<table>
<thead>
<tr>
<th>Title</th>
<th>An examination of the interactions between the real and financial economy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Author(s)</td>
<td>Ashe, Sinead</td>
</tr>
<tr>
<td>Publication Date</td>
<td>2015-10-15</td>
</tr>
<tr>
<td>Item record</td>
<td><a href="http://hdl.handle.net/10379/5755">http://hdl.handle.net/10379/5755</a></td>
</tr>
</tbody>
</table>
AN EXAMINATION OF THE INTERACTIONS BETWEEN THE REAL AND FINANCIAL ECONOMY

Sinéad Ashe

October 2015

Thesis Supervisor: Dr. Srinivas Raghavendra

Department of Economics, J. E. Cairnes School of Business and Economics, National University of Ireland, Galway
# Table of Contents

*Thesis Abstract* ................................................................................................................. i  
*Declaration* ....................................................................................................................... ii  
*Acknowledgements* .......................................................................................................... iii  
*List of Tables* .................................................................................................................... iv  
*List of Figures* ................................................................................................................... v  
*Glossary of Terms* ........................................................................................................... vii  

1. **Introduction** ................................................................................................................. 1  
   1.1 Thesis Overview ............................................................................................................ 1  
   1.2 General Context .......................................................................................................... 2  
   1.3 Monetary Policy Transmission under Financialisation .............................................. 8  
   1.4 The IS Puzzle ............................................................................................................. 10  
   1.5 Criticisms of Macroeconomic Modelling .................................................................. 11  
   1.6 Thesis Structure and Research Objectives ................................................................. 12  
   1.7 Thesis Abstracts .......................................................................................................... 15  
   1.8 Thesis Outputs .......................................................................................................... 18  

2. **DSGE Models and the Great Recession** ..................................................................... 20  
   2.1 Introduction ................................................................................................................ 20  
   2.2 Theoretical Foundations of DSGE Models ................................................................. 22  
   2.3 Literature Review ....................................................................................................... 28  
   2.4 The Prototypical DSGE Model .................................................................................. 34  
   2.5 Estimating a DSGE Model using Bayesian Methods .................................................. 45  
   2.6 Description of the Data ............................................................................................. 49  
   2.7 Estimations and Results ............................................................................................ 56  
   2.8 Limitations of DSGE Models ..................................................................................... 70  
   2.9 Conclusions .............................................................................................................. 71  

3. **Empirical Properties of Macroeconomic Data** ................................................................. 73  
   3.1 Introduction ................................................................................................................ 73  
   3.2 Linear Macroeconomic Model: ARMA ................................................................. 74
3.3 Nonlinear Dependence ................................................................. 75
3.4 Testing for Independence in Macroeconomic Data ...................... 77
3.5 Discussion of Results ..................................................................... 81
3.6 Conclusions .................................................................................. 82

4. Monetary Policy Transmission in the US: A Markov Switching
   Approach.......................................................................................... 84
   4.1 Introduction................................................................................... 84
   4.2 Monetary Policy Transmission Theory ........................................ 86
   4.3 Methodology ................................................................................ 94
   4.4 Data ............................................................................................ 101
   4.5 Results ......................................................................................... 108
   4.6 Conclusions ................................................................................ 123

5. Examining the Interaction between the Business and Financial Cycle
   Using Recurrence Analysis............................................................... 124
   5.1 Introduction................................................................................... 124
   5.2 Review of the Literature.............................................................. 126
   5.3 Nonlinear Dynamics Methodology .............................................. 133
   5.4 Data and Time Delay Embedding .............................................. 146
   5.5 Estimation Results ...................................................................... 150
   5.6 Conclusions ................................................................................ 165

6. Conclusions ..................................................................................... 167
   6.1 Thesis Overview and Contribution .............................................. 167
   6.2 Limitations ................................................................................... 171
   6.3 Future Research............................................................................ 172

Appendix .............................................................................................. 173

References ......................................................................................... 191
The primary aim of this thesis is to critically examine the interactions between the real and financial economy, particularly in the context of financialisation, and its implications for the transmission of monetary policy. Understanding this interaction has never been more important, particularly given the nature of the Great Recession. While the foundations that facilitated the Great Recession were financial in nature, the macroeconomic models in use by central banks for policy analysis did not include any role for the financial economy. A number of key deficiencies have therefore emerged: firstly, there is an inadequate integration of the financial economy within macroeconomic models, particularly with regards to the role of money, credit, and asset prices. Secondly, linear macroeconomic models are inadequate to capture the regime changes arising from the dynamic interactions between the real and financial economy. Finally, given these substantive and methodological limitations, the impact of monetary policy under financialisation remains unresolved. This is particularly evident when one examines the existence of the IS puzzle within the US economy. Given these deficiencies, the first objective of this thesis is to assess the empirical properties of the prototypical macroeconomic model used by central banks and policy makers in the run up to the Great Recession. The second objective of this thesis is to examine the nonlinear empirical properties of both macroeconomic and financial variables. Within the context of the IS puzzle in the US, and arising from our analysis, the third objective is to examine the transmission of monetary policy under financialisation. Finally, the fourth objective is to study the nature of the business cycle, the financial cycle, and their interaction using nonparametric methods, with a view to informing the development of alternative macroeconomic theory and policy.
DECLARATION

I declare that the contents of this thesis are entirely my own work.

Signed

...........................

Sinéad Ashe
I would like to express my sincere thanks to my supervisor, Dr. Srinivas Raghavendra. Dr Raghavendra’s expertise in macroeconomics, along with his patience and guidance, were invaluable in the completion of this thesis. Thank you for the encouragement and advice over the last few years.

I would also like to thank all the staff at the J.E. Cairnes School of Business and Economics for all their support. In particular, I would like to thank Cian Twomey, Alan Ahearne, John McHale, Aidan Kane, Claire Noone, Imelda Howley, Eithne Murphy, Tom Boylan, and Ger Turley. I would also like to thank Milovan Krnjajic and Petri Piironen in the School of Mathematics for their many helpful comments and advice. In addition to the staff at NUI Galway, I would also like to thank my fellow PhD students, from both the Dr. Joe Higgins Room and the Hardiman Building for their friendship and support while completing this thesis.

To my parents, Marion and Pat, my brothers and sisters in-law, my nephews and nieces, and my friends: thank you always for all of your support, encouragement, help and advice.

