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Did the Global Financial Crisis affect the Structural Relationship Between Policy Rates and Inflation in the Eurozone and United States?

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Abstract

The relationship between inflation and short-term nominal interest rates plays a significant role in the application of monetary policy. One of the primary reasons for the relationship's importance is the monetary authority's ability to stimulate or reduce economic activity to control inflation through policy rates. However, using interest rates to manage inflation requires a clear cause-and-effect relationship. Inflation and nominal interest rates have been on a downward trend since the 1980s. However, after the global financial crisis, both inflation and nominal interest rates were at simultaneous record lows, with policy rates seemingly unable to stimulate the economy and cause a corresponding rise in prices. This thesis examines the structural relationship between inflation and nominal interest rates in the case of the eurozone and the United States for data between 1999 and 2019 to make new contributions to the discussion about the relationship between inflation and nominal interest rates after the global financial crisis. The thesis examines the structural relationship between inflation and interest rates by employing structural break tests, a plethora of unit root and cointegration tests, and Granger causality tests.

The empirical results find no evidence for a structural break in the relationship between inflation and policy rates for the US. The results do, however, support the existence of a long-term equilibrium relationship between inflation and interest rates in the US, with a uni-directional Granger causality from the policy rate to inflation. Conversely, the thesis finds clear evidence for a structural break in the eurozone's relationship between inflation and the nominal interest rate while, accordingly, finding little evidence for a long-term equilibrium relationship. There is, however, evidence for a uni-directional Granger causality from inflation to nominal interest rates.

Keywords – Cointegration, Granger causality, inflation, interest rates, structural breaks

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1 Introduction

There is a rich literature analysing the relationship between nominal interest rates and inflation. Obviously, this is of tremendous academic interest. However, much more importantly, it bears significant policy implications. Many historical examples show how inflation running wild can put a severe strain on the economy and society. For example, episodes of hyperinflation have often corresponded with periods of great political turmoil. The Weimar Republic during the interwar period is a classic example. Extensive inflation can wipe out people's savings, it can cause hoarding and subsequent shortages of essential goods and massive unemployment might follow. It is no wonder, then, that central banks, whose responsibility it is to maintain stable prices, must spend many resources on gaining insight into the workings of inflation. Traditionally, nominal interest rates have been the most important tool that central bankers have for steering the inflation rate (Cukierman, 2012). As such, there is no surprise that much research has shed light on the relationship between nominal interest rates and inflation rates.

When discussing the relationship between nominal interest rates and inflation, we often take the so-called Fisher hypothesis as our starting point. The hypothesis asserts that expected future inflation equals the difference between nominal interest rates and real interest rates. Provided a change in nominal interest rates has no effect on the real interest rate, there is a one-to-one relationship between nominal interest rates and expected inflation (Hashimzade et al., 2017). Even so, this is certainly not the last word in the debate. In fact, the relationship between nominal interest rates and the inflation rate has been a contentious topic in the literature. This thesis will briefly review the literature and build on it by considering the structural properties of the nominal interest rate and inflation. However, it should also be mentioned that the classic Fisher effect states that nominal rates and inflation move together in the long run. This positive association is a robust empirical regularity (Uribe, 2022). As such, it is only natural that this thesis presents a theoretical overview of the supposed theoretical relationship between nominal interest rates and inflation. On this theoretical foundation, this thesis encounters and tries to shed light on the following realisation: In the past two decades, several advanced economies have been experiencing chronic below-target rates of inflation despite short-term nominal interest rates close to zero (Ciccarelli and Osbat, 2017). The relationship between nominal interest rates and the inflation rate seems to have weakened during the last couple of decades (Eggertsson et al., 2019) and, particularly in the aftermath of the Global Financial Crisis (Williams, 2014), since central banks have been unable to stimulate output and thus increase inflation through the use of record low nominal interest rates (Silvia and Iqbal, 2014). This weakened relationship has motivated several countries to consider unconventional policy measures such as quantitative easing. Alas, such measures. In June 2014, the European Central Bank (ECB, 2022a) introduced its negative interest policy when it decided to cut its deposit facility rate below zero for the first time. The ECB has cut its deposit facility rate four more times since then, reaching a nominal short-term interest rate of -0.50% in September 2019 (Claeys, 2021).

Over the years, economists have developed many tools for analysing time series. Statistical tests, such as the Chow test, have been designed to identify structural breaks in time series. Moreover, unit root tests such as the Phillips-Perron and Zivot-Andrews have been designed to test the stationary status of series in the presence of structural breaks, while cointegration models test for long-term relationships and the Granger causality test for directional explanatory power. Economists and statisticians create different statistical tests built on different sets of assumptions. Depending on the validity of different underlying assumptions, statistical tests might differ in the quantitative conclusions they yield. If they do so, we must investigate further why that might be. What assumptions (and, by association, statistical tests) are valid and which are not? On the other hand, if several statistical tests which build on different sets of assumptions all yield the same conclusion, our conclusions have much higher credibility. If we truly want to understand the mechanisms of complex phenomena such as financial crises and the relationship between nominal interest rates and inflation rates, we must ensure that our qualitative conclusions are sound and credible. As such, this thesis seeks to shed light on how time series tests can shed light on the effects of the financial crisis on the relationship between nominal interest rates and inflation. In order to get as much insight as possible into the structural properties of time series, various tests, such as the Fisher-Jenks algorithm, the Chow test and the Zivot-Andrews test, are used. This allows one to draw much more robust conclusions from the empirical analysis, which is a goal promoted by, e.g., Hansen and Sargent (2007). In addition to testing for structural breaks, this thesis will also employ cointegration tests to evaluate the series' long-term relationship and Granger causality to examine the directional explanatory power of the variables.

The abovementioned weakening of the relationship between the nominal interest rate and inflation has been particularly pronounced in advanced economies (Bernanke, 2022), and as such, this thesis will consider data for the eurozone and the US in its analysis. The empirical analysis suggests that there is, indeed, a structural break in the relationship in the eurozone. However, one fails to identify such a structural break in the US. There might be many reasons why these two areas differ in this regard. One factor might be differences in macroeconomic policies. The ECB's primary mandate is to ensure price stability (ECB, 2022c), whereas the Federal Reserve System is also mandated with ensuring financial stability while simultaneously seeking to achieve maximum employment(Fed, 2022c). The sovereign debt crisis in the eurozone might be another factor that has caused the structural break. However, this thesis does not seek to provide a complete explanation as to why this structural break has occurred. Instead, the focus is on identifying, quantifying and analysing the structural break, and evaluating the long-term relationship between inflation and policy rates. The data used covers the period 1999 to 2019, with the federal funds and deposit facility rate as the nominal interest rate for the United States and the eurozone, respectively. Accordingly, a consumer price index (CPI) for all consumers is used as the inflation rate for the US, while the Harmonised Index of Consumer Prices (HICP) is used as the inflation rate for the eurozone.

1.1 Objectives and Research Hypotheses

In light of the data from the eurozone and the US covering the outbreak and consequences of the GFC as well as the emphasis on using a plethora of statistical tests, the following research questions will be evaluated in the thesis:

1. Has there been a structural break in the relationship between in the time series data for inflation and nominal interest rates in the eurozone and US?
2. Is there a long-term relationship between inflation and the nominal interest rate in the eurozone and US?
3. Is there a casual relationship between inflation and nominal interest rates in the eurozone and US?

The better part of the thesis will be devoted to answering these three questions. However, as an illustration of the points made in the thesis, a brief vector autoregressive (VAR) model analysis will be performed for illustrative purposes.

1.2 Organisation of the Thesis

The thesis consists of six chapters. The remainder of this thesis is organized as follows. Chapter 2 describes the background of the data and the topic. Chapter 3 describes the theory related to the economic cause-effect relationship and related literature. Chapter 4 describes the methods applied in the thesis to answer the research questions. Insights into the findings from the methods described in chapter 4 are reported in chapter 5. Finally, a summary of the thesis, a conclusion, limitations of the study and suggestions for future research are presented in chapter 6.

2 Background

Chapter 2 will begin with a brief overview of the new trends and developments in monetary policy since the 1990s. Then, it will cover the ECB and the Fed and their respective goals, similarities and differences. Finally, the chapter will compare and contrast the two central banks' policies, especially after the Global Financial Crisis (GFC) of 2007-2009.

Inflation and policy rates in the eurozone and US reached their lowest recorded levels in decades after the GFC. Even so, Inflation rates have been declining steadily in advanced economies since the 1980s. In the early 1980s, average inflation in the Organisation for Economic Co-operation and Development (OECD) was above 10% for most OECD countries, with only two out of 30 countries having an inflation rate below 5%. By the second half of the 1990s, the number of OECD countries with an inflation rate below 5% had increased to 25, with an average inflation rate of 2% to 3% (Pain et al., 2006). Inflation rates were depressed further following the GFC, with the average inflation in the OECD being 1.2% in 2011.

Similarly, interest rates have also been trending downwards since the 1990s, especially in the early 2000s. However, the period since the GFC has been marked by an unusually broad-based disinflation around the world. About 80 % of countries worldwide experienced disinflationary tendencies immediately after the GFC. Roughly 80 % of advanced economies experienced outright deflation (Kose and Ohnsorge, 2019). During the recession after the GFC, median global trend inflation declined by three percentage points on average, from 3.1% to 0.10 %. For example, in 1990, the key policy rate in the US, the federal funds rate, was at 8% (Fed, 2022a). By 2010, after the GFC, it had decreased to 0.10%. The ECB's key policy rate, the ECB deposit facility rate, had correspondingly declined from 3.5% in May of 2000 to 0% in 2012, and then -0.5% in 2019 (ECB, 2022c).

The fallout after the GFC can, to a considerable extent, explain the record low inflation and policy rates in the mid-2010s. Even so, the downward trend started earlier as central banks implemented new monetary frameworks in the 1990s.

2.1 Central Banks

Until the 1990s, the design of monetary policy was typically centred around nominal monetary growth (Blanchard et al., 2013). Central banks chose a nominal growth target for the medium run and thought about short-run monetary policy in terms of deviations of nominal money growth from the target. However, in the past decades, this design has evolved. Today most central banks have adopted inflation targets rather than targets for nominal money growth. Consequently, short-term monetary policy is now viewed in terms of the nominal interest rate instead of changes in nominal money growth.

The adoption of inflation targeting is one of the most significant developments in monetary policy over the past three decades. What started as a new monetary policy framework for New Zealand's central bank quickly spread to other advanced economies as its success at keeping inflation low and steady became apparent. By the 2010s, most central banks in advanced economies had *de facto* adopted inflation targeting or inflation targeting-like policies (Williams, 2014). The ECB, for example, adopted inflation targeting in one of its first meetings in 1998, with a medium-term goal of an inflation rate of just under 2% (ECB, 2022c). The Fed, on the other hand, did not officially adopt inflation targeting until 2012; however, an inflation goal of 2% has been an implicit, undeclared target since 1996 (Fed, 2022c).

The primary goal of inflation targeting policies is to provide a nominal anchor for the economy. Past regimes, such as the gold standard, pegged exchange rates and targeting monetary aggregates, all attempted to provide a nominal anchor but proved to be flawed when it came to providing flexibility in dealing with business cycles and crises (Williams, 2014). Inflation targeting, on the other hand, is designed to anchor inflation expectations, thus enabling central banks to achieve greater macroeconomic stability in the short run while also ensuring long-run price stability. Consequently, the emphasis of short-term monetary policy was viewed in terms of nominal interest rates instead of changes in nominal money growth. Hence, up to the US subprime crisis in 2008, the conventional wisdom concerning monetary policy was, therefore, that the interest rate is the main policy instrument and a sufficient statistic for the stance of monetary policy. Accordingly, the central bank should lean against bubbles to push actual inflation away from the inflation target (Cukierman, 2012).

2.2 The European Central Bank

The European Central Bank (ECB) came into existence on June 1. 1998. Six months later, on January 1. 1999, the responsibility for conducting monetary policy was transferred from 11 European Union (EU) national central banks, thus establishing the eurozone. The eurozone is an economic and monetary union within the EU consisting of member states that have adopted the euro as their currency. The creation of the supernational ECB and the eurozone came to be seen as a milestone in the complex European economic and political integration process (Mishkin, 2019). The euro was virtually introduced in 1999, with banknotes and coins issued three years later, in 2002.

The ECB's goals are similar to those of other central banks. Accordingly, the ECB has three objectives: maintain price stability, support economic policies of the eurozone countries and ensure an independent and open market economy in the EU. The primary objective, however, is the maintenance of price stability (Parliament and of the European Union, 2009). The ECB shall also support the EU's general economic policies to contribute to the Union's objectives as laid down in Article 3 of the Treaty on European Union (Parliament and of the European Union, 2007). Nevertheless, the ECB's primary objective is to maintain a medium-term inflation rate close to, but below, 2%. As a result, the Governing Council of the ECB decides the interests and controls the money supply to achieve this goal. On the other hand, direct macroeconomic stimulation is not in the ECB's mandate. Macroeconomic stimulation is, therefore, primarily implemented through fiscal policies (Mishkin, 2019). And, therefore, the responsibilities of the governments and treasuries of the eurozone member states.

For the ECB to achieve its primary objective of maintaining price stability, it aims to maintain a medium-term inflation rate of just under 2% (ECB, 2022c). The ECB's Governing Council pursues this price stability goal by controlling the money supply and deciding interest rates. The ECB sets three key policy interest rates: the deposit facility rate, which is the rate on the tender to banks, the refinancing rate, which is the rate on overnight deposits within the Eurosystem and the marginal lending facility rate, which is the rate on overnight credit to banks from the Eurosystem (ECB, 2022a). Of these rates, the deposit facility rate is the most critical policy tool since it provides the bulk of liquidity to the banking system and determines how the ECB's quantitative easing program affects its sovereign bond yields (Mishkin, 2019).

Since September 2008, the ECB has introduced more unconventional monetary policies. The GFC, followed by the European sovereign debt crisis, made it apparent that traditional monetary policies had become inefficient at combating falling money supply and economic recessions in the eurozone. Therefore, the ECB introduced several unconventional monetary policies to combat these adverse trends in the eurozone economies (Claeys, 2021).

2.3 The Federal Reserve System

The Federal reserve system (Fed) is one of the world's largest and most influential central banks. The Fed is a privately owned entity and is independent of the government. Accordingly, its owners consist of banks and financial institutions. Even so, the Fed is subject to parliamentary oversight by Congress, which periodically reviews its activities. Nevertheless, its decisions are made independently of all branches of government. Moreover, the Fed supervises and regulates the banks and financial institutions in the US, its owners, while functioning as their bunker. In this regard, being an owner of the Fed does not entail control over the Fed; instead, it is the other way around, with the Fed exercising influence over banks and other financial institutions (Mishkin, 2019). Accordingly, in addition to being the monetary authority in the US, the Fed also acts as a financial supervisor.

Moreover, the Fed has two primary objectives: to maintain price stability and full employment. (Bernanke, 2022). Even so, US monetary policy reoriented to focus even more on price stability after Volcker's disinflation policy in the 1970s (Cukierman, 2012). The inevitable conclusion the Fed drew from its reorientation was that monetary policy should focus mainly, or even solely, on price stability in the long run. A *Great Moderation* followed Volcker's disinflation in both output and inflation, a period which lasted from the end of the 1980s until the bursting of the subprime bubble in 2008, which caused the GFC.

Further, the Fed's tools, policy framework and communications have changed radically since the 1950s; these changes have primarily resulted from changes in broad economic developments rather than as a consequence of changes in economic theory (Bernanke, 2022). One of these developments is the long-term decline in nominal interest rates, which is partly because of lower inflation. Even so, the general level of nominal interest rates, even when monetary policy is not adding stimulus to the economy, is much lower than in the past after the Fed introduced inflation targeting.

As can be seen, the ECB and Fed share many similarities in their policies and objectives, but there are some important differences. First, to clarify, the ECB only has one primary objective, namely, to achieve price stability in the medium-term. The Fed, on the other hand, have a dual mandate. Consequently, the Fed's mandate is to achieve price stability and macroeconomic objectives such as economic growth and full employment. For this reason, the Fed often ignores temporary changes in prices since unemployment is considered a more important priority (Mishkin, 2019).

