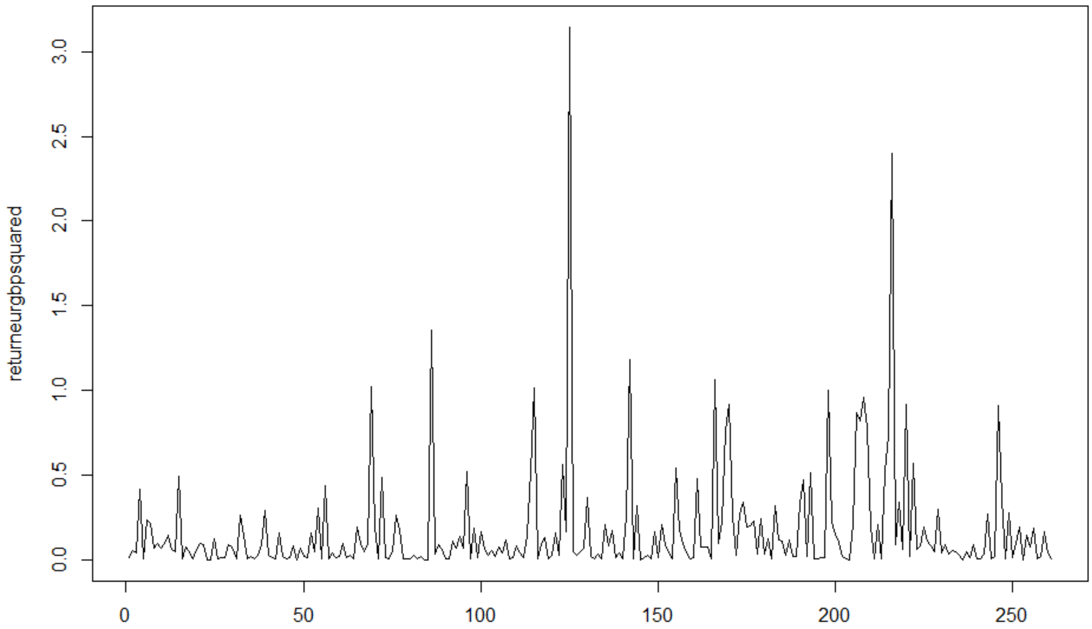
Appendix 35 – Squared of the GBP/USD returns (2017 – 2018)



Sources: Bloomberg – Own calculations.

Figure 35 – Squared of the GBP/USD returns (2017 – 2018)

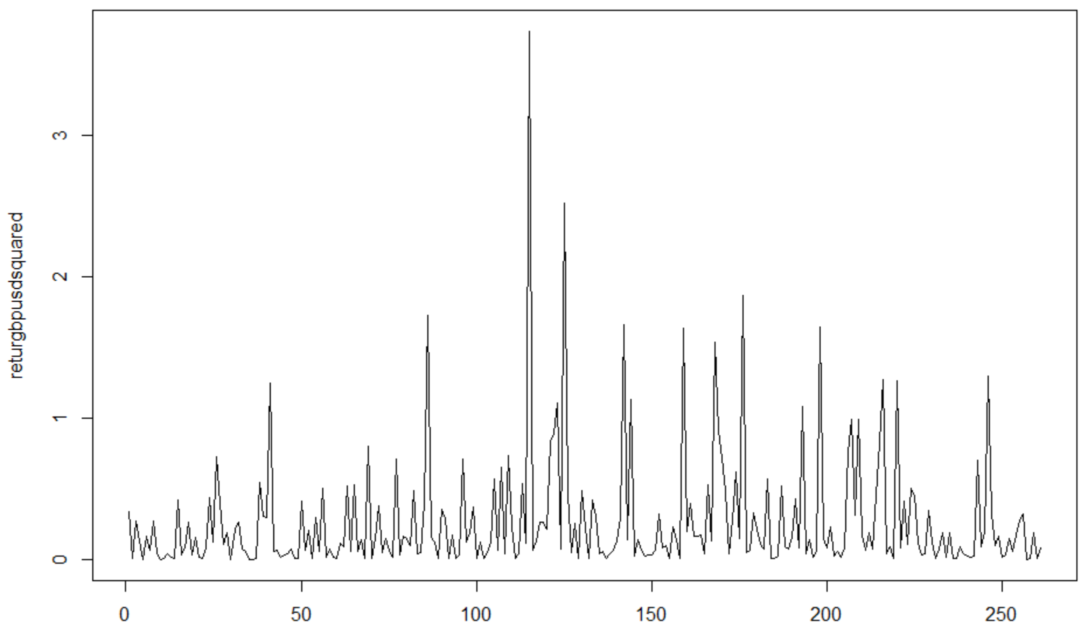
Appendix 36 – Squared of the EUR/GBP returns (2018 – 2019)



Sources: Bloomberg – Own calculations.

Figure 36 – Squared of the EUR/GBP returns (2018 – 2019)

Appendix 37 – Squared of the GBP/USD returns (2018 – 2019)



Sources: Bloomberg – Own calculations.

Figure 37 – Squared of the GBP/USD returns (2017 – 2018).