Finally, to Paul, thank you so much for making me laugh every single day, for encouraging me when I wanted to give up, and for reminding me that it will all work out in the end. Your constant support and patience helped more than you could ever know.
LIST OF TABLES

Table 2.1 Overview of DSGE Models developed by Central Banks
Table 2.2 Log-Linearised Equations: Variables, Parameters, and Exogenous Shocks
Table 2.3 Post WWII Recessions in the United States
Table 2.4 Prior and Posterior Distribution
Table 2.5 Prior and Posterior Distributions of the Shock Processes
Table 2.6 Variance Decomposition (%)
Table 2.7 RMSE for DSGE & BVAR Models
Table 3.1 Descriptive Statistics and Selection of an ARIMA Model
Table 3.2 BDS Test for a Selection of Macroeconomic Data
Table 4.1 Augmented Dickey Fuller unit root test
Table 4.2 Results from the Linear OLS Estimation
Table 4.3 Breakpoint Model Estimation Results
Table 4.4 Summary Statistics using the Breakpoint Dates
Table 4.5 Markov Switching Estimation Results
Table 4.6 Summary Statistics in State 1(Contractionary Regime)
Table 4.7 Summary Statistics in State 2 (Expansionary Regime)
Table 5.1 Small Scale Patterns in Recurrence Plots
Table 5.2 NBER Business Cycle Dates
Table 5.3 Embedding, Time Delay, and Threshold Parameters for the Business and Financial Cycle
LIST OF FIGURES

Figure 1.1 Federal Funds Rate in the US
Figure 1.2 Year on Year Percentage Change in House Prices and the Inflation Rate
Figure 1.3 Median Usual Weekly Earnings and Personal Consumption Expenditures
Figure 1.4 Personal Savings Rate in the US
Figure 1.5 Ratio of Household Debt to Disposable Income in the US
Figure 1.6 Credit Market Borrowing by Households
Figure 1.7 The Traditional IS Curve
Figure 1.8 The IS Puzzle in the US
Figure 1.9 Thesis Structure
Figure 2.1 The Basic Structure of DSGE Models
Figure 2.2 Year on Year Percentage Change in Real GDP
Figure 2.3 Year on Year Percentage Change in Personal Consumption Expenditure
Figure 2.4 Year on Year Percentage Change in Fixed Private Investment
Figure 2.5 Year on Year Percentage Change in Weekly Hours Worked in the Non-Farm Business Sector
Figure 2.6 Year on Year Percentage Change in Hourly Compensation in the Non-Farm Business Sector
Figure 2.7 GDP Implicit Price Deflator
Figure 2.8 Federal Funds Rate
Figure 2.9 Historical Shock Decomposition: Output
Figure 2.10 Historical Shock Decomposition: Consumption
Figure 2.11 Historical Shock Decomposition: Investment
Figure 2.12 Historical Shock Decomposition: Federal Funds Rate
Figure 2.13 Historical Shock Decomposition: Inflation Rate
Figure 2.14 Historical Shock Decomposition: Real Wages
Figure 2.15 Historical Shock Decomposition: Hours Worked
LIST OF FIGURES (CONTINUED)

Figure 2.16  DSGE Model Forecast
Figure 2.17  BVAR and DSGE Model Forecast
Figure 4.1  Characterising the financial cycle
Figure 4.2  Year on Year Percentage Change in Real GDP
Figure 4.3  The Estimated Output Gap
Figure 4.4  The Ex-Ante Real Interest Rate
Figure 4.5  Year on Year Percentage Change in Real Residential Property Prices
Figure 4.6  Year on Year Percentage Change in Total Credit to the Non-Financial Private Sector
Figure 4.7  Markov Switching Regimes and Real GDP
Figure 4.8  The IS Curve for the US in a Contractionary Regime
Figure 4.9  Ratio of Household Debt to Disposable Income
Figure 4.10  Credit Supply in the US
Figure 4.11  The IS Curve for the US in an Expansionary Regime
Figure 4.12  Credit and Property Prices during the Expansionary and Contractionary Regimes
Figure 5.1  Threshold and Unthresholded Recurrence Plots of (A) Periodic Motion, (B) Uniformly Distributed White Noise and (C) the Chaotic Rössler System
Figure 5.2  An illustration of the chaotic Hénon map in different dimensions: A 1D Hénon map, a 2D Hénon map and a 3D Hénon map
Figure 5.3  Log Year on Year Percentage Change in Real GDP. This variable is used to represent the Business Cycle
Figure 5.4  Log Year on Year Percentage Change in Real House Prices. This variable is used to represent the Financial Cycle
Figure 5.5  The Threshold Recurrence Plot for the Business Cycle with an embedding parameter $m$ of 4, a time delay $\tau$ of 1, and a threshold $\epsilon$ of 0.6. The Euclidean norm is estimated.
Figure 5.6 The Unthresholded Recurrence Plot for the Business Cycle with an embedding parameter of 4 and a time delay $\tau$ of 1. The jet plot shows the distance to the next recurrence point.

Figure 5.7 Recurrence Quantification Analysis measures of the variance, recurrence rate and determinism for the Business Cycle. Window size is 24, $m$ is 4, $\tau$ is 1 and $\varepsilon$ is 0.6.

Figure 5.8 Recurrence Quantification Analysis measures of the vertical lines in the RP. This includes the maximum vertical line, laminarity and trapping time.

Figure 5.9 Measures of the complexity of the system, including the entropy and longest diagonal line in the system.

Figure 5.10 The Threshold Recurrence Plot for the Financial Cycle with an embedding parameter $m$ of 4, a time delay $\tau$ of 1, and a threshold $\varepsilon$ of 0.6. The Euclidean norm is estimated.

Figure 5.11 The Unthresholded Recurrence Plot for the Financial Cycle with an embedding parameter of 4 and a time delay $\tau$ of 1. The jet plot shows the distance to the next recurrence point.

Figure 5.12 Recurrence Quantification Analysis measures of the variance, recurrence rate and determinism for the Financial Cycle.

Figure 5.13 Recurrence Quantification Analysis measures of the vertical structures in the RP of the Financial Cycle.

Figure 5.14 Recurrence Quantification Analysis measures of the complexity of the Financial Cycle.

Figure 5.15 The Threshold Cross Recurrence Plot of the Business and Financial cycle with an embedding parameter $m$ of 4, a time delay $\tau$ of 1, and a threshold $\varepsilon$ of 0.6. The Euclidean norm is estimated.

Figure 5.16 The Unthresholded Cross Recurrence Plot of the Business and Financial cycle with an embedding parameter of 4 and a time delay $\tau$ of 1. The jet plot shows the distance to the next recurrence plot.

Figure 5.17 Cross Recurrence Quantification Analysis Measures of the Business and Financial Cycle.