2.4 The Global Financial Crisis

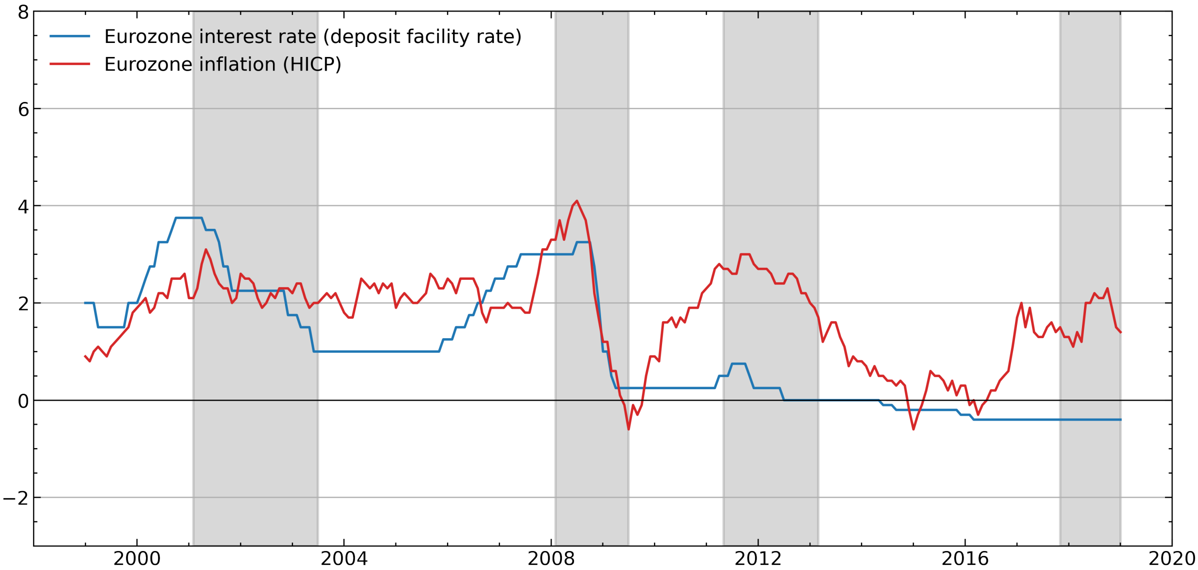
The Great Recession was the most significant downturn since the Great Depression in the 1930s. The crisis affected the entire world; however, advanced economies such as the US and the European Union were hit especially hard. The financial crisis of 2007-2008 and the following recession was the deepest and longest-running contraction since the Great Depression in the 1930s (Bilginsoy, 2014) until the current Covid-19 pandemic.

Global business cycles peaked in 2008, immediately before the GFC (Kose and Ohnsorge, 2019). The crisis, which originated in the US housing market, had been marked by unparalleled growth in the market for homes and mortgage-backed securities. The rapid growth eventually resulted in a housing bubble. Likewise, economic activity was growing rapidly, with a corresponding increase in inflation in both the euro area and the US. Accordingly, when the bubble burst, the following shock led to a stock market crash and later a large systematic banking crisis as the crisis spread from the mortgage originators to subprime lenders and, later, large American and European commercial and investment banks (Bilginsoy, 2014). As a result, the subsequent banking crisis brought on an economic recession with a decline in industrial production, trade, growing unemployment and eventually a sovereign debt crisis in the European Union (Mishkin, 2019).

Both the euro area and the US entered a recession following the GFC. In the eurozone, the recession lasted from March 2009 until July 2009 (OECD, 2022a). Similarly, the recession lasted from March 2009 until November 2009 in the US (NBER, 2022). Accordingly, inflation in the euro area declined from 4.10% at the onset of the GFC to -0.40% by July

2009% (OECD, 2022c). Similarly, in the US, inflation declined from 5.40% to -2.00% in July 2009 (OECD, 2022b). Although many economies rebounded quickly after the initial recession, inflation remained low throughout the 2010s for advanced economies globally, at about 2%, despite record low nominal interest rates (Kose and Ohnsorge, 2019). Correspondingly, nominal interest rates were reduced to stimulate the economy and to get inflation back to the target rate. As a result, the ECB reduced nominal short-term interest rates from 3.25 % to 0.50 % (ECB, 2022a). Likewise, the Fed reduced its nominal interest rates from 4.7 % to $\sim$ 0.20 % (Fed, 2022a).

The data for eurozone inflation and policy rates are presented in figure 2.1.

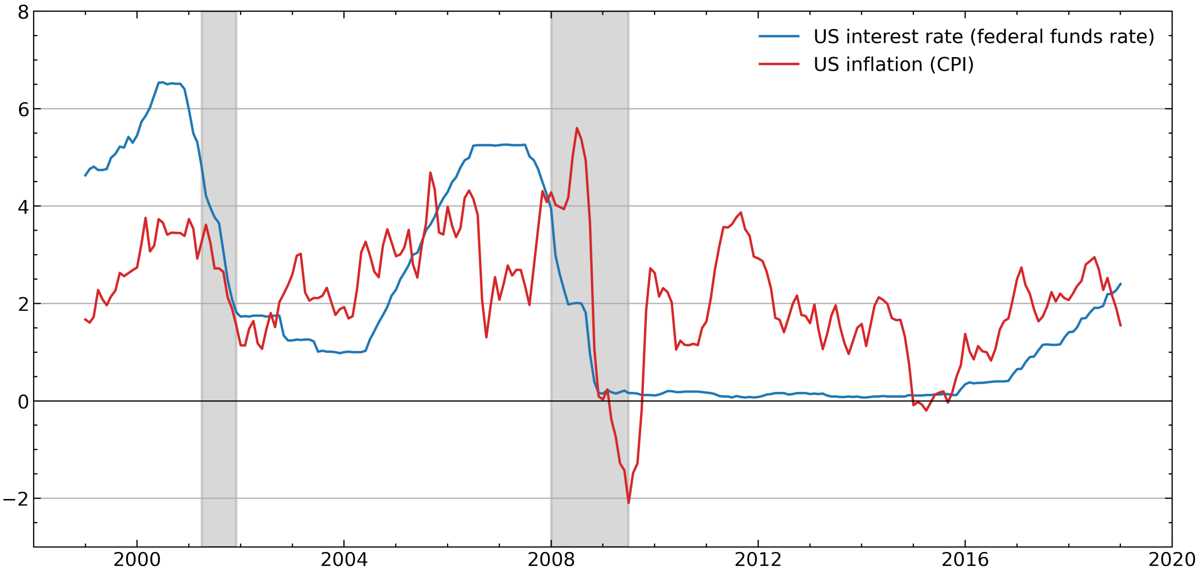


Source: ECB and OECD (2022).

Figure 2.1: United States inflation and interest rates, monthly percent change

Eurozone interest rates and inflation have been subdued since the GFC, as shown in figure 2.1. Euro area inflation hovered around the medium-term inflation target of 2% during most of the 1990s. Even the dot-com bubble and the subsequent recession from March 2001 until August 2003 (OECD, 2022a) did not cause inflation to diverge from the target since the ECB lowered the policy rate from the onset of the bursting of the dot-com bubble until the recession presided. Nonetheless, the lower short-term nominal interest rates did not cause inflation to rise above the target, even though it remained in place several years after the recession. While the policy rate remained at record low levels after the GFC, inflation rose above the inflation target during the European sovereign debt crisis, which started in 2010 (OECD, 2022a). Several European countries were forced to introduce austerity policies in the aftermath of the sovereign debt crisis, which depressed aggregate demand and output. Consequently, inflation remained under the inflation target from 2013 onward. For this reason, the ECB expanded its quantitative easing programme, which was initially introduced in 2008. In addition, the ECB introduced a negative interest policy (NIRP) in 2014 (de Haan et al., 2016).

The European sovereign debt crisis and austerity policies marked a stark difference from US policy during the same period. The data for US inflation and policy rates are reported in figure 2.2.



Source: FRED and NMBR (2022).

Figure 2.2: United States inflation and interest rates, monthly percent change

The GFC's effect on inflation and interest rates and the monetary policy response of the ECB and Fed have many similarities. In the same way as the ECB, the Fed lowered its policy rate when inflation was under the inflation target after the dot-com bubble and increased it when it was above the target before the GFC. After the GFC, however, inflation reached its lowest point in decades. It turned deflationary with its lowest point in July 2009, similarly to the inflation in the euro area. The Fed responded by lowering interest rates to record lows, yet the recovery in employment and output was at best subpar (Silvia and Iqbal, 2014). As a result, the Fed introduced quantitative easing to stimulate the economy since they could not lower nominal interest rates further without introducing NIRP (Mishkin, 2019).

This is where the similarities between the monetary response in the euro area and the US ends. The GFC was the US second recession in the 2000s before the downturn caused by the Covid-19 pandemic. On the other hand, the euro area had been through at least three (OECD, 2022a). Moreover, European governments were squeezed by austerity policies, which worsened the already severe fallout of the banking collapse in the eurozone (Mishkin, 2019). Further, the ECB introduced several unconventional monetary policies to stimulate the economy. While introducing experimental policies, the US mostly stuck to various forms of quantitative easing.

To summarise, the ECB and Fed used many of the same tools in response to the GFC and faced many of the same challenges. Even so, the Fed's response proved to be relatively more successful despite not using the same experimental tools as the ECB. Moreover, many European governments could not introduce fiscal stimulus because of the sovereign debt crisis, which followed the European banking collapse after the GFC in 2010. Nevertheless, both economies experienced record low inflation under the inflation target and policy rates on the lower zero bound or negative, which can suggests that the monetary policy intervention did not achieve its goals.

2.5 Macroeconomic Indicators

Table 2.1 presents the macroeconomic data for the eurozone countries.

GDP has been growing in the euro area over the past 20 years. Even so, the effects of the GFC can be seen in the period after 2009, with negative output growth, higher unemployment and more government debt. The current account balance, however, has been growing, partly explained by the lower real effective exchange rate. The growth in labour productivity after the GFC is also noteworthy.

The macroeconomic indicators for the US are reported in table 2.2. The US macroeconomic indicators are relatively better than those of the euro area from the same period. There have been no four-year periods with negative output growth. Unemployment, although high after the GFC, is still lower than in the euro area. Moreover, labour productivity growth has been relatively strong, although also slowing after the GFC.

While the US economy's growth rate and general performance might be considered subpar under other circumstances, it has outperformed the eurozone economy on almost all

Table 2.1: Macroeconomic indicators for the eurozone 11-19 (1999-2019)

	1999-2003	2004-2008	2009-2013	2014-2019
GDP, ***billion euro***				
GDP *(current prices, trillion euro)*	7,1	8,7	9,6	10,7
GDP growth *(volume growth (%))*	2.11	2.08	-0.34	1.95
Government deficit and debt				
Government deficit *(as % of GDP)*	-2.92	-1.98	-4.71	-1.63
Debt *(as % of GDP)*	69.21	68.78	87.48	89.68
Foreign trade, ***billion euro***				
Export of goods and services	619,22	846,96	988,25	1257,95
Import of goods and services	589,09	812,00	932,97	1143,33
Exchange rates and balance of payments				
Real effective exchange rate	92.24	104.40	99.22	92.63
Current account balance *(billion euro)*	-1617,67	-2021,26	3490,61	13330.10
Population and employment				
Population *(millions)*	321,7	329,7	335,6	340,0
Unemployment *(%)*	9.00	8.46	10.74	10.00
Labour productivity *(growth rate)*	0.79	0.84	0.29	0.67

Source: ECB (2022).

metrics from 1999 to 2019.

Table 2.2: Macroeconomic indicators for the United States

	1999-2003	2004-2008	2009-2013	2014-2019
GDP, ***billion dollars***				
GDP *(current prices, trillion dollars)*	10.4	13.5	15.5	18.7
GDP growth *(mean growth, quarter (%))*	0.70	0.42	0.42	0.57
Government deficit and debt				
Government deficit *(as million dollars)*	-2033.3	-29974.0	-93603.8	-51561.9
Debt *(as % of GDP)*	56.98	62.33	92.45	102.89
Foreign trade, ***billion dollars***				
Export of goods and services	1029.7	1488.5	2012.1	2359.1
Import of goods and services	1425.6	2216.0	2524.5	2894.8
Exchange rates and balance of payments				
Real effective exchange rate	121.28	107.98	98.92	110.89
Current account balance *(billion dollar)*	-1030.51	1817.42	-1012.37	-9877.99
Population and employment				
Population *(millions)*	285.1	298.86	312.3	324.4
Unemployment *(%)*	4.94	5.13	8.65	4.91
Labour productivity *(growth rate)*	3.69	1.41	1.88	0.89

Source: U.S. Bureau of Economic Analysis(2022) and Fed(2022).

3 Theory and Related Literature

Chapter 3 briefly revise the theoretical foundation of central banking by examining a New Keynesian monetary policy model before reviewing the literature on the relationship between interest rates and inflation.

3.1 Monetary Transmission

Most economists agree that changing interest rates through any of the central bank's tools can increase or reduce demand in the economy through the financial sector (Carlin and Soskice, 2015). Consequently, central banks indirectly make borrowing more or less attractive and thus reduce money created by private banks. Further, higher interest rates also make risky assets relatively less attractive compared to safer assets. As a result, the price of risky assets decreases with increases in interest rates. Conversely, lower interest rates make risky assets relatively more attractive, increasing their prices.

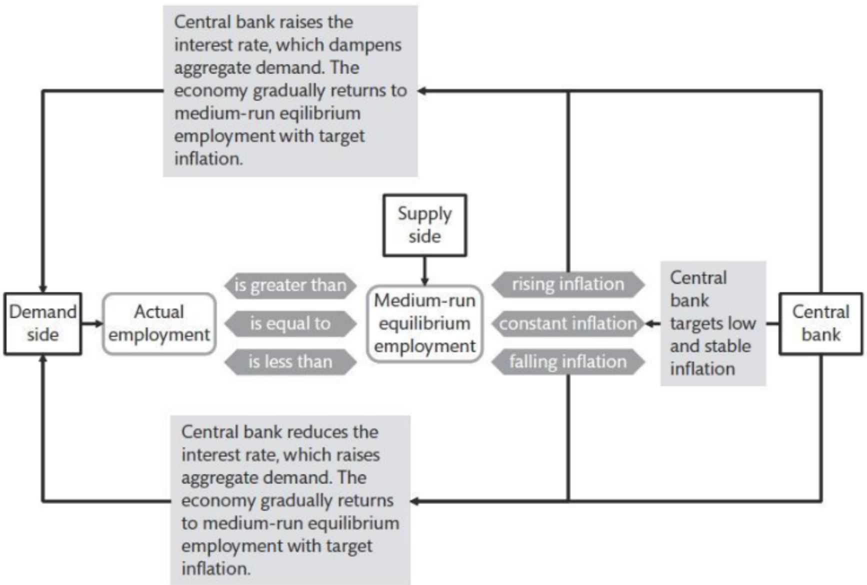


Figure 3.1: The monetary transmission mechanism
Source: Carlin and Soskice (2015).

Changes in interest rates also affect the real economy. For example, changes in bank rates make credit and loans more expensive, reducing the demand for goods and services and company growth opportunities. As a result, wages are less likely to rise, and prices are also less likely to rise. Moreover, lower asset prices can lead consumers to feel poorer, which again reduces their willingness to spend. Similarly, lower stock valuations can make companies less willing to invest and, thus, hire fewer people. As can be seen, adjustments to interest rate increases can, therefore, reduce inflation or vice versa.

Researchers often assume that expectations can be a source of inflation (De Fiore et al., 2022). Therefore, many central bankers believe that it might be possible for expectations about inflation to cause inflation without any policy changes to supply or demand directly. For instance, if firms expect prices to increase in the future, they might begin to increase prices today. Similarly, if employees expect inflation in the future, they may demand higher compensation for their work. As a result, prices and labour prices increase without changes to the monetary policy. Even so, research by Rudd (2021) found little empirical evidence for expectations-driven inflation.

3.2 3-Equation Model

The 3-equation model is a central model for explaining how central banks determine policy rates. The model is a so-called Keynesian model, which, accordingly, builds on Keynesian economics in a modernised form. Keynesian economics remains the central paradigm at the Fed and other central banks (Bernanke, 2022). As a result, the 3-equation model shows an inflation-targeting central bank's role in responding to shocks (Carlin and Soskice, 2015). Consequently, the model consists of both the demand and supply sides of the economy. Inflation-targeting central banks raise the interest rate in response to inflation if it is above the inflation target rate to dampen aggregate demand or lower interest rates if inflation falls below the target rate. Moreover, the central banks aim at maintaining output at equilibrium while preventing inflation from deviating too far from the inflation target.