Figure 5.18 Cross Recurrence Quantification Analysis Measures.
## Glossary of Terms

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>BIS</td>
<td>Bank for International Settlements</td>
</tr>
<tr>
<td>BVAR</td>
<td>Bayesian Vector Autoregressive Model</td>
</tr>
<tr>
<td>CDO</td>
<td>Collateral Debt Obligations</td>
</tr>
<tr>
<td>CRP</td>
<td>Cross Recurrence Plots</td>
</tr>
<tr>
<td>CRQA</td>
<td>Cross Recurrence Quantification Analysis</td>
</tr>
<tr>
<td>DET</td>
<td>Determinism</td>
</tr>
<tr>
<td>DJIA</td>
<td>Dow Jones Industrial Average</td>
</tr>
<tr>
<td>DSGE</td>
<td>Dynamic Stochastic General Equilibrium</td>
</tr>
<tr>
<td>ENTR</td>
<td>Entropy</td>
</tr>
<tr>
<td>FRED</td>
<td>Federal Reserve Economic Database</td>
</tr>
<tr>
<td>IID</td>
<td>Independent and Identically Distributed</td>
</tr>
<tr>
<td>IS</td>
<td>Investment Saving</td>
</tr>
<tr>
<td>LAM</td>
<td>Laminarity</td>
</tr>
<tr>
<td>LMAX</td>
<td>Longest Diagonal Line</td>
</tr>
<tr>
<td>MS</td>
<td>Markov Switching</td>
</tr>
<tr>
<td>NBER</td>
<td>National Bureau of Economic Research</td>
</tr>
<tr>
<td>NK</td>
<td>New Keynesian</td>
</tr>
<tr>
<td>NKM</td>
<td>New Keynesian Model</td>
</tr>
<tr>
<td>NNS</td>
<td>New Neoclassical Synthesis</td>
</tr>
<tr>
<td>RMSE</td>
<td>Root Mean Squared Error</td>
</tr>
<tr>
<td>RR</td>
<td>Recurrence Rate</td>
</tr>
<tr>
<td>RP</td>
<td>Recurrence Plots</td>
</tr>
<tr>
<td>RQA</td>
<td>Recurrence Quantification Analysis</td>
</tr>
<tr>
<td>RWMH</td>
<td>Random Walk Metropolis Hastings</td>
</tr>
<tr>
<td>SDR</td>
<td>Special Drawing Rights</td>
</tr>
<tr>
<td>SNA</td>
<td>System of National Accounts</td>
</tr>
<tr>
<td>TT</td>
<td>Trapping Time</td>
</tr>
<tr>
<td>VAR</td>
<td>Vector Autoregressive</td>
</tr>
<tr>
<td>VMAX</td>
<td>Maximum Vertical Line</td>
</tr>
</tbody>
</table>
CHAPTER 1

INTRODUCTION

1.1 Thesis overview

The central aim of this thesis is to critically examine and assess the complex interaction between the real and financial economy, particularly in the context of financialisation. Understanding this interaction has never been more important given the nature of the Great Recession\(^1\) of the late 2000s. This period, which represents the most severe downturn since the Great Depression, has had severe impacts on the most advanced economies in the world. Referred to by many initially as the ‘credit crunch’, the roots of the Great Recession are contained within the complex nature of the macroeconomy. Undoubtedly, the bursting of the housing bubble in the United States is the most cited cause of the Great Recession by researchers (see for example, Reinhart and Rogoff, 2009; Verick and Islam, 2010; Blanchard and Johnson, 2013). While economies the world over experience asset price booms and busts, few lead to a global recession. As outlined by Verick and Islam (2010), many warning signs of overheating were present in the US economy\(^2\): a large current account deficit, a period of unusually low interest rates, and growth in the development of financial innovation. Yet, the Great Recession came as a surprise to many.

As of 2006, the U.S. current account deficit was more than 6.5 percent of GDP (approximately $800 billion) and as money flooded into the US, many financial firms, such as Merrill Lynch, Goldman Sacs, and Lehman Brothers, saw huge increases in their profits. As such, the US financial sector, according to Reinhart and Rogoff (2009), more than doubled, from an average of 4 percent of GDP in the mid-1970s to almost 8 percent of GDP by 2007. In addition to the high levels of

---

\(^1\) The Great Recession is referred to differently in much of the literature. While, for the most part, the Great Recession is the term most commonly used, some use the term ‘Global Financial Crisis’. Reinhart and Rogoff (2009) refer to the crisis as the ‘Second Great Contraction’.

\(^2\) As stated by Verick and Islam (2010), “what started as seemingly isolated turbulence in the subprime segment of the US housing market mutated into a full blown recession by the end of 2007. The old proverbial truth that the rest of the world sneezes when the US catches a cold appeared to be vindicated as systematically important economies in the European Union and Japan collectively entered into recession by mid-2008”
borrowing being undertaken in the US, house prices were rising significantly. This rise in house prices coincides with increases in the ratio of household debt to GDP and a record low personal savings rate. Central to this was the role of financial innovation and misperceptions of risk as a result of the Great Moderation period. Alan Greenspan, in his October 2005 speech to the National Association for Business Economics, stated that the “…development of financial products, such as asset-backed securities, collateral loan obligations, and credit default swaps, that facilitate the dispersion of risk…These increasingly complex financial instruments have contributed to a far more flexible, efficient, and hence resilient financial system than the one that existed just a quarter-century ago” (as quoted in Bezemer, 2009).

While the foundations that facilitated the Great Recession were financial in nature, the macroeconomic models in use by central banks for policy analysis did not include any role for the financial economy. The Keynesian tradition regarding the role of the financial economy in the business cycle was built on real-side variables such as output and employment as a result of Keynes General Theory and the Hicks-Samuelson multiplier-accelerator analysis. Within this system, financial variables such as money and the interest rate entered passively though a two asset financial market, where the complexities of the financial system were omitted. As such, little financial detail was incorporated in the traditional macroeconomic framework (Sinai, 1992). The following section outlines in more detail the Great Recession and the general context within which this thesis works.

1.2 General Context

According to Baily et al. (2008) the origin of the crisis lies in “…an asset price bubble that interacted with new kinds of financial innovation that masked risk…”. This was combined with lax lending conditions by financial institutions and poor risk management strategies (Verick and Islam, 2010). The financial crisis was largely unanticipated by policymakers, academics and investors alike, who perceived the economy to be in a period of low volatility. This period of low volatility, also known as the ‘Great Moderation’, was attributed to structural changes and improved macroeconomic policies (Bernanke 2004).

Prior to the Great Recession, the housing market had been a key driver in the recovery of the US economy after the bursting of the 2001 dot-com bubble. The
bursting of this housing bubble was also the trigger for the financial crisis that ensued during the Great Recession. With the bursting of the dotcom bubble in 2001, the Federal Reserve began aggressively reducing the nominal interest rate from over 6 percent in 2001, to just 1 percent in 2003, as illustrated in Figure 1.1 below. In doing so, it ensured that the 2001 recession was both short-lived and shallow, but also laid the foundations for the 2008-2009 Great Recession (Verick & Islam, 2010). This loose monetary policy contributed to rapid growth in asset prices, as well as mortgages to less creditworthy borrowers.

![Source: Federal Reserve Economic Databank](image)

**Figure 1.1 Federal Funds Rate in the US**

Historically, house prices move at approximately the same rate as inflation, Baker (2008). Between 1997 and 2007, house prices had risen 50 percent while inflation remained relatively stable, as illustrated in Figure 1.2 below. This housing market bubble fuelled the economy in two ways; firstly by providing employment in the housing related sectors (for example, the construction industry, mortgage lending practices, etc.), and secondly through wealth effects for household consumption.
As house prices continued to rise, households utilised this increase in their equity by borrowing to fund their consumption. While consumption levels increased significantly, real wages remained stagnant, as illustrated in Figure 1.3. Over the period 2001 – 2007, there was modest growth in household income. Household consumption, on the other hand, continued to grow, as the personal savings rate declined as illustrated in Figure 1.4. This shows that, between 1995 and 2005, the personal saving rate of households fell from a peak of 6.1 percent to a low of 1.3 percent, indicating that consumption was increasing faster than income. The amount of consumer and mortgage loans increased significantly in the US in the run up to the boom with a very low interest rate environment and house price appreciation contributing to an increase in the mortgage refinancing behaviour of households.

So what was driving consumption if household income was remaining steady? Consumption was instead being financed by household equity from rising house prices. Homeowners were borrowing against the rising value of their home to finance their consumption.
An increase in leveraging in the US began in the 1980’s when the use of credit cards and home equity lines of credit became available. By 2000, household debt had increased to 90 percent of disposable income. This figure would rise to 138 percent by 2007, as illustrated in Figure 1.5 below.
According to Bauer & Nash (2012), this significant increase in household debt came from increases in mortgage liability. As a result, increases in house prices coupled with attainable mortgage financing caused a surge in the uptake of housing. Credit innovation allowed for less attractive mortgage candidates to enter the market and as mortgage debt soared (as illustrated in Figure 1.6 below), household net worth was also increasing as a result of rising house prices and stock market gains, producing a household wealth effect which fuelled consumer spending.

**Figure 1.5: Ratio of Household Debt to Disposable Income in the US**

**Figure 1.6: Credit Market Borrowing by Households**
Borrowers were under the impression that since house prices were increasing by 10 to 20 percent per year, the price of their house would have increased enough to allow them to re-finance the loan. The loan to value ratio would then decline to approximately 80 percent and homeowners could re-negotiate the terms of their mortgage. As a result, there was a severe underestimation of risk. This underestimation of risk was coupled with loose monetary policy: low interest rates allowed lenders to target riskier segments of the market, i.e. subprime and alt-A loans. These risky ‘subprime’ loans were repackaged as mortgage-backed securities and sold as financial instruments. This allowed lenders to remove ‘subprime’ risky loans from their balance sheet, and acquire additional leverage in doing so. By 2004/2005, there was a marked deterioration in lending standards. Households, who under normal circumstances would not be able to secure a loan, were taking out mortgages which had a high loan to value ratio. This loan to value ratio would be as high as 100 percent. This implies that households had no initial equity in their asset. Given the riskiness of these borrowers, interest rates would be higher than normal. However, ‘teaser’ interest rates were introduced, which meant that initial mortgage repayments would be low for two or three years and would then revert to a higher monthly amount.

House price declines beginning in 2006 caused a sharp drop in household net worth and in the value of debt backed by households (Krainer, 2012). The 2012 IMF report ‘Dealing with Household Debt’ found that, in advanced economies, housing busts and recessions tend to be more pronounced and protracted when they are preceded by larger run ups in household debt. The increase in household leverage, coupled with reductions in house prices, meant that households had very high levels of debt relative to their assets. Once the Federal Reserve began increasing interest rates, delinquency rates on home loans began to rise, as subprime borrowers struggled to meet mortgage repayments (Astley et al., 2009). The housing market began to unravel, and this unravelling was further aggravated by the complex nature of financial innovation. The complexity of financial innovation meant this was not a domestic problem, but a global one, and financial institutions were struggling to assess their true exposure to these losses. In the mean time, liquidity began to dry up,

\[\text{Alt-A loans or Alternative A-Paper is a loan which, for a variety of reasons, has a risk potential that is greater than prime loans.}\]
and lending came to a stand still. The culmination of these events caused the US economy to enter recession in December 2007.

The ratio of household debt to disposable income fell significantly during the 2007-2009 period in the US as households defaulted on loans, paid down debt and reduced their uptake of new loans. This deleveraging effect may be constraining consumer spending, which is contributing to a decline in overall economic activity. Mian et al. (2011) and Dynan (2012) find that the decline in consumption is more severe when a household has a highly leveraged balance sheet. This implies that the role of debt accumulation is important in understanding the consumption collapse of the Great Recession. In order to deleverage their balance sheet, the household can either default on their repayments or they can begin active repayments of the debt principal. Since defaulting is costly, a household is likely to cut back heavily on consumption and to forego a substantial fraction of their savings. A report by McKinsey (2012) found that the US has the highest rate of deleveraging, with 66 percent of the debt reduction reflecting default.

1.3 Monetary Policy Transmission under Financialisation

The three-equation New Keynesian Model (NKM) has become a standard tool used in the analysis of monetary macroeconomics (Carlin and Soskice, 2005) and is used by several highly influential macroeconomists as the basis for their macroeconomic modelling (see for example, Woodford, 2003; Clarida, Gali and Gertler, 1999; Goodfriend and King, 1997). The NKM typically consists of a Phillips curve that determines inflation, an IS curve that determines the level of output, and a monetary policy rule that determines the short term interest rate set by the central bank or the monetary authority.

A key component of this canonical model is the IS curve which describes the transmission of monetary policy to the real economy. A simple illustration of the IS curve is provided in Figure 1.7 below. The slope of the IS curve indicates how a change in the real interest rate affects output.
The interest rate channel is the main monetary policy transmission mechanism for the standard Keynesian IS-LM model of Hicks (1937). According to this interest rate channel, an inverse relationship exists between the real interest rate and aggregate demand, as illustrated in Figure 1.7 above where the IS curve is downward sloping. Expansionary monetary policy leads to a fall in the nominal interest rate that translates into a fall in the real interest rate. This lowers the cost of capital, thereby causing a rise in investment and consumption spending, which leads to an increase in aggregate demand (Mishkin, 1996). This mechanism is contained within the conventional ‘IS’ curve of the IS-LM model. In addition to its inclusion within the standard IS-LM model, this interest rate channel also lies at the heart of more recent prominent New Keynesian DSGE models where the short-term interest rate is sufficient to model the monetary side of the economy (Goodhart and Hofmann, 2008).

Given the nature of the Great Recession, however, how does one reconcile the interest rate as the main channel of monetary policy transmission? There is a separate branch of research that suggests monetary policy has a diminishing impact on the real economy. For example Goodhart and Hofmann (2005) suggest an ‘IS puzzle’ exists. This IS puzzle implies that central banks cannot stabilize the real economy. In their study of monetary policy transmission in G7 economies, the

---

4 Examples of these New Keynesian DSGE models include Smets and Wouters (2003, 2007); Christiano et al. (2005); in addition to a wide variety of DSGE models for Central Banks including the Bank of England, Federal Reserve, the ECB, the Bank of Japan and so on.
10 authors find that the standard specification of the IS curve is insufficient to capture the effects of the interest rate on aggregate demand. As such, a broader framework that can account for the demand effects of other variables, especially property prices, is suggested as an improvement upon the current framework.