Three elements are required to model a central bank's response to shocks. First, a clear definition of the central bank's goals. Second, how the central bank views the constraints it faces which arise from the behaviour of the private sector. Third, how the central bank implements monetary policy. Consequently, the central bank's responses can be summarised as a simple monetary policy rule. The rule is produced by adding the monetary rule (MR) curve to the investment-saving (IS) curve from the demand side of the economy. In addition, the Phillips curve (PC) from the supply side of the economy is combined with the *MR* curve and *IS*, curve as can be seen in figure 3.2. Central banks in advanced economies, such as the Fed and the ECB, aims to achieve an economy close to equilibrium output and inflation close to its inflation target of about 2% (Carlin and Soskice, 2015). If inflation deviates too much from the target, the central bank may be penalised by the government or suffer reputational damage. Thus, the central bank is interested in maintaining output at the medium-term equilibrium and keeping inflation under control. Even so, the economy is subject to shocks to demand and supply. Consequently, both inflation and output may be affected. Output may deviate from its medium-term equilibrium, and accordingly, inflation may deviate from the inflation target resulting in either too high or too low inflation. For example, an unforeseen boom in the economy can take the output above equilibrium and increase inflation as workers' position in the labour market strengthens (Carlin and Soskice, 2015). This aspect of wage behaviour is captured by the Phillips curve, as shown in figure 3.2. As a result, exogenous shocks can prevent the central bank from achieving its target, and it must, therefore, consider this information when assessing the prospects of economic stabilisation. Ultimately, the central bank must take unforeseen shocks and, accordingly, adjustments to these shocks, including the persistence of inflation, into account when designing its response to the initial shocks to the economy.

The central bank translates its objective into monetary policy by employing the monetary policy rules. The monetary policy rule is represented in the same diagram as the Phillips curves. Thus, demonstrating how the central bank will choose its preferred policy curve (Carlin and Soskice, 2015). Given the above, when central banks implement their preferred policy response, it diagnoses the shock and its forecasted effects on inflation and output. Then, the forecast and its preferences for stabilisation are used to estimate the output gap it is trying to achieve. As a result, the MR curve illustrates the central bank's best response to the shock. The choice is then implemented using the relationship between the interest rate and output from the *IS* curve.

3.2.1 Monetary Policy Response to a Permanent Demand Shock

Several types of exogenous shocks can cause a central bank intervention—for example, a persistent boom in consumption. Figure 3.2 shows how central banks analyse demand shocks to the economy. The consumption boom has an initial positive impact on output and employment. As a result, the *IS* curve shifts to the right from A to B in the *IS* diagram. By following the diagram from top to bottom, the effects of changes to output on the labour market and inflation become clear. The labour market impact of the consumption boom is reflected in a disturbance in the initial constant inflation equilibrium. Accordingly, unemployment fall and the first wage-setting round following the shock causes wages and prices to rise from the inflation target of 2%. As shown in figure 3.2, the shock has opened up a gap of 1% between the prevailing real wage and the high real wage, which is consistent with the tighter labour market following the consumption boom.

Consequently, workers receive a 2% wage rise to compensate them for the erosion in real wages due to the last period's inflation in addition to a 1% increase to bring their real wage up to the level indicated by the wage-setting curve. As a result, wages increase by 3%. Correspondingly, firms raise their prices by 3% to protect their profit margins. Hence, inflation rises to 3%.

The increase in inflation from the initial 2% to the new 3% is shown by the movement along the Phillips curve from A to B. From this point, the higher inflation of 3% becomes embedded in the expectations of wage setters. The central bank must, therefore, anticipate expected inflation of 3% for the next wage-setting round. Consequently, the relevant Phillips curve facing the central bank for its stabilisation decision is the Phillips curve labelled $PC(\pi_t^E = 3\%)$ in figure 3.2. Given this forecast of inflationary behaviour, the central bank chooses its best response to the situation (new point on the PC). If the central bank's preference is for a balanced response, then point C is preferable since it will get inflation back towards the inflation target without imposing a harsh recession. Accordingly, this is a point on the *MR*, which represents the optimal output-inflation pair for any Phillips curve it faces (Carlin and Soskice, 2015).

If the central bank takes the view that the consumption boom would persist in the absence of any response on its part, then it would need to choose the higher interest rate shown at point C on the *IS* curve to dampen aggregate demand sufficiently to move the economy onto the path which will lead to the inflation target. Once the economy reaches point C on the *MR* curve, inflation will come down as forecasted. Accordingly, lower inflation reduces inflation expectations. Thus, the Phillips curve shifts downwards to point $PC(\pi_t^E = 2.5\%)$. Consequently, the central bank will choose point D as its best response to the new inflation

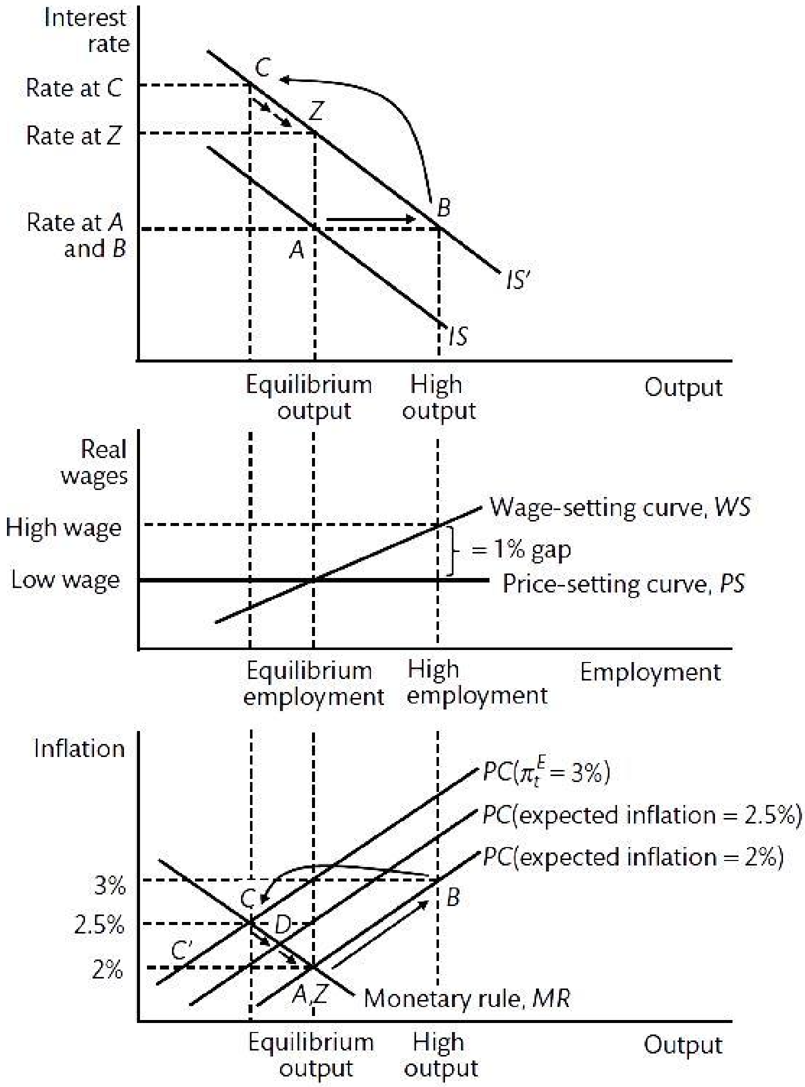


Figure 3.2: Adjustment to a permanent demand shock
Source: Carlin and Soskice (2015).

environment it faces and will adjust the policy rate down from its peak at point C in the IS curve. For subsequent periods, the central bank will continue to guide the economy along the MR curve by reducing interest rates as inflation returns to the inflation target rate. The adjustment process is finished once the economy is back at equilibrium output and targets inflation at point Z on the IS and PC curves. There will, however, be a higher interest rate at the new equilibrium since a reduced level of investment is needed to offset the persistent consumption boom.

3.2.2 Monetary Policy Response to an Inflation Shock

The 3-equation model can also explain the central bank's response to shocks. Initially, the economy is at the central bank's bliss point. Output is at equilibrium, and inflation is at the inflation target.

If the economy is subject to an inflation shock, which refers to an exogenous shift in the Phillips curve, then the central bank follows two main steps to stabilise the economy after the shock. The dynamic adjustment of the economy to the shock is summarised in figure 3.3, starting from the top and following the arrows clockwise.

First, the central bank must choose the position on the Philips curve to minimise the loss function since the inflation shock shifts the Phillips curve upwards. The shift can be seen in figure 3.4. The new position will be where the *MR* curve intersects the new Phillips curve. Moreover, since inflation is above the inflation target, the central bank will have to reduce output below equilibrium to squeeze inflation out of the system.

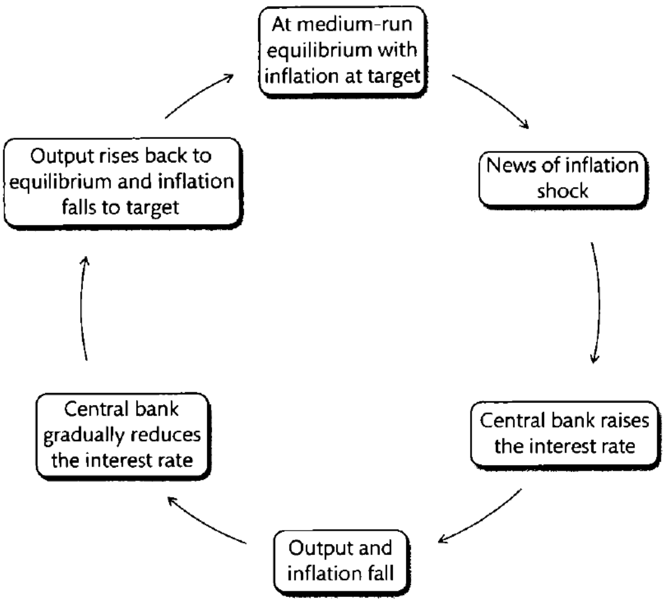


Figure 3.3: Dynamic adjustment to an inflation shock
Source: Carlin and Soskice (2015).

The second step is to use the *IS* curve to find the required increase in real interest rates to get the economy back onto the *MR* curve. Since the higher interest rate dampens output, inflation starts to fall. Finally, the central bank can then gradually reduce the interest rate until output rises back to equilibrium and inflation returns to the inflation target.

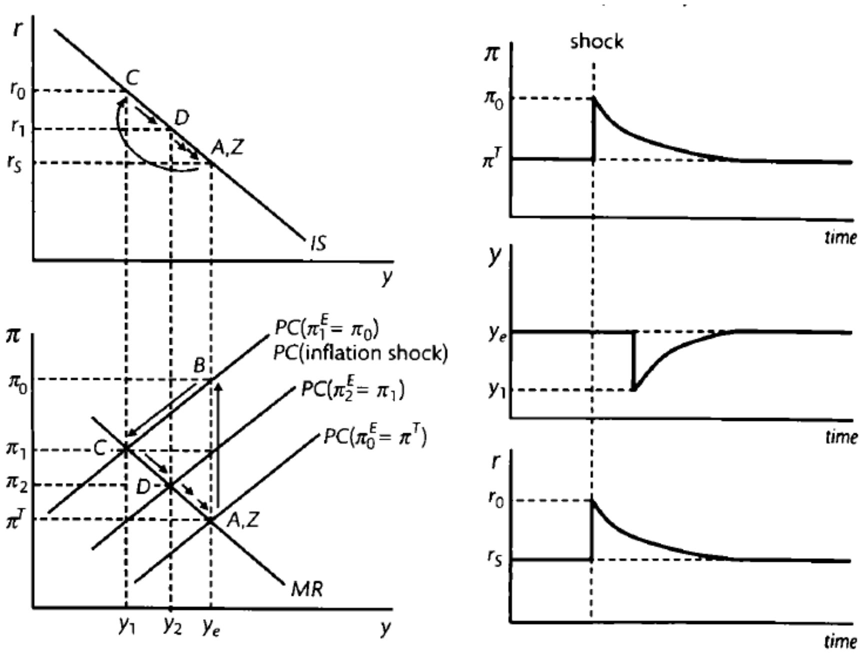


Figure 3.4: Inflation shock and the monetary rule
Source: Carlin and Soskice (2015).

To illustrate further, the impulse response function three of key macroeconomic variables, inflation π, output, Y, and interest rates, r, are shown to the right of the 3-equation model in figure 3.4. The impulse response functions indicate that inflation rises from the inflation target π^T to a higher inflation rate π_0 after the inflation shock before being slowly brought back to the target. Similarly, the interest rate mirrors the impulse response function of inflation as nominal interest rates are increased from r_s to r_0 to bring inflation back to the inflation target π^T. Conversely, output falls from one period after the shock since an increase in interest rates takes one period to affect output (Carlin and Soskice, 2015), which subsequently reduces output from equilibrium Y_e to a new, lower point, Y_1, before output slowly recovers as interest rates are reduced when inflation gets squeezed out of the economy. Finally, the adjustment to the inflation shock ends when the economy is back to point Z on the IS and MR curves, with output at Y_e and interest rates at r_s.

3.3 The Fisher Effect

The relationship between inflation, nominal interest rates and real interest rates is commonly referred to as the Fisher effect. According to the Fisher effect, there should be a one-for-one change in the nominal interest rate in response to a change in the inflation rate, and vice versa. It follows from the hypothesis that in a country where inflation is expected to be steady, the real interest rate is independent of monetary variables, in particular, the nominal interest rate (Hashimzade et al., 2017).

The relationship between nominal interest rates and inflation is, therefore, given by the Fisher equation:

$$i + r = \pi^E. \tag{3.1}$$

Where i is the nominal interest rate, r is the real interest rate and π^E is the expected inflation. Accordingly, the long-run Fisherian theory of interest states that a permanent shock to inflation will cause an equal change in the nominal interest rate so that the real interest rate is not affected by monetary shocks in the long run (Fisher, 1930).

3.3.1 Policy Implications for Monetary Policy

Problems could arise for monetary authorities if the real interest rates needed to stabilise demand cannot be achieved because the nominal interest rate cannot be decreased further. Central banks adjust the nominal interest rate, i when responding to economic shocks. As a result, the real interest rate, r, is also affected, which in turn affects aggregate demand through the *IS* relation. Thus, the central bank must take expected inflation, π^E, into account, as shown by the Fisher equation 3.1. Accordingly, the central bank can be modelled as setting the real interest rate when applying the Fisher relationship. The central bank responds to falling inflation by reducing the interest rates to stimulate aggregate demand, as seen in figure 3.1. Nevertheless, many economists argue that there is a limit to the extent to which the central bank can reduce nominal interest rates. Figure 3.5 shows the lowest nominal interest rate the central bank can set according to this school of thought (Carlin and Soskice, 2015).

From the Fisher equation (3.1), we know that the real interest rate is given by:

$$r = i - \pi^E. \tag{3.2}$$

for example, if the central bank's chosen output gap on the *MR* curve is 0.50% and expected inflation is 1%, then a nominal interest rate of -0.50% would be required. With a zero lower bound on the nominal interest rate, the minimum real interest rate that can be achieved is set by:

$$min\ r \geq -\pi^E. \tag{3.3}$$

This suggests that the minimum real interest rate achievable is 1% if the expected inflation is 1%. As a result, the interest rate is too high to get the economy onto the *MR* and back to equilibrium, as shown in figure 3.5, where the stabilising real interest rate is below the minimum feasible rate of 1%. Consequently, it will be impossible to achieve the equilibrium level of output by using conventional monetary policy alone, given the depressed state of aggregate demand as depicted by the *IS* curve if inflation has fallen to -1%. As a result, the economy is stuck at point *A* on the *IS* curve.

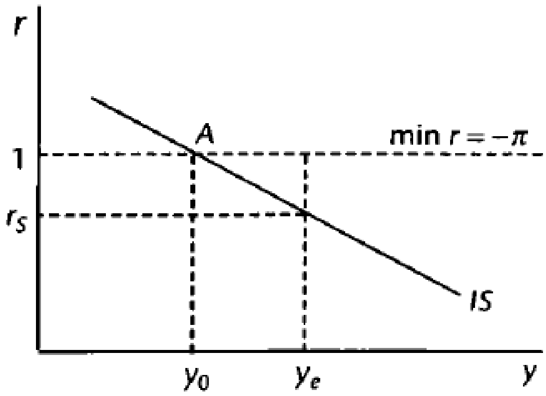


Figure 3.5: The zero lower bound on nominal interest rate
Source: Carlin and Soskice (2015).

There is no technical reason why nominal interest rates cannot be negative. Even so, it might have major policy implications, especially in the presence of currency, since nothing stops people from holding their savings in cash, which has a nominal interest rate of zero. High-denomination bills accordingly reduce the cost associated with carrying large sums of money in cash. Currency, therefore, ultimately acts as a limiting factor in setting negative nominal interest rates.

3.4 Literature Review

Naturally, the relationship between inflation and interest rates is closely related to the effectiveness of monetary policies. As such, the need to identify the relationship is of key essence. Seeing as it is a complex issue, the causality between inflation and interest rates has been debated in the literature. There are two leading schools of thought. The Fisher Hypothesis contends that a rise in prices leads to an increase in interest rates by decreasing the real money balance. On the contrary, some economists assert that changes in interest rates lead to changes in inflation. This is referred to as the so-called interest rate-led hypothesis (Karahan and Yılgör, 2017).