1.4 The IS Puzzle

To examine this IS puzzle in more detail, Figure 1.8 below illustrates the IS curve in the US using the real interest rate (adjusted for price inflation) and output. As shown, the IS curve is clearly *upward* sloping. That is, a positive, rather than negative relationship exists. This evidence clearly shows that, in the US, monetary policy transmission under financialisation is ineffective in stabilising the real economy. In addition to the real interest rate, policy-makers must also examine and include in their analysis, additional features that are pertinent to the real economy.

Take for example the role of house price increase in the US in the run up to the Great Recession. As stated in section 1.2, house prices increases and access to credit helped to fuel consumption in the US, as household income remained stagnant.

Source: Federal Reserve Economic Databank

Figure 1.8: The IS Puzzle in the US
Given this, it is suggested that an increase in asset prices (for example, through increases in property price income), results in positive wealth effects for households as the value of their asset (house) increases. This increase in house prices, which is treated as collateral within mortgage markets, thereby allows consumers to access additional credit, and therefore accumulate additional debt from banks, to fund their consumption. In this case, regardless of the real interest rate, output expands as result of consumption demand arising from house (asset) price increase. Thus, under financialisation, tighter monetary policy may not be effective in restraining consumption led expansion, and is suggested as one reason for the existence of this IS puzzle. There is currently, however, little consensus within the literature on the interaction of the financial economy and financial imbalances, within the study of the transmission of monetary policy. Given this limitation, one objective of this thesis is to critically examine the transmission of monetary policy in the US under financialisation.

1.5 Criticisms of Macroeconomic Modelling

Given the severity of the Great Recession, macroeconomic theory, macroeconomic modelling, and economic forecasting have been subject to intense scrutiny. Much of this criticism is centred on developments in macroeconomic modelling over the last 30 years, a period that coincides with the development and use of the dynamic stochastic general equilibrium (DSGE) models by policy makers. Among the most critical were Willem Buiter (2009), who states that graduates of macroeconomics and monetary economics over the past 30 years “... may have set back by decades serious investigations of aggregate economic behaviour and economic policy-relevant understanding” and Paul Krugman (2009), who outlined three problems of DSGE models that make them unsuitable for crisis periods. Firstly, they’re ‘unwieldy’ and difficult to explain to non-economists. Secondly, they assume the data we see comes from a regular process of random shocks, with strong incentives for the modeller to assume the shocks are normally distributed. Finally, the desire to make them tractable tends to favour linearity, or at least models that can be estimated in terms of linear approximations, which according to Krugman, is not a modelling style that leaves one ready to deal with sudden financial crisis, which may involve

---

3 A simple theoretical model is provided in Appendix A1 of this thesis which addresses why this IS puzzle may arise.
multiple equilibria and, at the very least, involves regime change in which the effects of a given policy or shock may suddenly become quite different.

In addition to the problems suggested by Krugman (2009), Bill White (2010), in his lecture on “Some Alternative Perspectives on Macroeconomic Theory and Some Policy Implications” stated that “the prevailing macroeconomic frameworks simply allowed no room for crises of the sort we are currently experiencing....Absent an analytical framework that included the possibility of crises and deep economic slumps, it is not surprising that the crisis was not commonly anticipated. Nor is it surprising that no policy efforts were made to prevent the crisis from happening”. White (2010), therefore, argues that a new analytical synthesis is required. The following would need to be incorporated into the new synthesis: an increased focus on credit, a focus on stocks rather than flows (balance sheets), the possibility of stock “imbalances” (in particular, excessive levels of debt), and finally, allowing for the process of transition from periods of stability to crisis periods.

A number of key deficiencies therefore emerge: firstly, there is an inadequate integration of the financial economy within macroeconomic models, particularly with regards to the role of money, credit, and asset prices. Secondly, linear macroeconomic models are inadequate to capture the regime changes arising from the dynamic interactions between the real and financial economy. Finally, given these substantive and methodological limitations, the impact of monetary policy under financialisation remains unresolved. This is particularly evident when one examines the existence of the IS puzzle within the US economy.

1.6 Thesis Structure and Research Objectives

This thesis is presented in monograph style and contain six interlinked chapters. Chapter 1 (Introduction) provides the general context, motivation, and research objectives for this thesis. From this, the kernel of the thesis is presented in four empirically linked chapters with the conclusions from each chapter informing the objectives of the next. An illustration of this is provided in Figure 1.9 below.
Figure 1.9: Thesis Structure

The research objective of Chapter 2 is to critically assess the empirical properties of the prototypical macroeconomic model used by central banks and policy makers in the run up to the Great Recession. From this, two central conclusions are obtained: one methodological conclusion and one substantive conclusion. Given this, Chapter 3 of this thesis deals with the methodological conclusion of Chapter 2, which is to examine the nonlinear properties of both macroeconomic and financial variables. To examine the substantive conclusion of Chapter 2, and given the findings of Chapter 3, the objective of Chapter 4 is to examine the transmission mechanism of monetary policy under financialisation. This objective is achieved in two ways: firstly, by introducing the financial economy through the incorporation of house prices and credit, and secondly by modelling the nonlinear transmission of monetary policy that can arise as a result of the interaction between the real and financial economy. Our findings in Chapter 4 indicate that the asymmetric impact of monetary policy is due to the nonlinear interaction between the real and financial economy. However, the nature of the nonlinearity driving this asymmetric impact still needs to be examined. As a result, the objective of Chapter 5 is to study the nature of the business cycle, the
financial cycle, and their interaction using nonparametric methods, with a view to informing the development of alternative macroeconomic theory and policy.

As a result, there are four research objectives for this thesis:

1. The first objective of this thesis is to assess the empirical properties of the prototypical macroeconomic model used by central banks and policy makers in the run up to the Great Recession. Since the benchmark macroeconomic policy model in use today is the Dynamic Stochastic General Equilibrium model, Chapter 2 of this thesis undertakes a critical examination of its output.

2. The second objective of this thesis is to examine the nonlinear properties of both macroeconomic and financial variables.

3. In the context of the IS puzzle in the US, and arising from the analysis of the previous chapters, the third objective is to examine the transmission mechanism of monetary policy under financialisation. This objective is achieved in two ways: (i) by introducing the financial economy through the incorporation of house prices and credit, and (ii) by modelling the nonlinear transmission of monetary policy that can arise as a result of the interaction between the real and financial economy.

4. In Chapter 4, we established that the asymmetric impact of monetary policy is due to the nonlinear interaction between the real and financial economy. However, the nature of the nonlinearity driving this asymmetric impact still needs to be examined. Thus, the fourth objective is to study the nature of the business cycle, the financial cycle, and their interaction using nonparametric methods, with a view to informing the development of alternative macroeconomic theory and policy.

In the context of the above research objectives, the Central Research Question is:

*To critically examine the interactions between the real and financial economy, particularly in the context of financialisation, and its implications for the transmission of monetary policy*
1.7 Thesis Abstracts

Given the stated central research question, an abstract from each of the four empirical chapters of this thesis are provided below.

**CHAPTER 2: DSGE MODELS AND THE GREAT RECESSION**

**ABSTRACT**

The objective of this chapter is to assess the empirical properties of the prototypical macroeconomic model used by central banks and policy makers in the run up to the Great Recession. The global financial crisis has sparked renewed debate over the state of macroeconomic modeling, particularly in the lead up to the Great Recession. The standard workhorse of macroeconomic modeling, the Dynamic Stochastic General Equilibrium (DSGE) model, has been subject to intensive scrutiny. Over the past decade, there has been a significant increase in the use of DSGE models by central banks for policy analysis and forecasting. The majority of central banks from developed countries have established DSGE models, including the Federal Reserve Bank, the European Central Bank, the IMF, and the Bank of England. Given their prevalence among central banks coupled with their use by policy makers for analysis and forecasting, we assess the typical output produced by these DSGE models in the run up to a financial crisis. A DSGE model is therefore estimated for the United States for the pre-crisis period 1947Q1 to 2007Q4. We find the DSGE model of Smets and Wouters (2007) does not provide any indication that a downturn is imminent. Given that there is no role for the financial economy, we suggest that the building blocks of DSGE models are too simplistic to effectively model key dynamics within the economy. We use the role of debt accumulation by US households as a means of illustrating this.
CHAPTER 3: EMPIRICAL PROPERTIES OF MACROECONOMIC DATA

ABSTRACT
Since the dynamics between the real and financial economy can create regime changes, the objective of this chapter is to examine the nonlinear empirical properties of both macroeconomic and financial variables. The assumption of linearity is tested using the BDS test for a range of macroeconomic and financial variables in the US. The most parsimonious linear model was fitted to the data to remove any linear structure. The BDS test was then performed on the residuals of the linear model. The evidence rejects the assumption of i.i.d. for all variables considered, with the exception of investment data, and finds evidence of nonlinear dependence within the data.

CHAPTER 4: MONETARY POLICY TRANSMISSION IN THE US: A MARKOV SWITCHING APPROACH

ABSTRACT
The objective of this chapter is to examine the transmission mechanism of monetary policy under financialisation, particularly in light of the existence of the IS puzzle in the US. Within the current suite of popular macroeconomic models, the risk free short-term interest rate is sufficient to model the monetary side of the economy (Goodhart and Hofmann, 2008). As such, money, credit and asset prices do not interact within the standard versions of these models. The suitability of these models comes under criticism when one considers the financial boom and subsequent bust phases experienced within the United States. Given this, we firstly examine the extent to which changes in the US financial economy have impacted upon the transmission of monetary policy by incorporating a role for the financial economy in the form of property prices and credit. Secondly, we examine if monetary policy has asymmetric effects: that is, does monetary policy have a bigger impact during expansions or recessions. Using the Markov switching model of Hamilton (1989), the analysis shows that financial variables are important determinants of aggregate demand within the economy. Additionally, the results of the Markov switching model indicate that monetary policy is asymmetric in the US. During an
expansionary regime, monetary policy has no influence on aggregate demand. Instead, aggregate demand is driven by credit to the non-financial private sector. However, during the contractionary regime, all variables included in the estimation (output gap, the real interest rate, real residential property prices and total credit to the non-financial private sector) become statistically significant and are correctly signed.

CHAPTER 5: EXAMINING THE INTERACTIONS BETWEEN THE BUSINESS AND FINANCIAL CYCLE USING RECURRENCE ANALYSIS

ABSTRACT

The objective of this chapter is to examine the nature of the business cycle, the financial cycle, and their interaction using nonparametric methods, with a view to informing the development of alternative macroeconomic theory and policy. This objective is achieved through the use of recurrence plots (RPs) and recurrence quantification analysis (RQA), which are nonlinear dynamic techniques. Although there are several methodologies prevalent in the literature to achieve this objective, these models typically rely on linear techniques and therefore have limited capacity to detect and characterise nonlinearities, such as regime changes inherent in a system as complex as the macroeconomy. Given the importance of the financial economy to the propagation of the business cycle, recurrence analysis (recurrence plots and recurrence quantification analysis) is used to observe the key features present in both cycles to aid understanding of the complex macroeconomic system. Additionally, the interaction between the business and financial cycle is undertaken to determine their convergence and synchronicity. To our knowledge, this is the first study to use recurrence analysis to examine the characteristics of the business cycle, financial cycle, and their interactions. Overall, the results of this study indicate the complexity of the macroeconomic system and the importance of the financial economy to the real economy. The results indicate that a possible lead-lag relationship exists between the two cycles, with the financial cycle leading the business cycle which can have important implications for the business cycle. The importance of reconsidering the complexity that exists in financial and macroeconomic variables should be addressed and carefully included in the modelling of the macroeconomy. These
features should be considered carefully by policymakers regarding their decisions on policy.

1.8 Thesis Outputs

The outputs from this thesis are discussed below. Regarding journal submission, three papers will be submitted to academic journals and are based on edited versions of each of the chapters of this thesis. In addition to journal submissions, details on conference presentations are also provided.

**Papers**

Each chapter of this thesis will be submitted as separate papers to economic journals. Chapter two, titled “DSGE Models and the Great Recession” will be submitted to *Applied Economic Letters*. Chapter four, titled “Monetary Policy Transmission in the US: A Markov Switching Approach”, will be submitted to the *International Review of Applied Economics*. Finally, chapter five, titled “Examining the Interaction between the Business and Financial Cycle using Recurrence Analysis” will be submitted to *Macroeconomic Dynamics*. In addition to these three papers, two NUI Galway working papers have been submitted based on the work completed during this thesis. These include “Assessing the Empirical Performance of DSGE Models during the Great Recession”, and “Nonlinear Dynamics in Macroeconomic Time Series”.

**Conferences**

- NUIG, PhD Student Seminars, ‘A DSGE Model for Ireland’, May 2013
• Multidisciplinary workshop on visualization and analysis, NUIG, “Money in a Prototypical DSGE Model’, April 23rd and 24th 2014

CHAPTER 2
DSGE MODELS AND THE GREAT RECESSION

2.1 Introduction
The objective of this chapter is to assess the empirical properties of the prototypical macroeconomic model used by central banks and policy makers in the run up to the Great Recession. The global financial crisis has sparked a renewed debate over the state of macroeconomic modelling. This crisis led to the simultaneous decline of almost every asset category, allowing investors to be adversely exposed across a wide variety of investments and asset classes. Global per capita output also saw the biggest contraction the world had experienced since World War II. According to the National Bureau of Economic Research (NBER), the US recession began in December 2007 and ended in June 2009, therefore lasting 18 months in total and representing the longest recession in US history since World War II (which lasted 43 months). National unemployment, which was 5 percent in December 2007, rose to 9.5 percent by June 2009, and the decline in employment was greater than any recession in recent decades (Bureau of Labor Statistics, 2012). Real GDP growth declined 4.06 percent by June 2009 and real personal consumption expenditure growth moved from a peak of 3.29 percent in December 2006 to a decline of 2.69 percent by June 2009. The standard workhorse of macroeconomic modelling adopted by the most influential central banks across the world, the DSGE model, has been subject to particularly intense scrutiny for its non-detection of many of the warning signs of crisis periods.