Fisher (1930) hypothesized that nominal interest rates are made up of two primary components: the expected inflation rate and real interest rate. Assuming rational expectations, the expected rate of inflation next period will equal inflation in this period. Fisher argued that a change in the nominal interest rate would not affect the real interest rate, and so he argued for a one-to-one relationship between nominal interest rates and inflation. There is a huge literature investigating the soundness of this hypothesis.

Fama (1975) examines the relationship between nominal interest rates and inflation rate, using monthly data on 1-month Treasury Bills as the nominal interest rate and the 1-month changes in the Consumer Price Index as the inflation rate. His analysis covers the period from January 1953 until July 1971. He tests the hypothesis of a constant real rate by regressing realised inflation rates on the market interest rate and past inflation rates. His results produced two conclusions. He shows that there is a definite relationship between nominal interest rates and inflation rates. There is a substantial variation in nominal interest rates during the 1953-1971 period, and this seems to be caused entirely by variations in expected inflation rates. As such, the real returns on Treasure Bills seem to be constant during this period, thus supporting the Fisher hypothesis. Finally, the market seemed to be efficient in the sense that past inflation rates provided further information on realised inflation rates, above and beyond the information provided by the nominal interest rates.

Nelson and Schwert (1977) argued that Fama's (1975) model might not be strong enough to assess the joint hypothesis of efficiency and constancy. They argued that it would be impossible to assess market efficiency without a model for the behaviour of the ex ante real interest rate. Using the same data as Fama (1975), Nelson and Schwert (1977) employed both autocorrelative and regression models. They found that past inflation rates contain very little information about future inflation rates. They are able to use the information in the inflation rates more efficiently by linking the variances and covariances of observed variables to those of the unobserved components of those variables (i.e., by modelling the uncertainty in the inflation rates more explicitly). By doing this, they reject Fama's joint hypothesis. They conclude that the expectations of inflation accounted for most of the variation in short-term interest rates during the study period and that these expectations embodied significant information beyond that contained in past inflation rates alone.

Mishkin (1992) reexamined the Fisher effect by studying the relationship between inflation and interest rates and studied the Fisher effect's lack of robustness on postwar US data. The study was conducted in the aftermath of Nelson, and Plosser's (1982) finds that many macroeconomic time series, such as inflation and interest rates, may be characterised as having stochastic trends, and the potential for misleading inference from Granger and Newbolds (1974) and Phillips's (1988) work on the spurious regression phenomenon. The author used monthly data on inflation and one- to twelve-month US Treasury bills from February 1964 to December 1986. Mishkin first analysed the data with regressions, ARIMA models, the Augmented Dickey-Fuller test and Monte Carlo simulations. Then, the author tested for long-run and short-run Fisher effects using Engle-Granger cointegration tests. The results indicated that the forecasting relationship between inflation and short-term interest rates might be spurious for the postwar period. As a result, the author found little evidence for a short-run Fisher effect. Even so, the cointegration tests for a common trend found evidence for a long-run Fisher effect.

Crowder and Hoffman (1996) examined the long-run dynamic relationships between the short-term nominal interest rate and inflation. They used quarterly data for the three-month T-bill rate as the interest rate and the implicit price deflator for total consumption expenditures for inflation. Annualized log changes in the price served as a proxy for expected inflation. Their sample ran from 1952:1 to 1991:4. The authors tested for stationarity by employing a multivariate unit root analysis. They found that the three-month US T-bill rate and US inflation rates are cointegrated and, therefore, share a common stochastic trend. Furthermore, they found that the long-run Granger-cause ordering is univariate from the inflation rate to the interest rate, implying that the inflation rate contains information about the future path of the nominal interest rate.

Booth and Ciner (2001) studied the long-run bivariate relationship between short-term interest rates and inflation for nine European countries and the US to provide an international perspective on the dynamic relationship between the short-term nominal interest rate and inflation. The authors used monthly 1-month nominal Eurocurrency interest rates and monthly inflation rates for the ten countries as interest rates and inflation, respectively. The Eurocurrency rates were end-of-month bid rates quoted at approximately 10:00 Swiss time. Eurocurrency rates were chosen because they were thought to be less affected by capital controls and legal regulations than domestic rates. Inflation rates were proxied by monthly changes in the CPI indices. All rates were annualized percentages. The sample period was from January 1978 to February 1997. Hence, nine European economies prior to the introduction of the euro. First, the authors employed the Augmented Dickey-Fuller test to test for stationarity. Then they used Johansen's cointegration test to test for cointegration and the long-run implication of the Fisher hypothesis to characterize the changes in the level of nominal short-term Eurocurrency interest rates. The authors found that each country's Eurocurrency rate was cointegrated with its inflation rate, with one European exemption, France. In addition, for the majority of the countries, the long-run one-to-one relationship between changes in the expected inflation rate and the Eurocurrency rate was not rejected. Furthermore, the authors found more evidence supporting the Fisher hypothesis in international data than in US data. Finally, the authors identified that the common stochastic trend, the variables shared, and the Eurocurrency rate was mainly responsible for the behaviour of the common trend. This suggests that the information contained in the nominal interest rate concerning the future path of the inflation rate was consistent with the assumption of rational agents in a well-functioning market's ability to incorporate the predictable portion of the inflation rate into nominal rates when setting prices.

Beyer, Haug and Dewald 2009 examined the effects of structural breaks in cointegration relations and their effects on the cointegration test results (spurious unit root) in the framework of the long-run Fisher effect. They then applied new break tests and tested for nonlinearity in the cointegration relation on data for 15 OECD countries. Inflation rates were calculated from the first differences of the natural logarithm of CPI, and 3-month treasury bills rates were used as interest rates where data was available. For some countries, money market rates or deposit rates were used as the variable for interest rates, depending on availability. The data series had a quarterly frequency. The authors employed the test for structural change proposed by Carrion-i-Sylvestre and Sansó, which is based on the Kwiatkowski–Phillips–Schmidt–Shin (1992) test. They also used generalized least squares methods to locally demean or demean and detrend the series. Then, the authors applied the Dickey-Fuller unit root test to test the stationary status of the time series. Lag augmentations were chosen based on the modified Akaike criterion. Then, the authors tested for cointegration by using Johansen's cointegration test. Cointegration was tested with a model without deterministic time trends, which is consistent with the Fisher hypothesis. Their results supported cointegration after accounting for breaks which supported the long-run linear Fisher relationship. Moreover, the authors rejected fewer variables as non-stationary after employing improved stationarity tests.

Karahan and Yilör (2017) studied the causal nexus of inflation and interest rates in the Republic of Türkiye and its role in the application of monetary policy. They used monthly data from 2002 to 2016 (and thus include the Financial Crisis) with the deposit rate as the variable for nominal interest rates and the consumer price index for inflation. First, the authors employed the Augmented Dickey-Fuller and Phillips-Perron unit root tests to determine the variable's stationary status. Then, they performed the Engle-Granger and Johansen's cointegration tests to determine if there was a long-term relationship between inflation and interest rates before performing a Granger causality test. Their results found that the inflation and nominal interest series had unit roots for both tests at the level, both with and without a deterministic trend. Furthermore, all series were non-stationary after taking the first difference. They then found a clear long-run relationship between the variables by performing the Engle-Granger and Johansen's cointegration tests. Finally, the authors found a unidirectional Granger causality based on the vector autoregression model running from inflation to interest rates.

Lukmanova and Rabitsch (2018) augmented a standard monetary VAR on output growth, inflation and nominal interest rate with the central bank's inflation target, which they estimated from a New Keynesian DSGE model. The empirical framework of the study was to examine the transmission mechanisms of monetary policy. The authors used quarterly data for the US from 1947Q3 through 2017Q3. The 3-variable VAR model consisted of the growth rate of real GDP and inflation expressed as the rate of change of the consumer price index and the 3-month Treasury bill rate. The authors also estimated the VAR from 1973Q3-2017Q3 to start from the Volcker period of the Fed's chairmanship and 1973Q3-2008Q2 to exclude the period of zero interest rates and 1947Q3-2008Q2 for the same reason. Finally, the VAR was estimated with Bayesian methods using an independent Normal-Wishart prior. Their results indicated that inflation target shocks gave simultaneous increases in inflation and nominal interest rate in the short run at no output expense. Thus, providing empirical evidence in favour of the existence of a Fisher-like effect. Further, their model indicated that there had been a reduction in the persistence of inflation target shocks, which likely contributed to a decrease in inflation persistence.

Uribe (2022) examined how the normalization of nominal interest rates affected interest rates and inflation in the short run and, consequently, how monetary authorities can reflate their economies to levels closer to their inflation targets. Using Bayesian techniques, the author employed a latent-variable empirical model driven by transitory and permanent monetary and real shocks. Uribe used quarterly US data spanning the period 1954:Q3 to 2018Q2. The model consisted of three variables. The Federal Funds Effective rate was used as the interest rate, the logarithm of seasonally adjusted GDP, and the growth rate of the implicit GDP deflator expressed per cent per year. Uribe's empirical evidence drawn from the empirical and optimization model indicated that a gradual and permanent increase in the nominal interest rate would lead to a quick and monotonic adjustment of inflation to a permanently higher level, low real interest rates and no output loss. As a result, the paper's findings are consistent with the neo-Fisherian prediction that a gradual return of the nominal interest rate from the vicinity of zero to historically normal levels could achieve a swift reflation of the economy without reducing the activity level in the economy.

Economists agree that there is a relationship between inflation and interest rates. Even so, there is an ongoing debate about the nature of these relationships, especially after decades of low inflation and nominal interest rates close to the zero lower bound or even negative. The relationship between inflation, the nominal interest rate and other variables varies from study to study. Moreover, the results of the various evaluations differ depending on the methodology, variables, transformations and data periods. Therefore, this thesis employs unit root tests, cointegration tests and Granger causality to test for relationships between inflation and nominal interest rates. Additionally, this thesis illustrates how these relationships play out in a stylized VAR analysis. However, as the data series for the eurozone is relatively short, there will be a greater emphasis on identifying structural breaks and testing for cointegration and Granger causality in the series themselves than on an empirical examination of the consequences of said breaks.

4 Methodology

4.1 Data

Monthly time series data were collected for the eurozone and US. The initial data sets were sliced from their original length into new series from 1999:M1 through 2019:M1. The data set consisted of 10 variables—five for each economy. Thus, the initial data sets covered two monetary economic unions over 20 years and consisted of 2410 observations. The comprehensive data set was gathered to explore the relationship between inflation and the nominal interest rate between 1999 and 2019, and to illustrate how these relationships play out in a stylised Vector autoregressive (VAR) model analysis.

The Federal Funds rate (Fed funds) is the interest rate at which financial institutions trade balances held at the Federal Reserve Bank with each other overnight. For example, an institution with a surplus balance in its reserve account lends to other banks needing larger balances. Hence, a bank with excess liquidity will lend to another institution that needs to raise its liquidity quickly (Fed, 2007). The two banks determine the resulting rate the borrowing institution pays the lender. The weighted average for all such negotiations is called the effective federal funds rate (Fed, 2022b). As a result, the effective federal funds rate is essentially determined by the market; however, it is influenced by the Federal Reserve through open market operations to reach the federal funds target. The time series for Fed funds was downloaded from the Federal Reserve Bank of St. Louis (Fed, 2022a) as a monthly, unadjusted time series measured in percentages.

The ECB's deposit facility rate is one of three interest rates the ECB sets as part of its monetary policy. The rate defines the interest banks receive for overnight deposits with the central bank. As a result, the deposit facility rate provides the bulk of liquidity to the banking system and can, therefore, be considered the most important ECB nominal interest rate (Mishkin, 2019). The time series for the ECB facility rate was downloaded from the ECB's Statistical Data Warehouse, and the data is reported in percentages. The data is not seasonally adjusted.

There are several different measures for inflation in the US. For example, some indices measure the changes in prices for urban consumers, while others de-emphasise food and energy prices (*core inflation*). This analysis will be performed on the US Consumer Price Index *(CPI, total all items for the US)*, which measures the average price change for a market basket of consumer goods and services paid by all US consumers over time. The time series for US inflation was sourced from the OECD through FRED and is reported as a year-on-year growth rate measured in percentages. The series is not seasonally adjusted (OECD, 2022c).

The Harmonised Index of Consumer Prices (HICP) measures consumer price changes in the euro area. The HICP referred to as harmonised because all countries in the European Union follow the same methodology, which ensures that the consumer price data can be directly compared between member states and, therefore, combined into an index for the entire eurozone. The time series for the HICP was sourced from the OECD and downloaded through FRED. The series is reported as a year-on-year growth rate measured in percentages (OECD, 2022b). The data is not seasonally adjusted.

Gross domestic product (GDP) is one of the main measures of economic activity. A country's GDP is defined as the total market value of all goods and services produced within a country in a given period of time (Hashimzade et al., 2017). The normalised GDP time series data for the eurozone (OECD, 2022e) and the US (OECD, 2022f) is sourced from the OECD through FRED. The data is an index and has a monthly frequency. The data is seasonally adjusted.

The unemployment rate measures the total number of unemployed people as a percentage of the corresponding total labour force (Hashimzade et al., 2017). The time series data for unemployment in the euro area (OECD, 2022d) and US (OECD, 2022i) are sourced from the OECD through FRED. The data for the eurozone is, similarly to the data on inflation, harmonised. The data is measured in percentages and has a monthly frequency. The data is seasonally adjusted.

M3 is a broad definition of money. M3 comprises M1 and M2 as well as large-time deposits, institutional money market funds, short-term repurchase agreements, and larger liquid assets. M1 is a narrow definition of money and consists of notes and coins in circulation, private sector current accounts, and deposit accounts transferable by cheque. M2 is a possible definition of broad money. It includes notes and coins in circulation, non-interest-bearing bank deposits, building society deposits, and national savings accounts. In the

US, M2 includes, in addition to M1, money market deposit accounts, balances in money market mutual funds, and savings and time deposits under $ 100,000 (Hashimzade et al., 2017). In the eurozone, M3 is the sum of M2, repurchase agreements, money market fund shares or units, and debt securities with a maturity of up to two years (ECB, 2022b). Accordingly, M3is used because it serves as the institutional definition of money in the eurozone and plays a prominent role in the definition of monetary policy (Benchimol and Fourcans, 2016). The time series data for M3 for the euro area (OECD, 2022g) and the US (OECD, 2022h) is sourced from the OECD through FRED. The data is in national currencies, euro and dollar, respectively. The data has a monthly frequency and is seasonally adjusted.

The series for eurozone inflation and interest rates and US inflation contained negative and zero values. Therefore, the series could not be transformed since taking the logarithm of the series would result in the loss of important information—all the other series, except for US interest rates, were log transformed to log form. Moreover, euro area and US inflation and interest rates were differenced once to check their stationary status and order of integration, and to ensure they were non-stationary before using the series for cointegration analyses. Finally, both data sets were differenced twice before being used in the VAR model since euro area unemployment and US unemployment were non-stationary after taking the first difference.

FRED's time series were sourced directly to Python through an API (Application Programming Interface) with Pandas-DataReader 0.9.0. The data from other sources were downloaded in csv. format. The data is analysed using Python (Jupyter Lab 3.2.2) by detecting structural breaks with the Fisher-Jenks algorithm, performing unit root tests, cointegration tests and finally, a VAR model. The main Python libraries used in this thesis are ARCH models 5.3.1, Jenkspy 0.2.0, Matplotlib 3.5.1, Pandas 1.4.3, SciPy 1.7.3 and Statsmodels 0.13.2. Additionally, RStudio 1.4.1717 was used for the Chow tests and other ad hoc statistical tests.

4.2 Structural Break Identification

Break points in time series data can often be seen when the series are visualized. Even so, the analysis of structural breaks in this thesis will apply the Fisher-Jenks Algorithm

(Fisher, 1958; Jenks & Caspall, 1971; Jenks, 1977) alongside visual identification, as a more robust method for identifying potential break points in the data sets.

There are many different techniques for identifying breakpoints in time series data. These techniques can be classified into two distinct categories; detection, which finds one or more breakpoints in the data, and tests, which checks whether there is a structural break in the time series or not for a given point in the data. For this analysis, the Fisher-Jenks algorithm will be used to detect breakpoints in the time series for inflation and interest rates. Then, a Chow test (1960) will be applied to test whether there is a break point at the detected point in the data and, consequently, whether there is a structural break in the relationship between the time series data at the specific break point.

4.2.1 Fisher-Jenks Algorithm

The Fisher-Jenks algorithm is a powerful tool for classifying breaks in a data sample. To illustrate, the Fisher-Jenks algorithm has three phases: the first phase computes the diameter matrix, which stores the distance between each observation. The diameter matrix is triangluar since the first distance is symmetrical to the second distance. Second, the error matrix that stores the minimum variance of observations when classified is populated. Finally, optimal data partitions are located by minimising intra-class variance and maximising inter-class variance (Hartigan, 1975). Accordingly, the Fisher-Jenks algorithm detects and then produces suggestions for possible breaks in the processes. Moreover, the amount of detections and the estimation period can be specified as a part of the algorithms code. Given the above, the Fisher-Jenks algorithm accurately detects possible breaks and, accordingly, suggests as many break points as the programmer desires for the estimation period.

4.2.2 Chow Test

The Chow test is a test for the equality of estimated coefficients in two linear regressions on two different data samples. In time series data, the test is used to check the stability of coefficients and, as a result, to assess whether there is a structural break in the model (Chow, 1960). Potential break points are assumed to be exogenous, typically for macroeconomic data, due to regime changes in policy. Consequently, the break points must be specified prior to the event. Admittedly, the Chow test results are not valid if the timing of the break depends on the data or if the break is endogenous.

The null hypothesis of the Chow test is that the coefficients in the two regressions are the equal. Conversely, the alternative hypothesis is that the coefficient on at least one explanatory variable is unequal (Wooldridge, 2020). For example, if one of two time series moves away from the trend or changes abruptly because of policy changes, shocks or other exogenous events while the other series remains unchanged. On the contrary, if two series are similarly affected by an exogenous shock or in the absence of a significant exogenous change, then their coefficients will remain the equal. Ultimately, one of the time series coefficients has to deviate from the other due to an exogenous shock on a specific break point for it to be registered as a structural break in the relationship between the data samples.

The test statistic involves the residual sum of squares from three different regressions on the two different time series: two separate regressions on two samples divided by the break point, and one regression on the pooled sample, as can be seen in equation (4.1). Moreover, the test statistic from the Chow test can be considered a straightforward application of the standard F-test formula, which therefore, can be tested against the critical values from the F - distribution table (Brooks, 2014). Finally, if the value of the test statistic is greater than the critical value from the F-distribution table, which is an $F(k, T-2k)$, then the null hypothesis that the parameters are stable over time can be rejected.

The Chow test statistic is given by:

$$\frac{(RSS - (RSS_1 + RSS_2)}{RSS_1 + RSS_2} \times \frac{T-2k}{k} \tag{4.1}$$

where RSS is the residual sum of squares of the pooled sample, RSS_1 is the residual sum of squares of the sub-sample before the break point while RSS_2 is the residual sum of squares of the sub-sample after the break point. T is the number of observations and $2k$ is the number of regressors in the *unrestricted* regression, where k is the number of regressors in each *unrestricted* regression (Brooks, 2014).

4.3 Unit Root Tests

It is important to distinguish between stationarity $I(0)$ and non-stationarity $I(1)$ in time series data. For example, when performing cointegration analyses with different time series, or when using multivariate time series models such as the variable autoregressive model. It is especially important to distinguish between stationary and non-stationary series when methods require one or the other. In fact, the stationarity or otherwise of a time series can strongly influence its behaviour and properties. A time series can be considered strictly stationary if the probability distribution of its values does not change over time (Brooks, 2014). Since strict stationarity implies that all higher-order moments are constant, including mean and variance, strictly stationary time series are rarely found in practice. However, since the conditions and assumptions of weakly stationary time series are sufficient for them to be regarded as stationary, they will be considered adequate for this thesis' analyses. A process is considered weakly stationary if the mean, variance and autocovariances are constant over time for each given lag (Brooks, 2014). Non-stationary time series, however, have properties that change over time. As a result, the mean and variance for these processes can change over time. Trends, cycles and random walks or a combination of all three, for example, are typical non-stationary behaviour. Macroeconomic variables such as GDP, or financial data such as stock market indices, for instance, are good examples of non-stationary time series.

Because non-stationary processes change over time, using models with non-stationary variables can lead to false interpretations of the results. Ordinary least squares estimations, for instance, will produce misleading results with non-stationary variables, a phenomenon Granger and Newbold (1974) referred to as spurious regression results. Ultimately, spurious regression results would produce results without any meaningful economic relationship between the variables, even though the test statistics would indicate otherwise. For instance, if standard regression techniques are applied to non-stationary data, the regression would appear good under standard measures, but would in reality be valueless (Brooks, 2014). Ultimately, it is essential to distinguish between stationary and non-stationary time series and to apply the correct variables when employing different methods and models to avoid misleading results.

Stationary variables are integrated of order 0, denoted $y_t \sim I(0)$. Non-stationary variables, on the other hand, are integrated of order d, where $d \geq 1 : y_t \sim I(d)$.

Some methods require stationary variables. Consequently, non-stationary variables can often be transformed by taking the first difference one or more times until the processes becomes stationary. For example, if a time series contains a unit root (i.e., being integrated by order one), then taking the difference of the series will make the time series variable stationary. To illustrate, a unit root process in time series data can be described as a non-stationary process whose first difference is stationary, also referred to as an integration of order one or an $I(0)$-process. Taking the first difference can also be used to find the order of integration of different variables, which is essential for some methods and models. For example, time series data of the same integration order can be used to test for cointegration. As can be seen, taking the difference of non-stationary processes can first transform the data into stationary series and secondly identify their order of integration. For this reason, taking the difference will be used to make non-stationary processes stationary for the models and tests requiring stationary variables and to check the variable's order of integration.

4.3.1 Augmented Dickey-Fuller Test

The ADF test (ADF) is an extension of the Dickey-Fuller test. Accordingly, the original Dickey-Fuller test tested the null hypothesis that a stochastic process is a random walk with the possibility of deterministic drift. The alternative hypothesis is that the process is stationary, assuming that the model's random fluctuations is white noise. Conversely, the ADF test, while having many similarities with the original, accommodates some forms of serial correlation in the disturbances. Moreover, the ADF test statistics have non-standard distributions. As a result, their critical values are tabulated using simulations. In fact, the ADF statistic is a negative number. The more negative the number is, the more substantial the evidence for the rejection of the unit root hypothesis will become.

More specifically, the ADF test tests the null hypothesis is that there is a unit root. The alternative is that there is no unit root in the series. The p-values are obtained through regression surface approximation from MacKinnon (1994) using the updated 2010 tables (MacKinnon, 2010). The autolag option and maximum number of lags to use when selecting lag lengths for it are described in Greene (2011). The equation for the ADF test is specified as (Brooks, 2014):

$$\Delta y_t = \psi y_{t-1} + \sum_{i=1}^{p} \alpha_i \Delta y_{t-i} + u_t \tag{4.2}$$

and the test statistic is given by:

$$ADF\ test\ statistic = \frac{\hat{\rho}}{SE(\hat{\rho})} \tag{4.3}$$

And the null hypotheses of the ADF test are:

Table 4.1: ADF test hypotheses

Hypotheses	
$H_0 : y_t \sim I(1)$	The process is stationary
$H_1 : y_t \sim I(0)$	The process is non-stationary

4.3.2 Phillips–Perron Test

The PP (PP) test is similar to the ADF test. However, Phillips and Perron (1988) have developed a more comprehensive theory of unit root non-stationarity. For example, the PP test incorporates an automatic correction to the Dickey-Fuller procedure, which allows for autocorrelated residuals. For instance, unlike the ADF test, the regression estimates of the PP test only includes one lag of the dependent variable in addition to the trend terms (Phillips and Perron, 1988). In addition, a long-run Newey-West variance estimator accounts for any potential serial correlation in the regression errors. Even so, the tests often produce the same conclusions and, accordingly, suffer from most of the same limitations as the ADF test (Brooks, 2014).

The ADF and PP tests share the same null and alternate hypotheses. It follows that the test's null hypothesis, H_0, is that the process is stationary $y_t \sim I(1)$. Consequently, the alternative hypothesis, H_1, is that the series is non-stationary $y_t \sim I(0)$. Similarly, to the ADF test, the p-values for this thesis is obtained through the regression surface approximation from MacKinnon (1994) using the updated 2010 tables (MacKinnon, 2010).

The PP test is specified as (Brooks, 2014):

$$\Delta y_t = \psi y_{t-1} + \mu + \alpha_1 D_t + \alpha_2 (t - T_b) D_t + \lambda_t + \sum_{i=1}^{p} \alpha_i \Delta y_{t-i} + u_t \tag{4.4}$$

4.3.3 Criticism of Dickey-Fuller and Phillips-Perron Type Tests

There are several criticisms of the ADF test and the PP test. The most important criticism is that test power is low if the process is stationary but with a root close to the non-stationary boundry (Brooks, 2014). Accordingly, the source of this problem is that the null hypothesis for classical hypotheses testing frameworks is never accepted since they are either rejected or not. As a result, the failure to reject a hypothesis could occur because the null hypothesis was correct or because there is insufficient information in the sample to reject the hypothesis. One way to get around this problem is to use both unit root and stationarity tests, such as the KPSS test (Kwiatkowski et al., 1992).

Moreover, the standard unit root tests, such as the ADF and PP tests, do not perform well if there are one or more structural breaks in the series. This suggests that the tests have low power in such circumstances; therefore, they fail to reject unit root null hypotheses if they are incorrect. In general, larger structural breaks and smaller data samples result in lower power of the tests (Brooks, 2014). For example, Leybourne et al. (1998) have shown that unit root tests are oversized in the presence of structural breaks in the data samples. Consequently, the null hypotheses get rejected too often when it is correct. In fact, Perron (1989) demonstrated that allowing for structural breaks in the testing framework would allow multiple macroeconomic variables that Nelson and Plosser (1982) identified as non-stationary to be considered stationary. Therefore, most economic series are best characterised by *broken trend and stationary processes* (Brooks, 2014), where the data generating process is a deterministic trend with a structural break around one or more break points, such as 1929, that permanently changed the levels of the series. Given the above, standard unit root tests may struggle with small data samples and data series with the presence of significant structural breaks and, as a result, identify stationary time series as non-stationary.

4.3.4 Zivot-Andrews Test

The Zivot-Andrews test tests for unit roots in a univariate process in the presence of a serial correlation and a structural break (Zivot and Andrews, 1992). Accordingly, the test was developed as a response to Perron's (1989) testing of the Nelson and Plosser (1982) macroeconomic data, and the comments Perron (1989) made about several of the variables stationary status. Consequently, the Zivot-Andrews test treats the break point as endogenous and, as a result, finds less evidence against the unit root hypothesis than the standard ADF and PP tests. Accordingly, by allowing for a single structural break, multiple macroeconomic variables, which would otherwise have been deemed non-stationary, would now be considered stationary since the Zivot-Andrews test have higher test power in the presence of structural breaks in the series. Consequently, the Zivot-Andrews test would not fail to reject the unit root null hypothesis that other tests might have failed to reject despite being characterised by a broken trend and stationary processes. Moreover, since the procedure can identify the date of the structural break, it facilitates the analysis of whether a structural break on a certain variable is associated with a particular event, such as a change in government policy, a currency crisis, or war. However, the Zivot-Andrews test only allows for one structural break. In the Zivot-Andrews tests, a break date will be chosen where the evidence is least favourable for the unit root null. Ultimately, the Zivot-Andrews test has more power in the face of structural breaks in time series data than the ADF test and the PP test.

It follows that the null hypothesis, H_0, of the Zivot-Andrews test is that the process contains a unit root with a single structural break. As a result, the alternative hypothesis, H_1, is that the process is trend and break stationary (Zivot and Andrews, 1992), as can be seen in table 4.2. The algorithm for the Zivot-Andrews test in this thesis follows Baum's (2004/2015) approximation of the original method. As a consequence, the results will have a slightly more pessimistic trend statistic than in the original method.

The Zivot-Andrews test is specified as (Brooks, 2014):

$$\Delta y_t = \psi y_{t-1} + \mu + \alpha \tau_t(t_{used}) + \lambda t + \sum_{i=1}^{p} \alpha_i \Delta y_{y-1} + u_t \tag{4.5}$$

And the null hypotheses of the Zivot-Andrews test are:

Table 4.2: Zivot-Andrews test hypotheses

Hypotheses	
$H_0 : y_t \sim I(1)$	The process contains a unit root with a single structural break.
$H_1 : y_t \sim I(0)$	The process is trend and break stationary

4.4 Cointegration Analysis

A set of variables are defined as cointegrated if a linear combination of them is stationary. For instance, if two or more series of non-stationary random variables have a stationary linear combination or relationship. Typically, many time series are non-stationary yet move together over time. In other words, there exist some influence on the series, for example, market forces, which implies that the two series are bound by some relationship in the long run. Consequently, a cointegration relationship may be seen as a long-run relationship, or equilibrium phenomenon, since cointegrated variables may deviate from their relationship in the short run. Even so, their association would return in the long run (Brooks, 2014). Accordingly, cointegrated series, therefore, share a common stochastic trend. For this reason, cointegration tests are the standard tool for investigating the linear combination of time series variables since the method finds the presence of the number of cointegrating vectors, which indicates the long-run relationship between the variables. Given the above, the Engle-Granger (1987), Phillips-Ouliaris (1990) and Johansen's (1991) cointegration tests are performed to indicate whether or not inflation and interest rates in the eurozone and the US have a long-run relationship.

Cointegration implies that the error term u in the regression equation

$$y_t = \beta_0 + \beta_1 x_t + u_t, \tag{4.6}$$

does not have a unit root while both y and x do (Heiss and Brunner, 2020). Tests for cointegration can be based on the following finding: first, estimation of the model by ordinary least squares (OLS) and then testing for unit roots in the residual $\hat{u}$ and finally, adjusting the distribution of the test statistics and critical values. This approach is referred to as the Engle-Granger test or the Phillips-Ouliaris test. In addition, any cointegration found can be used to estimate error correction models.

The cointegration methods employed in this thesis have lags chosen by the Bayesian information criterion (BIC). Moreover, all cointegration models are calculated with a constant only, i.e., without deterministic time trends, which is consistent with the Fisher hypothesis (Beyer et al., 2009).

4.4.1 Engle-Granger Cointegration Test

The Engle-Granger test is implemented as an ADF test of the estimated residuals from the cross-sectional regression using a set of critical values determined by the number of assumed stochastic trends when the null hypothesis is true (Engle and Granger, 1987). The null hypothesis of the Engle-Granger cointegration is that the series are not cointegrated. The alternative hypothesis is that the series are cointegrated.

The Engle-Granger cointegration test is specified as:

$$Y_t = X_t\beta + D_t\gamma + \epsilon_t \tag{4.7}$$

Where $Z_t = [Y_t, X_t]$ is being tested for cointegration. The deterministic term, D_t, may include constant, time or quadratic trend. The null hypotheses (H_0) we want to test with the Engle-Granger cointegration test is that there is no cointegration, while the alternative hypothesis (H_1) is that there is a cointegration relationship.

4.4.2 Phillips-Ouliaris Cointegration Tests

The Engle-Granger method have limitations. For example, if there are more than two variables, the method may show more than two cointegrating relationship. Another limitation is that the Engle-Granger cointegration test is a single equation method. Some of these drawbacks, however, have been addressed in the Phillips-Ouliaris test and the Johansen's test.

Phillips and Ouliaris (1990) found that residual-based unit root tests applied to the estimated cointegrating residuals do not have the usual Dickey-Fuller distributions under the null hypothesis of no-cointegration. Instead, because of the spurious regression phenomenon under the null hypothesis, the distribution of the tests has asymptotic distributions that depend on two factors. First, the number of deterministic trend terms and second, the number of variables with which cointegration is being tested. Accordingly, these distributions are known as the Phillips-Ouliaris distributions.

The first two steps are identical to the Engle-Granger cointegration test. The following steps and four Phillips-Ouliaris cointegration tests are specified as:

Define the cross-sectional regression:

$$y_t = x_t\beta + d_t\gamma + u_t \tag{4.8}$$

where d_t are any included deterministic terms. Let $\hat{u}_t = y_t - x_t\hat{\beta} + d_t\hat{\gamma}$.

The $Z\alpha$ test based on the debiased AR(1) coefficient, and the Zt test, based on the t-statistic from an AR(1) statistics are defines as:

$$\hat{Z}_\alpha = T \times z \tag{4.9}$$

$$\hat{Z}_t = \frac{\hat{\sigma}_u}{\hat{\omega}^2} \times \sqrt{T}z \tag{4.10}$$

$$z = (\hat{a} - 1) - \hat{\omega_1^2}/\hat{\sigma_u^2} \tag{4.11}$$

where $\hat{\sigma}_{u^2} = T^{-1}\sum_{t=2}^{T}\hat{u}_t^2, \hat{\omega}_1^2$ is an estimate of the one-sided strict autocovariance, and $\hat{\omega}^2$ is an estimate of the long-run variance of the process.