Over the past three decades, there has been significant increase in the use of DSGE models by central banks and monetary authorities for policy analysis, forecasting and prescriptions. The majority of central banks from both developed and emerging economies have established DSGE models. This includes, for example, the Federal Reserve Bank’s “SIGMA” model\(^6\) which is used for policy analysis, the European

\(^6\) For an overview of the Fed’s “SIGMA” model see Erceg et al 2006.
Central Bank’s “NAWM” model\(^7\) which is used for ‘broad macroeconomic projection exercises’ and the Bank of England’s “COMPASS” model\(^8\) which is used as “the main organising framework for the construction of the forecast; to analyse and explain the forecast; and to assess the sensitivity of the forecast to alternative assumptions”. Given the prevalence of DSGE models among central banks, one must consider why they have become so popular. Despite widespread criticism after the financial crisis (see for example, Goodhart and Tsomocos, 2011; Borio, 2012; Krugman, 2009; and Buiter, 2009), DSGE models are still being used to identify important sources of fluctuations, perform counterfactual experiments, to forecast and predict the effects of policy changes and to answer questions about structural change within the economy (Tovar, 2008).

Given the objective of this chapter, the performance of the DSGE model using data up to 2007Q4 is assessed by examining the typical output produced by the model and their forecasts. These forecasts are then evaluated on an absolute basis by comparing them with the observed data. The results of this exercise show that the forecasting performance of the DSGE model in the run up to the 2008-2009 crisis was poor. The relative performance of the DSGE model is examined by computing forecasts made by a Bayesian VAR (BVAR) model using the same dataset over the same period. The results indicate that the BVAR model does a better job in predicting an economic downturn, however only marginally. This is verified by the calculation of the root mean squared errors (RMSE) for the two models. Additionally, this analysis indicates that monetary policy shocks within the model do not appear to be an important source of business cycle fluctuation. Price and wage mark up shocks are the main drivers of fluctuations in inflation, the interest rate and the real wage, while consumption and investment fluctuations are driven primarily by risk premium and investment specific shocks respectfully. Given these results, this chapter suggests that the foundations upon which DSGE models are built are too limited to cope with crisis periods. Given the financial nature of the Great Recession, the exclusion of financial frictions within the baseline model meant that key fundamentals within the economy were not incorporated into the model. As such,

\(^7\) The ECB’s New Area Wide-Model or the “NAWM” is described by Christoffel et al 2008

\(^8\) In 2011, the Bank of England adopted a new central organizing model, COMPASS, to assist with the production of forecasts presented by the Monetary Policy Committee (MPC). Burges et al 2013 provide an overview of this model.
their impact on the real economy could not be assessed. Evidence of this is provided by examining the role of debt accumulation by households in the run up to the Great Recession.

The overall conclusion from the estimations of this chapter is that the building blocks of DSGE models are too simplistic to effectively model key dynamics within the economy, mainly due to the absence of financial frictions in the model.

2.2 Theoretical Foundations of DSGE Models

In the following section, the macroeconomic theory underlying DSGE models is outlined in addition to a non-technical outline of the foundations of DSGE models.

2.2.1 Macroeconomic Theory underlying DSGE models

The 1970s represents a period of great change in macroeconomics, and as stated by Blanchard (2008), marks the emergence of three alternative groups, or views, of macroeconomics. These are the New-Classical, the New-Keynesian, and the New Neoclassical Synthesis (NNS).

**New Classical Approach**

As noted widely in the literature, the impetus for the New Classical paradigm was due to the failure of Keynesian economists to predict the period of stagflation in the US economy during the 1960s. This acceleration of inflation is said to have discredited the Phillips curve, which represented a key concept of the neoclassical synthesis. According to Friedman and Phelps (1968) and later Lucas and Sargent (1979), the Phillips curve was fundamentally flawed and widely incorrect. As an alternative, Lucas and Sargent (1979) proposed the movement to an alternative branch of macroeconomics: the New Classical approach. The New Classical approach relies on several fundamental concepts: it is built on microeconomic foundations, within a general equilibrium framework, with the inclusion of rational expectations by Lucas (1972). The rational expectations hypothesis was developed by Muth (1961) and later applied to macroeconomics by Lucas (1972). The concept implies that agents use publicly available information in an efficient manner and that agents fully understand the structure of the economy. They, therefore, base their expectations of variables on this knowledge and make no mistakes when formulating
their expectations. The inclusion of rational expectations had one particularly major implication for macroeconomic models: the Lucas critique. The Lucas critique implied that the current macroeconomic models could not be used to design policy, since they did not incorporate expectations explicitly. Rather, these macroeconomic models were formulated using current and past values of variables (including policy variables). Lucas argued that, should these policies change, the way people form expectations would also change, making existing macroeconometric models poor guides of what would happen under new policies.

In addition to rational expectations, the New-Classical economists wanted macroeconomic models that were built on microeconomic foundations within a general equilibrium framework. Within this framework, all agents optimised their utility subject to some constraint in a market that always clears, thereby yielding a structural model of equations (McCallum, 1989). Additionally, central to the New Classical approach to macroeconomics, was the movement away from monetary business cycle theory towards the Real Business Cycle theory of Kydland and Prescott (1982) and Long and Plosser (1983). The Real Business Cycle (RBC) model involved the demotion of nominal rigidities, money, and the Phillips curve. As such, the RBC model assumes that money in the economy is neutral, even in the short term. Monetary policy is therefore assumed to have no impact on real activity. Instead, RBC theorists believe money supply is endogenous within the model.

In addition to the neutrality of money assumption within the New Classical paradigm, fluctuations in the economy are assumed to arise due the effects of technological shocks in competitive markets with fully flexible prices and wages. These technological shocks are assumed to cause fluctuations in output and employment: output and employment fall during recessions because the available production technology deteriorates, thereby lowering output and reducing the incentive to work, (Mankiw, 2013). As such, recessions within the New Classical paradigm, are as a result of technological regress. While this paradigm was criticised
heavily, it would represent the main macroeconomic agenda over the 1970s and 1980s.