The variance-ratio test, $\hat{P}_u$ is defined as:

$$\hat{P}_u = \frac{\hat{\omega}_{11\cdot 2}}{\hat{\sigma}_u^2} \tag{4.12}$$

where $\hat{\sigma}_u^2 = T^{-1}\sum_{t=1}^{T}\hat{u}_t^2$ and

$$\hat{\omega}_{11\cdot 2} = \hat{\omega}_{11} - \hat{\omega}\prime_{21}\hat{\Omega}_{22}^{-1}\hat{\omega}_{21} \tag{4.13}$$

and

$$\hat{\Omega} = \begin{bmatrix} \hat{\omega}_{11} & \hat{\omega}\prime_{21} \\ \hat{\omega}_{21} & \hat{\Omega}_{22} \end{bmatrix} \tag{4.14}$$

is an estimate of the long-run covariance of ξ_t, the residuals from VAR(1) on $z_t = [y_t, z_t]$ that includes and trends included in the test.

$$z_t = \Phi z_{t-1} + \xi_t \tag{4.15}$$

The final test, the Pz test of the trace of the product of an estimate of the long-run residual variance and the inner-product of the data, is defined as:

$$\hat{P}_z = T \times tr(\hat{\Omega} M_{zz}^{-1}) \tag{4.16}$$

The null hypotheses (H_0) of the Phillips-Ouliaris cointegration test is that there is no cointegration, while the alternative hypothesis (H_1) is that there is a cointegration relationship between the variables.

4.5 Johansen's Test

The Johansen's test is another improvement over the Engle-Granger test. The Engle-Granger and Phillips-Ouliaris do not permit for testing of hypotheses on the cointegration relationships themselves. On the other hand, the Johansen test permits the testing of hypotheses about the equilibrium relationship between the variables (Brooks, 2014). Consequently, the Johansen test allows for the testing of hypotheses about one or more coefficients in the cointegration relationship. Moreover, the Johansen's test is based on a maximum likelihood estimation which allows for the testing of long-run relationships between variables by employing maximum eigenvalue and trace statistics (Johansen, 1988). Both maximum eigenvalue and trace statistics critical values are used to detect whether or not there is a long-run relationship among the variables. Unlike the Engle-Granger and Phillip-Ouliaris tests for cointegration, the Johansen's cointegration tests allow for more than two variables and treat all variables as endogenous, thus removing the need for a dependent variable (Wassell and Saunders, 2008). Therefore, many authors agree that the Johansen's test is an improvement over the Engle-Granger cointegration test since it avoids the issue of choosing a dependent variable as well as issues created when errors are carried from one stop to the next. Consequently, the Johansen's test can detect multiple cointegrating vectors, which makes it more appropriate than the Engle-Granger or Phillips-Ouliaris tests for multivariate analysis. Even so, the test is far from perfect. For example, Gonzalo and Lee (1998) found that for most situations, the Engle-Granger test was more robust than Johansen's likelihood ratio test. For this reason, the authors recommended using both the Engle-Granger cointegration test and Johansen's test to discover or avoid any pitfalls. Ultimately, the Johansen's test has several advantages over the Engle-Granger and Phillips-Ouliaris tests. Even so, it is less robust than the two previous cointegration tests. Therefore, all three cointegration tests will be performed on the data to examine the long-term relationship and equilibrium between inflation and nominal interest rates in the eurozone and US.

There are two types of Johansen's test: the first uses trace statistics, and the second uses maximum eigenvalues. Both forms of the test will determine if cointegration is present. The null hypothesis for both forms of the test is that there are no cointegrating equations. The difference is in the alternative hypothesis. The alternative hypothesis for the trace statistic is that the number of cointegrating relationships is at least one, indicated by the number of linear combinations. The maximum eigenvalue test, on the other hand, has an alternative hypothesis of K0 + 1 (instead of K > K0). Rejecting the null hypothesis in this situation equates to saying stating that there is only one combination of the non-stationary variables, which gives a stationary process.

The Johansen's test technique based on VARs for a set of variables under consideration that are $I(1)$ and which may thought to be cointegrated, must first be turned into a a vector error correction model (VECM)(Brooks, 2014). The transformation to VECM form produces the following model:

$$\Delta y_t = \Pi y_{t-k} + \Gamma_1 \Delta y_{t-1} + \Gamma_2 \Delta y_{t-2} + ... + \Gamma_{k-1} \Delta y_{t-(k-1)} + u_t \tag{4.17}$$

where $\Pi = (\sum_{i=1}^{k} \beta_i) - I_g$ and $\Gamma_i = (\sum_{j=1}^{i} \beta_j) - I_g$ (Brooks, 2014).

Johansen's (1991) full information maximum likelihood method is then used to test the cointegration restrictions. This involves estimating the rank of the impact matrix, which summarises the long-run relationship among the variables. Accordingly, cointegration is equivalent to a reduced rank of the impact matrix. Solving Johansen's (1991) eigenvalue specification yields the estimates of the eigenvalues and the associated eigenvectors. The two likelihood ratio tests may then be constructed for the number of cointegration vectors

r. The trace test which is given by:

$$\lambda_{trace}(r) = -T \sum_{i=r+1}^{g} ln(1 - \hat{\lambda}_i) \tag{4.18}$$

And the maximum eigenvalue test is given by:

$$\lambda_{max}(r, r+1) = -Tln(1 - \hat{\lambda}_{r+1}) \tag{4.19}$$

The null hypotheses of the Johansen's test are:

Table 4.3: Johansen's test hypotheses

Hypotheses
Trace tests (λ_{trace})
$H_0 : K = K_0$
$H_0 : K > K_0$
Maximum Eigenvalue test (λ_{max})
$H_0 : K = K_0$
$H_0 : K = K_0 + 1$

4.6 The Vector Autoregressive Model

It is common in economics to model the relationships among multiple time series. For example, an economist may wish to understand the impact of monetary policy on inflation, output and unemployment. A widely used tool for analysing multiple time series is the vector autoregressive model. The vector autoregressive model is a generalisation of the univariate model of an autoregressive process to a system of equations describing multivariate time series. All variables are treated equally as endogenous variables. Moreover, the evolution of each variable is modelled as a linear function of its own lags in addition to all the other variables and their lags. Consequently, At each point in time, $K - vector\ Y_t$ of data points are observed, one for each time series. Accordingly, these can be modelled similarly to an AR process (McKinney et al., 2011).

The VAR model is specified as (Lütkepohl, 2006):

$$Y_t = A_1 Y_{t-1} + ... + A_p Y_{t-p} + \varepsilon_t. \tag{4.20}$$

In this case, the coefficients A_i are square matrices. The error ε_t is typically assumed to be normally distributed and uncorrelated over time. Moreover, VAR models require stationarity $I(1)$ to avoid the spurious regression phenomena described by Granger and Newbold (1974). Accordingly, all variables used in the VAR model will be differenced if their unit root test results indicate non-stationarity $I(0)$. In this thesis, the VAR model will be estimated by ordinary least squares (OLS).

4.6.1 Model Specification

The VAR model is specified to illustrate how the relationship between inflation and nominal interest rates plays out and to visualise the impulse responses from monetary policy. Accordingly, each of the five variables in the model is assumed to act as a dependent variable. Thus, the relationships are modelled with five different models. The final model specifications for the euro area and the US analysed in Python are presented in equations (4.21) to (4.25).

$$Inf_t = Int_t + GDP_t + M3_t + Unem_t \tag{4.21}$$
$$Int_t = Inf_t + GDP_t + M3_t + Unem_t \tag{4.22}$$
$$M3_t = Inf_t + Int_t + GDP_t + Unem_t \tag{4.23}$$
$$Unem_t = Inf_t + Int_t GDP_t + M3_t \tag{4.24}$$
$$GDP_t = Inf_t + Int_t + M3_t + Unem_t \tag{4.25}$$

Where Inf_t is the respective inflation rates, Int_t is the respective short-term nominal interest rates, $M3_t$ is the respective broad money measures, $Unem_t$ is the respective unemployment rates and GDP_t is the respective gross domestic product measures.

4.6.2 Impulse Response Analysis

Impulse responses are of interest in econometric analyses. Impulse response analyses visualise how shocks in one variable affect itself and the other independent variables. Accordingly, they estimate the responses to the unit impulse in one of the variables and are computed using $MA(\infty)$ representation of the $VAR(p)$ process. (Lütkepohl, 2006):

$$Y_t = \mu + \sum_{i=0}^{\infty} \Phi_i u_{t-i} \tag{4.26}$$

For this reason, this study uses impulse analyses to visualise how shocks in inflation and nominal interest rates affect themselves and the other independent variables. The impulse responses are visualised with asymptotic standard errors at the 95% significance level.

4.6.3 Granger Causality

Causality tests seek to answer a simple question; do changes in one variable cause changes in another variable? Accordingly, if y_1 causes y_2, lags of y_1 should be significant in the equation for y_2. If this is the case, then y_1 can be said to Granger-cause y_2 (Brooks, 2014). For this reason, if one time series is said to be caused by another series in the Granger sense, then the information on the past and present in the second time series helps improve the forecast of the first. Nevertheless, causality in Granger's sense, or Granger causality, does not imply true causality since it does not have anything to say about contemporaneous causality between the first and second series. In fact, it does not allow the determination of whether the first or second series are exogenous or endogenous variables (Wooldridge, 2020). Further, true causality refers to the concept of cause and effect and is often postulation or implied by economic theory. On the other hand, Granger causality is a test for the bi-directional or unidirectional explanatory power of one series on the movements of another. As a result, it is a statistical tool for the study of directional forecasting power between variables rather than a test for true causality. Granger causality can, therefore, be explained as predictive causality for two series, or in Granger's (1977) own words, *The temporal relation* between two series. Ultimately, Granger causality cannot test for true causality; however, it is a helpful tool for determining the directional forecasting relationship between two time series. The hypotheses for Granger causality and its implied restrictions on VAR models can be seen in table 4.4.

Table 4.4: Granger causality tests and implied restrictions on VAR models

	Hypotheses	Implied restriction
1	Lags of y_{1t} does not explain current y_{2t}	$\beta_{21} = 0$ and $\gamma_{21} = 0$ and $\delta_{21} = 0$
2	Lags of y_{1t} does not explain current y_{1t}	$\beta_{11} = 0$ and $\gamma_{11} = 0$ and $\delta_{11} = 0$
3	Lags of y_{2t} does not explain current y_{1t}	$\beta_{12} = 0$ and $\gamma_{12} = 0$ and $\delta_{12} = 0$
4	Lags of y_{2t} does not explain current y_{2t}	$\beta_{22} = 0$ and $\gamma_{22} = 0$ and $\delta_{22} = 0$

Source: Brooks (2014).

Granger causality can test for unidirectional causality or bi-directional feedback. For example, if one series causes another in the Granger sense, but not the other way around, then one series can be said to Granger-cause the other, or that there is proof for a unidirectional relationship from one variable to another. On the other hand, if both series and their lags cause each other, then the relationship can be said to be bi-directional. Consequently, while not being able to test for true causality, Granger causality is helpful in testing the forecasting power and, therefore, the predictive causality between two time series.

Granger causality can, therefore, help determine the directional forecasting power between inflation and interest rates in the eurozone and the US for the estimation period. Accordingly, the hypothesis tests for inflation and interest rates can be seen in table 4.5, where the Granger causality test allows for the directional testing relationship of the series.

Table 4.5: Granger causality hypotheses

	Null Hypotheses
Eurozone	
3	Eurozone inflation does not Granger-cause eurozone interest rates.
4	Eurozone interest rates does not Granger-cause eurozone inflation
US	
1	US inflation does not Granger-cause US interest rate.
2	US interest rate does not Granger-cause US inflation.

Table 4.6: The Research Matrix

Research question	Hypotheses	Data	Methods of data analysis
1. Has there been a structural break in the relationship between inflation and interest rates during the GFC?	H_0: No break H_1 : Break	Time series data for inflation and interest rates.	Fisher-Jenks Algorithm Chow Test
2. Is there a long-term relationship between inflation and interest rates?	H_0: No relationship H_1 : Long-term relationship (cointegration)	Time series data for inflation and interest rates.	Engle-Granger test Phillips-Ouliaris Tests Johansen's test
3. Is there a (Granger) causal relationship between inflation and interest rates?	H_0: No causality H_1 :bi-directional causality H_2 :unidirectional causality	Time series data for inflation and interest rates.	Granger causality

4.7 Research Matrix

Chapter 5 will analyse the research questions introduced in chapter 1. The research questions are presented in the research matrix. The research matrix summarises the thesis goals, objectives, hypotheses, variables and analysis methods. As can be seen in table 4.6, there are three main hypotheses. The first hypothesis tests if there has been a structural break in the relationship between the time series for inflation and policy rates in the eurozone and the US.

The second research question examines whether the data has a long-term relationship between inflation and policy rates. Finally, the third research question asks about a directional causal relationship between inflation and interest rates.

5 Results

Chapter 5 begins with the summary statistics before giving a detailed description of the findings from the structural break detection and testing, the unit root tests and cointegration tests before, and finally, providing the findings from the stylised vector autoregressive model and the Granger causality test.

5.1 Descriptive statistics

The descriptive statistics for both data sets were performed in Python using the Pandas and SciPy libraries. The Jarque-Bera values for eurozone inflation and interest rates provide clear evidence for non-normality in the distributions of the variables since their respective Jarque-Bera statistics of 6.37 and 22.72 are statistically significant at the 5% and 1% levels. The mean inflation rate over the 20-year period in the euro area has been 1.745%, which is $\sim$ 0.25% under the ECB's medium-term goal (ECB, 2022c). The nominal interest rates have been even lower, with an average value of 1.039% over the same period.

Table 5.1: Descriptive statistics for the eurozone data

	Inflation	Interest rate
Mean	1.745	1.037
Std. Err.	0.933	1.266
Min	-0.600	-0.400
Max	4.100	3.750
Kurtosis	-0.158	-0.911
Skewness	-0.391	0.600
Jarque-Bera	6.371**	22.724*
Count (n)	241	241

Note: * and ** indicate the significance level at 1% and 5%, respectively.

The standard deviation has been slightly higher for the euro area's policy rates, yet both are close to 1. The minimum values of -0.60% for inflation and -0.40% for nominal interest rates highlight the euro zones deflationary tendencies after the GFC and the negative interest rate policy after the GFC and the European sovereign debt crisis.

Similar to the euro area data, the US data has high Jarque-Bera statistics. These results are correspondingly statistically significant at the 1% level. On the other hand, the means for inflation and nominal interest rates are noticeably higher than in the euro area. Inflation is close to the Fed's long-term target of 2% (Fed, 2022c), and policy rates have had an average of about 2%. The average is low in a historical context but still noticeably higher than for the euro area. Standard deviations for inflation and interest rates are 1.24 and 2.0, respectively, with a slightly higher standard deviation for the Fed funds.

Table 5.2: Descriptive statistics for the US data

	Inflation	Interest rate
Mean	2.189	1.927
Std. Err.	1.245	2.034
Min	-2.097	0.070
Max	5.600	6.540
Kurtosis	0.838	-0.691
Skewness	0.383	0.865
Jarque-Bera	12.166*	34.624*
Count (n)	241	241

Note: * and ** indicate the significance level at 1% and 5%, respectively.

Conversely, the minimum values for the US data are noticeably different from the euro area data. Inflation reached a minimum value of -2.09% and a maximum value of 5.60%, indicating higher fluctuations than for the eurozone data during the 20-year period. US policy rates fluctuated similarly, although the Fed never implemented negative short-term nominal interest rates, as can be seen by the minimum value for the US interest rate.

5.2 Identification of Structural Breaks

5.2.1 Structural Break Detection

The Fisher-Jenks algorithm detected several possible break dates from 1999 to 2019. However, there was the most substantial evidence for a structural break in all series in July 2009, especially for the inflation series. In fact, July 2009 marked the end of the recessions in the US and the euro area, according to the NBER and OECD, respectively, and the point with the lowest inflation rates in both economies. Accordingly, the break point corresponded with the visual identification of a possible structural break. Therefore, July 2009 ($2009-07-01$) was chosen as the break date for the following Chow test.

5.2.2 Structural Break Tests

Three structural break tests were performed, two for the US data and one for the eurozone data. First, the data was sliced into two groups, the first from January 1999 to July 2009 and the second from August 2009 to January 2019. Then, the coefficients for the regressions of the first and second data slices were estimated and tested for equality. Finally, the test statistic and corresponding p-values were calculated and used to test the hypotheses.

Table 5.3: Chow test for a structural break in July 2009 (2009-07-01)

	F Statistic	P-Value
US inflation and interest rate*	1.680	0.188
Eurozone inflation and interest rate	20.641	0.000

Note: The Chow test results for US inflation and interest rates* clearly indicated a structural break when performed on longer series (1979-2019).

For the US data, a Chow test was performed from 1979 for the first and 1999 for the second test since the data was readily available. Accordingly, the Chow test with a data slice from 1979 was highly significant. Conversely, the Chow test on US data from 1999 did not produce statistically significant results, as seen in table 5.3. For this reason, the significant results indicated by the longer time series data might not have anything to do with the GFC but instead come as a result of previous regime shifts in monetary policy or inflation dynamics. For instance, stagflation in the 1970s and Paul Volcker's chairmanship at the FED, or on the other hand, the chairmanship of Alan Greenspan and Ben Bernanke. Even so, inflation has been remarkably stable since the introduction of inflation targeting policies, which covers most of the estimation period. As described, many factors may have resulted in a statistically significant test for a structural break in the time series when testing the longer US time series. Nevertheless, there is not any strong evidence for a structural break when performing the test on the shorter data slice, and as a result, the changes in inflation and interest rates around and after the GFC does not seem to deviate far enough from the recent trends for it to be considered a structural break.

Moreover, interest rates have likewise been on a steady, falling trend. As a result, the period around the GFC might not have resulted in shifts in inflation rates or interest rates that deviated enough from the trend to cause a structural break in the time series data. For example, unorthodox monetary policies such as quantitative easing can explain the relative lack of movement away from the trend in the series when interest rates are close to the lower bound. Ultimately, there is no clear evidence for a structural break in the US data during the GFC from the results of these tests.

The data for the eurozone, on the other hand, produced a clear hypothesis test with a p-value of ≈ 0.0000, as can be seen in table 5.3. However, only a single test was performed due to a lack of eurozone and ECB data before the late 1990s. Even so, the euro area data results strongly indicate a structural break in the time series data for inflation and interest rates in July 2009. In fact, the relative change in both inflation and interest rates has been considerable during the period, especially compared to the US. Unorthodox monetary policies such as various forms of monetary (quantitative) easing do not appear to have changed this fact. On the contrary, the ECB's negative interest rate policy may contribute to the structural break in the relationship between the euro area's inflation and policy rate. To summarise, there is strong evidence for a structural break in the relationship between eurozone inflation and interest rate during the estimation period.

Given the above, the conclusion that can be drawn for the identification of structural breaks in the time series data is that there is clear evidence for a structural break in the eurozone data. Admittedly, there is no strong evidence for a structural break in the US data for the same estimation period with the same break point, although there is clear evidence of a structural break when testing the time series with a longer data set.

5.3 Unit Root Tests

5.3.1 Augmented Dickey-Fuller and Phillips-Perron

Two unit root tests were performed. First, the ADF test under two different assumptions. Then the PP test, also under two assumptions: one with a constant trend component (*constant*) and one trend component which includes a constant and a linear time trend (*constant+trend*). Moreover, the tests were performed on both level, untransformed data and on the first differenced data, since it allows for the testing of whether the variables are integrated of the same order. The results from the initial unit root tests are reported in table 5.4.

Table 5.4: ADF and PP Unit Root Tests

	ADF (Augmented Dickey-Fuller)		**PP** (Phillips-Perron)	
Variables	Level	First Difference	Level	First Difference
US inflation (constant)	-2.068	-8.964*	-3.018*	-9.413*
US inflation (constant+trend)	-2.411	-8.942*	-3.295**	-9.387*
US interest rate (constant)	-1.849	-6.508*	-1.939	-7.413*
US interest rate (constant+trend)	-1.472	-6.607*	-1.771	-7.467*
Euro inflation (constant)	-2.904*	-5.274*	-2.759	-13.566*
Euro inflation (constant+trend)	-3.400**	-5.282*	-3.207	-13.551*
Euro interest rate (constant)	-1.800	-5.274*	-1.469	-12.463*
Euro interest rate (constant+trend)	-3.764*	-5.282*	-2.680	-12.438*

Note: * and ** indicate the significance level at 1% and 5%, respectively.
Maximum lag length is specified by the Bayesian information criterion (BIC).

The findings from the two tests show that not all variables are stationary at the level since some of their values are lower than the critical values for both methods, for instance: eurozone inflation for both assumptions and eurozone interest rates under the assumption of a constant trend component for the ADF test. In addition, US inflation for both assumptions of the PP test shows evidence for stationarity. Even so, the two tests come to indicate different results for all variables that might be stationary. Further, the first differentiation of all series becomes stationary since their test statistics exceed the critical values. As a result, all series are integrated at the same order,$I(1)$, indicating that the data sets are suitable for employing cointegration tests.

5.3.2 Zivot-Andrews

The Zivot-Andrews unit root test allows for the possibility of a single structural break in the time series. Therefore, the Zivot-Andrews test was also performed since there was a

Table 5.5: Zivot-Andrews Unit Root Test

	ZA (Zivot-Andrews)	
Variables	Level	First Difference
US inflation (constant)	-3.682	-9.299*
US inflation (constant+trend)	-3.676	-9.285*
US interest rate (constant)	-2.662	-7.357*
US interest rate (constant+trend)	-2.714	-7.396*
Euro inflation (constant)	-3.975	-8.899*
Euro inflation (constant+trend)	-4.273	-8.894*
Euro interest rate (constant)	-4.793	-5.609*
Euro interest rate (constant+trend)	-4.662	-5.900*

Note: * and ** indicate the significance level at 1% and 5%, respectively.
Maximum lag length is specified by the Bayesian information criterion (BIC).

suspicion of, and now evidence for, a structural break in at relationship between at least one of the data sets, especially in the time series for eurozone inflation and interest rate. The results from the Zivot-Andrews tests are reported in table 5.5. Similarly to the ADF test and the PP test, the Zivot-Andrews test statistics were estimated with two sets of assumptions. Correspondingly, like the previous unit root tests, with a constant trend component (*constant*) and tests with a constant and a linear time trend (*constant+trend*) were calculated. The results provide clear evidence for trend and break stationarity for all level values. On the other hand, the test statistics for the differenced variables clearly indicate that they are stationary at the 1% significance level. In conclusion, the Zivot-Andrews test provides clear evidence for the presence of unit roots in all level variables independently of test assumptions. While in addition, providing clear evidence for the stationarity of all the differenced variables, independently of test assumptions.

While similar overall, the differences between the results in the ADF test and the PP test on the one side, and the Zivot-Andrews test on the other side, can be explained by its ability to test for unit roots in the presence of a single structural break.

5.4 Cointegration

Cointegration tests are the standard tools for investigating the linear combination of time series variables. The method first finds the presence of number of cointegrating vectors, which indicate the long run relationship between the variables. Accordingly, this thesis performed the Engle-Granger, Phillips-Ouliaris and Johansen's cointegration tests to examine whether inflation and nominal interest rates have a long run relationship in the eurozone and US.

The cointegration tests where performed on all variables for inflation and interest rates since there was sufficient evidence about the non-stationary status of the variables from the unit root tests. Finally, all the cointegration tests were also performed on data before and after the break point from Chapter 5.3, and all the tests produced the same conclusions as the tests presented in the following subsection.

5.4.1 Engle-Granger Test

The Engle-Granger test is one of the standard methodologies for investigating the linear combination of two stationary time series. Accordingly, the method finds the presence and number of cointegrating vectors which indicate whether there is a long run relationship between the variables.

The results from the Engle-Granger cointegration test are reported in table 5.6. The test statistic and p-values for the eurozone data clearly indicate a failure to reject the null hypothesis of on cointegration between inflation and nominal interest rates. Similarly, the results from the US inflation and nominal interest rate series give the same conclusion, even though the test results are closer to the 10% significance level. It can be concluded that there is little evidence for a cointegration relationship between inflation and nominal interest rates during the estimation period for the euro area and the US based on the results from the Engle-Granger cointegration test.

Since the Engle-Granger cointegration test is implemented as an ADF test of the estimated residuals from the cross-sectional regression, some of the same drawbacks of the ADF test

Table 5.6: Engle-Granger Cointegration Test.

Dependent Variable	Test Statistic	P-Value
US		
US inflation	-2.857	0.149
US interest rate	-2.728	0.190
Eurozone		
Eurozone inflation	-2.797	0.167
Eurozone interest	-1.827	0.617

Note: * and ** indicate the significance level at 1% and 5%, respectively.
Constant deterministic trend.

might apply, especially in the face of possible structural breaks in the time series data. As a result, the Engle-Granger test might struggle with existing long-term relationships even if they exist. Nevertheless, the Engle-Granger test has, ultimately, found little evidence for a long-term relationship between inflation and nominal interest rates in the euro area and the US.

5.4.2 Phillips-Ouliaris Tests

The Phillips-Ouliaris tests found little evidence for a cointegration relationship between eurozone inflation and eurozone nominal interest rates. Consequently, no null hypothesis of no cointegration can be rejected for the euro area data at the 5% significance level. Even so, the Zt test, the test based on the t-statistic from $AR(1)$ and P_u, the variance-ratio test, with inflation as the dependent variable, are both statistically significant at the 10% level. Nevertheless, the evidence for a cointegration relationship from the Phillips-Ouliaris test on the eurozone data is insufficient to draw any significant conclusions.

There is, however, stronger evidence for a cointegration relationship for the US data. All the tests with inflation as the dependent variable are statistically significant at the 5% level. In fact, three of the four tests, with the exception of Pz, the test of the trace of the product of an estimate of the long-run residual variance and the inner-product data, are statistically significant at the 1% level. Admittedly, only one test, Pz, is statistically significant when the nominal interest rate is the dependent variable. Ultimately, there is more evidence for a cointegration relationship for the US data during the estimation period. Even so, there is mostly evidence for such an relationship when inflation is the

Table 5.7: Phillips-Ouliaris Cointegration Test

Dependent Variable	Test	Test Statistic	P-Value
US			
Inflation	$Z\alpha$	-32.234	0.004
Inflation	Zt	-4.110	0.005
Inflation	P_u	62.374	0.002
Inflation	Pz	69.151	0.012
Interest rate	Z_α	-11.801	0.253
Interest rate	Zt	-2.609	0.234
Interest rate	P_u	8.708	0.508
Interest rate	Pz	69.151	0.012
Eurozone			
Inflation	Z_α	-16.982	0.103
Inflation	Zt	-3.070	0.095
Inflation	P_u	32.353	0.061
Inflation	Pz	43.899	0.130
Interest rate	Z_α	-6.341	0.517
Interest rate	Zt	-1.881	0.590
Interest rate	P_u	10.057	0.467
Interest rate	Pz	43.899	0.130

Constant deterministic trend.

dependent variable.

5.4.3 Johansen's Tests

The potential presence of a long-run relationship between inflation and interest rates is also checked by performing the Johansen's cointegration test. The results are reported in table 5.8. The results for US inflation and interest rates show that the computed values of the trace statistic and the maximum eigenvalue statistic are larger than the critical value at the 5% level for the null hypothesis of no cointegration relationship or no long-run relationship between US inflation and US interest rates $(r = 0)$. Further, the test statistic for the second hypothesis $(r \leq 1)$ also exceeds the 5% critical value. As a result, the hypothesis of no cointegration relationship $(r = 0)$ between inflation and interest rates for the US data is rejected. Consequently, there is evidence for an equilibrium relationship between inflation and nominal interest rates in the US.

The results from the eurozone data set are also reported in table 5.8. The results for

Table 5.8: Johansen's Cointegration Test

	Trace Statistics		Maximum Eigenvalue Statistics	
Null Hypothesis	Test Statistic	5% Critical Value	Test Statistic	5% Critical Value
US				
$r = 0$	23.417*	15.494	19.008*	14.263
$r \leq 1$	4.408*	3.841	4.408*	3.841
Eurozone				
$r = 0$	13.820	15.494	11.694	14.263
$r \leq 1$	2.126	3.841	2.126	3.841

Note:* indicates the significance level at 5%.
Constant deterministic trend.

eurozone inflation and interest rates show that the computed value of both trace and maximum eigenvalue statistics are smaller than their respective critical values at the 5% significance level. Accordingly, the null hypothesis of no long-run relationship between inflation and interest rates *($r = 0$)* is not rejected at the 5% significance level. Thus, there is no clear evidence for an equilibrium relationship between the variables. Given the above, it can be concluded that there is no evidence for a long-run relationship between inflation and interest rates in the euro area for the estimation period. On the other hand, there is evidence for an equilibrium relationship between US inflation and nominal interest rates. Ultimately, the test results mirror the Engle-Granger and Phillip-Ouliaris cointegration tests in providing more evidence for a cointegration and equilibrium relationship between US inflation and nominal interest rate while failing to produce similar evidence with the euro area data.

5.5 Vector Autoregressive Model

The summary statistics for the VAR model are reported in table 5.9 for the euro area and 5.10 for the US, respectively. Gross domestic product, GDP, broad money, $M3$, and unemployment,$Unem$ are reported as log-transformed variables in both tables.

All variables in both tables have also been differenced twice in addition to the log-transformation of GDP, M3 and unemployment since the unemployment data in both data sets were non-stationary after taking the first difference. Consequently, all variables in both panels are stationary after the second difference, making them suitable for a vector autoregressive model. These variables were used to build the VAR model, which

Table 5.9: Descriptive statistics for the eurozone VAR model variables

	Inf	Int	GDP	M3	Unem
Mean	1.745	1.039	4.607	29.714	2.247
Std	0.933	1.266	0.010	0.301	0.132
Min	-0.600	-0.400	4.583	29.123	1.988
Max	4.100	3.750	4.633	30.146	2.501
Kurtosis	-0.158	-0.911	0.123	-1.054	-0.686
Skewness	-0.391	0.510	0.344	-0.501	0.161
Jarque-Bera	6.371**	22.724*	4.793	21.169*	5.904
Count (n)	241	241	241	241	241

Note: * and ** indicate the significance level at 1% and 5%, respectively.

Table 5.10: Descriptive statistics for the US VAR model variables

	Inf	Int	GDP	M3	Unem
Mean	2.189	1.927	4.606	29.725	1.734
Std	1.245	2.035	0.009	0.349	0.2806
Min	-2.097	0.070	4.583	29.113	1.308
Max	5.600	6.540	4.6233	30.300	2.303
Kurtosis	0.838	-0.691	-0.121	-1.184	-0.803
Skewness	-0.383	0.865	-0.248	0.001	0.578
Jarque-Bera	12.166*	34.624*	2.637	14.074*	19.846*
Count (n)	241	241	241	241	241

Note: * and ** indicate the significance level at 1% and 5%, respectively.

subsequently was used to produce the stylised impulse response analysis and Granger causality test. The variables and their stationary statuses are reported in table 5.11 for the euro area data and 5.12 for the US data.

Table 5.11: Stationary test for eurozone VAR model variables

Variable	ADF_{level}	ADF_{diff}	PP_{level}	PP_{diff}	ZA_{level}	ZA_{diff}
Inf_c	-2.904*	-5.274*	-2.759	-13.566*	-3.975	-8.899*
Inf_{ct}	-3.400**	-5.282*	-3.207	-13.551*	-4.273	-8.894*
Int_c	-1.800	-5.274*	-1.469	-12.463*	-4.793	-5.609*
Int_{ct}	-3.764*	-5.282*	-2.680	-12.438*	4.662	-5.900*
GDP_c	-4.274*	-6.195*	-2.841	-3.079**	-4.678	-6.842*
GDP_{ct}	-4.277*	-6.181*	-2.844	-3.443**	-4.914	-6.827*
$M3_c$	-3.012**	-10.735*	-2.175	-46.976*	-3.909	-11.189*
$M3_{ct}$	-2.350	-10.708*	-1.062	-46.860*	-5.186*	-11.165*
$Unem_c$	-1.976	-13.938*	-1.378	-38.607*	-3.655	-14.374*
$Unem_{ct}$	-1.941	-13.908*	-1.274	-38.709*	-3.782	-14.345*

Note: * and ** indicate the significance level at 1% and 5%, respectively.
Maximum lag length is specified by the Bayesian information criterion (BIC).

Table 5.12: Stationary test for US VAR model variables

Variable	ADF_{level}	ADF_{diff}	PP_{level}	PP_{diff}	ZA_{level}	ZA_{diff}
Inf_c	-2.068	-8.202*	-3.018*	-35.649*	-3.682	-8.429*
Inf_{ct}	-2.411	-8.177*	-3.295**	-35.520*	-3.676	-8.412*
Int_c	-1.849	-11.247*	-1.939	-25.822*	-2.662	-11.488*
Int_{ct}	-1.472	-11.227*	-1.771	-25.839*	-2.714	-11.486*
GDP_c	-2.959**	-5.846*	-2.583	-3.041**	-4.189	-6.322*
GDP_{ct}	-2.864	-5.843*	-2.553	-3.063**	-4.235	-6.308*
$M3_c$	-1.046	-11.856*	-0.946	-52.912*	-3.498	-11.979*
$M3_{ct}$	-2.739	-11.828*	-2.247	-52.813*	-3.929	-11.970*
$Unem_c$	-2.337	-13.089*	-1.350	-68.243*	-3.562	-13.590*
$Unem_{ct}$	-2.226	-13.063*	-1.011	-68.042*	-5.414**	-13.588*

Note: * and ** indicate the significance level at 1% and 5%, respectively.
Maximum lag length is specified by the Bayesian information criterion (BIC).

5.5.1 Impulse Response Analysis

Impulse response analyses are useful when studying macroeconomic data since the method describes and visualises how shocks in one variable affect itself and other variables. The impulse response analysis for the eurozone data is reported in 5.1. Each column contains the impacts of shocks to each variable on a specific variable over 12 months.

The impulse response analysis for the euro area data indicates that inflation bounces after one to two months when it is subject to an interest rate shock before stabilising after three to four months. This suggests that the lag between policy rates and inflation in the euro area is about one to two months, which is consistent with the model covered in chapter

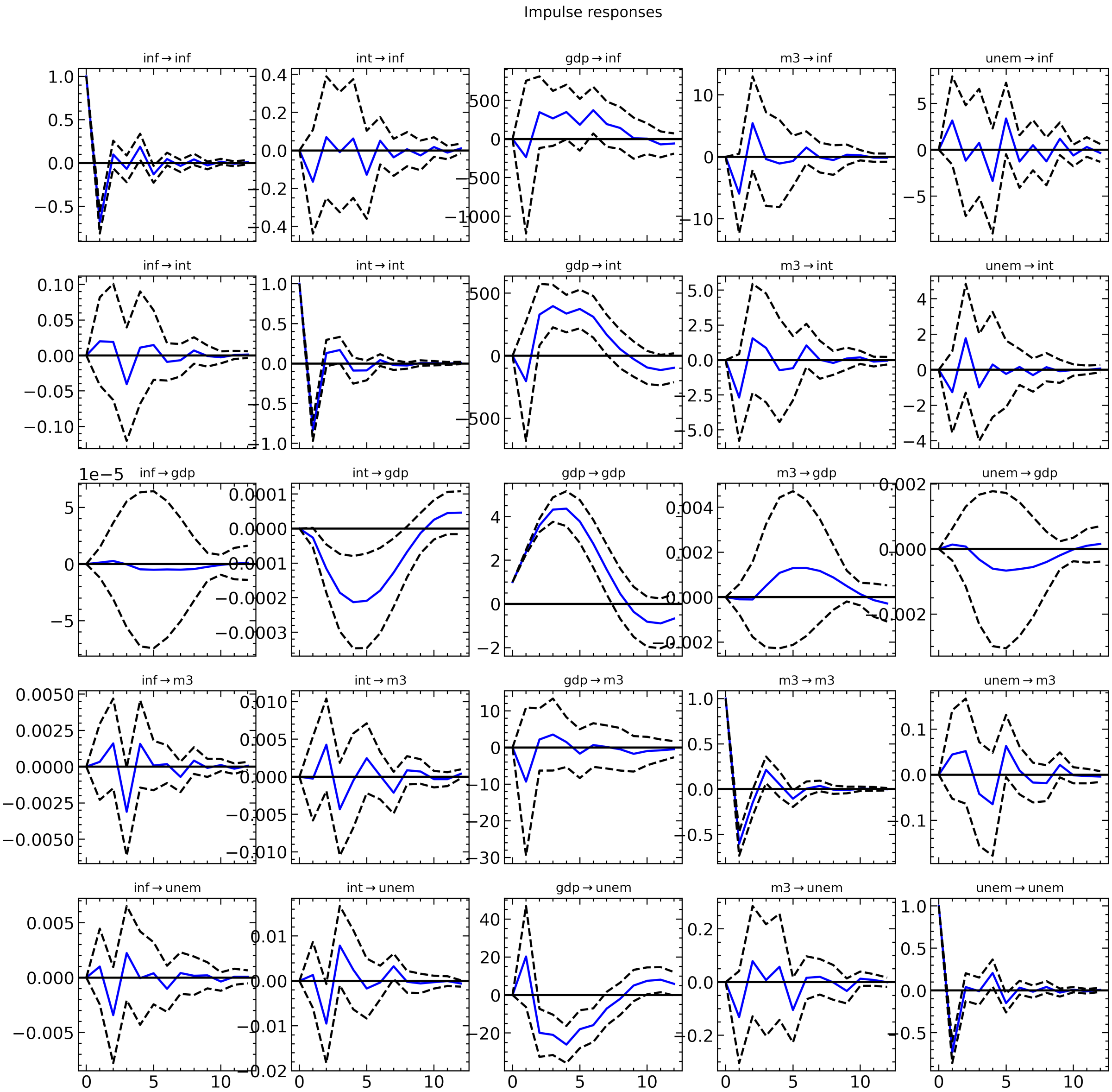


Figure 5.1: Eurozone impulse response

3. On the other hand, interest rates bounce after three to four weeks. Accordingly, the response to shocks from inflation to interest is slower than from policy rates to inflation. Interestingly, neither inflation nor short-term nominal interest rates affect each other after one year. Conversely, nominal interest rate shocks on output, GDP, clearly have a negative effect for the first nine months before flattening out at a slightly higher level. Inflation shocks, on the other hand, barely affect eurozone output, although the standard error bands are substantial.

The impulse analysis for the US are reported in 5.2 Interest rate shocks on inflation in the US appear to have a significantly more volatile effect on inflation, with an initial increase

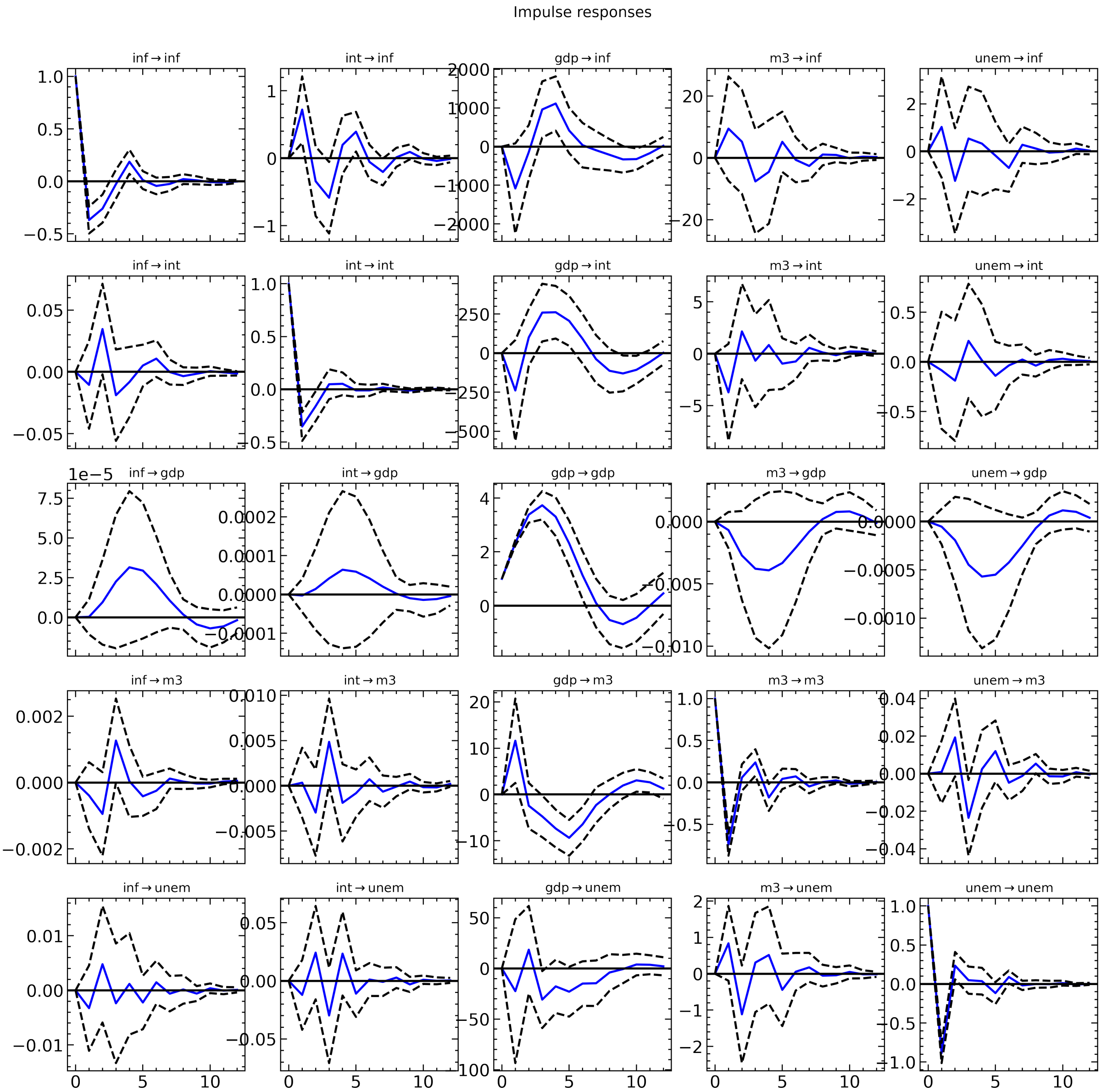


Figure 5.2: US impulse responses

after one to two months, followed by a decrease after three months, before flattening out. Moreover, inflation shocks have a similarly volatile effect on interest rates, causing interest rates to bounce with the same pattern. Even so, neither shock is able to change the variables from their initial starting point. Moreover, inflation and policy rates have an almost identical shock effect on output, with a positive increase during the first ten months before turning slightly negative, then ending on the initial level. Nevertheless, the asymptotic standard errors are large, similarly to the output in the euro area data set.

The results from the impulse response analysis build on a relatively short data set. Even so, the results indicate that neither inflation nor policy rates significantly affect the long-run path in the euro area or the US.

5.5.2 Granger Causality

The Granger-causality test used is based on the vector autoregression model. A two-way Granger-causality test was run to explore the relationship between the inflation and interest rates in the euro area and US. The test results are presented in table 5.13.

Table 5.13: Granger Causality Test

Null Hypothesis	F Statistic	P-Value	Decision
Eurozone			
Eurozone inflation does not Granger-cause eurozone interest rates	7.068*	0.008	Rejected
Eurozone interest rates does not Granger-cause eurozone inflation	3.861	0.145	Accepted
US			
US inflation does not Granger-cause US interest rate	1.101	0.348	Accepted
US interest rate does not Granger-cause US inflation	3.739*	0.011	Rejected

Note: * indicates the significance level at 5%.
Maximum lag length is specified by the Bayesian information criterion (BIC).

One null hypothesis was accepted, and one was rejected for both data sets. The test results indicates a uni-directional relationship from inflation to policy rates in the eurozone. This result can partly be explained by the ECBs primary objective, which is price stability. Conversely, the test results for US produced the exact opposite results, were there is evidence for a uni-directional relationship running from the policy rate to inflation. Even so, neither data has a bi-directional relationship, which the literature used to imply the existence of a Fisherian relationship.

6 Conclusions

Economists have long debated the relationship between inflation and interest rates. Accordingly, there is a rich literature discussing the relationship between the two variables. However, the directional relationship between inflation and policy rates is still controversial amongst many scholars. Some economists support the Fisher hypothesis, arguing that inflation is an important factor affecting interest rates. Conversely, other researchers argue that interest rates mainly influence inflation. Even so, most economists agree that there is a relationship between inflation and interest rates. This thesis aims to contribute to the literature through rigorous testing of the variables and the relationship between inflation and policy rates around the period of the GFC to examine if there has been a structural break in the relationship between inflation and interest rates in the euro area and the US. Accordingly, this study aims to analyse if there is a link between inflation and interest rates in the eurozone and EU by using structural break, unit root, cointegration and (Granger) causality tests. Finally, a stylised VAR model with an impulse response analysis was performed for illustrative purposes.

The findings from the Chow test point to a structural break in the relationship between inflation and policy rates in the eurozone at the break point specified by the Fisher-Jenks algorithm. Conversely, there is little evidence for a break in the US data. Moreover, the unit root tests, while mostly uniform in the results, had some outliers. The ADF test results indicated that eurozone inflation was stationary under both assumptions and that the eurozone interest rate was stationary under the assumption of a constant and deterministic trend. Further, the results for the PP implied that US inflation was stationary under both assumptions. Even so, the Zivot-Andrews test clearly failed to reject all level variables, suggesting that some of the variables might be non-stationary with a single structural break. While not providing definitive outcomes, this difference in unit root test results can indicate the presence of a single structural break in the time series for eurozone inflation and interest rates and US inflation.

Three cointegration tests were employed to thoroughly test whether there is a long-term relationship between inflation and policy rates. There were no statistically significant test results for the eurozone data. Conversely, two out of three tests suggested a long-term relationship between US inflation and policy rate, with the Johansen's test providing the clearest evidence for a long-term equilibrium relationship.

The Granger causality tests produced two unique sets of results. First, the test for the eurozone data suggested a uni-directional Granger causality from inflation to policy rates. The test from interest rates to inflation was not statistically significant. Conversely, the Granger causality test for the US data indicated a uni-directional Granger causality relationship from policy rates to inflation.

The uni-directional Granger causality from inflation to nominal interest rates can have implications for the ECB's monetary policy. Since inflation causes changes in policy rates in the Granger sense, policymakers should pay attention to the stability of the general price level to affect the interest rate. In the case of the Eurozone, this makes sense since the ECB's primary mandate is to control price levels. Even so, a causality from inflation to nominal interest rates can prove challenging when inflation is below target, or deflationary, as we have seen in the aftermath of the GFC. Another policy implication is the need for economic stimulus from sources other than short-term nominal interest rates, such as quantitative easing or, more importantly, fiscal stimulus, which can boost aggregate demand, or in some cases, the end of austerity for national governments in the euro area. On the contrary, the policy implications for the Fed is the opposite. On the contrary, the policy implications for the Fed are quite different from these results. For example, suppose the long-term and the uni-directional relationship between inflation and policy rates hold. In that case, the Fed can take the lead when performing expansionary or contractionary policies to either reduce or increase inflation by adjusting the policy rate according to the central bank's goals.

Finally, the stylised VAR model's impulse response analysis illustrated how shocks in inflation and policy rates affected each other over 12 months after the initial shock. The results from the eurozone data displayed the lag of one to two months (periods) between policy rates and inflation and how both variables returned to their initial positions after the respective shocks. The VAR model's impulse response analysis illustrated how shocks in inflation and policy rates affected each other over 12 months after the initial shock. The results from the eurozone data displayed the lag of one to two months (periods) between policy rates and inflation and how both variables returned to their initial positions after

the respective shocks. The US data mirrored the eurozone datas general trend, although with substantially more volatility during the first periods.

6.0.1 Limitations of the Study and Potential Future Research

This study has limitations due to the timeframe of the data. While there exist some substitutes for European data, eurozone data generally and ECB data specifically have not been available for more than 23 years. For this reason, it may be challenging to test for long-run structural relationships in time series data, especially with the possibility of considerable breaks in the data. However, some cointegration tests, like the Gregory Hansen (1996) test, could be used to test for cointegration in the presence of a single regime shift. In addition, further research on the topic could include tests that allow for one regime change for the same period to see if there is a long-term relationship in the eurozone data when adjusted for the structural break.

Examining one relationship between two significant macroeconomic variables can clarify specific aspects of their relationship. Even so, larger and more advanced models are necessary for explaining the drivers of change in the variables. Further research, for example, could include macroeconomic Bayesian or VAR models, which could be used on data before and after the break point found in this thesis to examine whether there is a regime shift and its consequences.

Unconventional monetary policies became widely adopted after the GFC when policy rates reached their zero lower bound, and central banks struggled to get inflation back to target. The ECB, especially, introduced several experimental monetary policies. However, this study does not necessarily pick up the effects of unconventional monetary policies on inflation or short-term interest directly. Consequently, there is potential for future research on the relationship between inflation and short-term nominal interest rates and other monetary policy tools such as monetary aggregates.

Inflation and policy rates have been very low for decades in Japan. In many ways, mirroring the monetary policy environment in the eurozone and US after the GFC. Some researchers (Eggertsson et al., 2019) argue that demographics play a significant role in determining the inflation rate and, consequently, policy rates. This suggests that there may be a strong and relatively unexplored relationship between inflation, nominal interest rates and demographics, which can be a good starting point for future research.

To summarise, these findings indicate that there is evidence for a change in the structural relationship between inflation and policy rates in the eurozone around the GFC. Nevertheless, the results for the US data suggest that there is evidence for a long-term relationship between inflation and policy rates and an absence of a structural break during the GFC and the Great Recession. More research is needed, however, to understand better how the relationship has been working over the past fifteen years and how it worked under other conditions before the GFC.

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Appendix

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