**New-Keynesian Approach**

A separate branch of macroeconomic theory, New Keynesian macroeconomics, disagreed with the New Classical paradigm over several of their key assumptions, most notably, with regards to their treatment of prices and wages. Within the New Classical paradigm, wages and prices are flexible and prices clear markets by quickly adjusting supply and demand. As such, New Classical economists believe that the market imperfection of sticky prices and wages is not important in understanding economic fluctuations (Mankiw, 2013). However, New Keynesian’s believe that this market clearing behaviour cannot explain short-run fluctuations in the economy. Instead, wages and prices are sticky and this stickiness has implications for unemployment and monetary policy. Once it is assumed that prices are inflexible, then all markets will not clear instantly and aggregate output may be below what would be obtained when prices are flexible. As a result of sticky prices, an increase in the money supply can cause a short-run increase in real spending, and therefore an increase in real output (Whelan, 2005). Additionally, according to Goodfriend and King (1997), New Keynesian economists have stressed that imperfect competition can have important implications for the effects of money on output in the real economy, if there is price and wage stickiness, by impacting upon firms marginal costs and real wages.

This work on price and wage stickiness represented the first generation of New Keynesian models by Gordon (1981) and Taylor (1980) who incorporated a gradual price equation and a rational expectations approach to wage setting, respectively, within the general New Keynesian framework. New Keynesian economists began to build on work by Fischer (1977a), and Phelps and Taylor (1977) which focused on research that attempted to build on the microeconomic foundations of this price and

---

9 Several criticisms of this approach have been outlined in the literature, with most criticizing that assumption that wages and prices are flexible, that technology shocks represent the main sources of economic fluctuations, and that money is neutral

10 Prices are assumed to be sticky in the New Keynesian model due to menu costs, which means firms only intermittently adjust their prices. Additionally, overlapping staggered contracts are included within the New Keynesian model which limits the flexibility of wages. These factors are referred to as nominal rigidities.
wage stickiness (Gordon, 1990), as well as providing the microfoundations to incorporate the inefficiency of aggregate fluctuations, and the non-neutrality of money (Gali and Gerlter, 2007). As such, the New Keynesian approach includes the concepts of rational expectations as well as the assumptions that agents maximise their utility.

*New Neoclassical Synthesis (NNS) Approach*

The NSS, which is first introduced by Samuelson (1955), incorporates elements from both the Classical and Keynesian perspective into a single framework. It builds on the core RBC model to provide an understanding of fluctuations in employment and inflation and a framework for thinking about monetary policy. The NNS is defined by two central elements: Firstly, it builds on the New Classical macroeconomics and RBC analysis by incorporating intertemporal optimization and rational expectations within dynamic macroeconomic models. Secondly, it builds on New Keynesian macroeconomics by incorporating imperfect competition and costly price adjustment. Like the RBC model, it seeks to develop quantitative models of economic fluctuations.

According to Goodfriend and King (1997), the NNS suggests a set of major conclusions about the role of monetary policy. Firstly, unlike the New Classical theorists, NNS models suggest that monetary policy actions can have an important effect on real economic activity. Monetary policy actions can lead to a gradual adjustment of individual prices and the general price level, thereby having a persistent impact on the economy. Secondly, NNS models suggest that significant gains can be achieved from eliminating inflation, which stems from increased transactions efficiency and reduced relative price distortions. Finally, NNS models imply that credibility plays an important role in understanding the effects of monetary policy. The NNS has been applied widely in research on monetary policy, including research by Clarida, Gali, and Gertler (1999), Woodford (2003), Gali and Gerlter (2007), and Gali (2008).

This NNS theory underlies the prototypical macroeconomic model used by central banks all over the world, and it is the central model used to examine the sources and
consequences of economic fluctuations. This model is called the Dynamic Stochastic General Equilibrium (DSGE) model.

2.2.2 Structure of DSGE Models

DSGE models are intertemporal macroeconomic models built from microeconomic foundations. The dynamic element of the DSGE model comes from the inclusion of explicit time within the model. The stochastic element is in the form of random variables within the model. Finally, the model is said to be a general equilibrium model since it is assumed to describe the behaviour of the entire economy, rather than just parts of the economy (Gordon, 2012). Within these models, macroeconomic fluctuations occur as a result of exogenous shock processes that cause perturbations to the economy. In addition to exogenous shocks, nominal rigidities are also present in DSGE models to reflect key underlying features of the data. For example, to address the real effects of monetary policy shocks, nominal price rigidities are introduced.

Figure 2.1 below illustrates the key building blocks of a DSGE model, and is obtained from Sbordone et al. (2010). Accordingly, three interrelated blocks exist: a demand block, a supply block, and a monetary policy block. All agents within each of these blocks interact with one another in a market that always clears (hence, the model is a general equilibrium model). The demand block of the DSGE model determines real activity \( Y \) as a function of the ex-ante real interest rate \( i - \pi_e \) and expected future real activity \( Y^e \). This demand block captures the concept that when the real interest rate is high, agents would rather save than consume or invest. Additionally, when expectations about future real activity \( Y^e \) are positive, agents will be willing to spend more, regardless of the ex-ante real interest rate.

Real economic activity \( Y \) from the demand block is a key determinant of inflation \( \pi \) within the supply block, in addition to inflation expectations \( \pi^e \). This relationship between the demand block and the supply shock is illustrated in Figure 2.1 by the connecting line. This implies that when economic activity is high, firms must increase employee wages, which increases marginal cost. An increase in marginal cost puts upward pressure on prices, thereby generating inflation. Output
and inflation, as generated by the demand and supply blocks, feeds into the monetary policy block within the model (as illustrated by the dashed lines in Figure 2.1). The monetary policy block determines how the central bank sets the nominal interest rate. The central bank, in adjusting the nominal interest rate, impacts on real activity, thereby impacting inflation.

Central to the DSGE model is the role of expectations and the direction of the arrows within Figure 2.1 illustrate this, where the flows moves from the monetary policy block, to the demand block, which flows finally to the supply block. Therefore, expectations about key central bank policy decisions represent the main channel through which monetary policy affects the real economy. Expectations within the DSGE model therefore reflect their dynamic nature. Finally, the stochastic nature of DSGE models is illustrated in Figure 2.1, where random exogenous shocks cause fluctuations in the equilibrium condition of each block in the model. For example, a demand side exogenous shock (such as changes in consumer preferences), perturbs real economic activity as determined by the demand block. These exogenous shocks...
are the only source of fluctuations within the model, and should they be omitted, the economy would evolve accordingly along a perfectly predictable path, free from expansions and recessions.

The DSGE model yields a system of nonlinear equations. Generally nonlinear equations cannot be solved analytically so we need to approximate linear equations from the nonlinear equations. This can be achieved using either a Taylor series approximation or by log-linearising the model. The latter is the approach generally used in the literature for solving DSGE models. This method involves taking logs of the variables and then linearising the logs around a simple steady state path in which all variables are growing at the same rate. This approximation around the steady state is assumed to be accurate since the economy is assumed to be stochastic; therefore the variables will tend to fluctuate around the values given by this path.

2.3 Literature Review

DSGE models were first introduced by Rotemberg and Woodford (1997) and represent a broad class of macroeconomic model that combines elements of the standard neoclassical growth model of King, Plosser and Rebelo (1988), the Real Business Cycle theory of Kydland and Prescott (1982), with the introduction of real and nominal frictions within a New Keynesian framework, as popularized by Christiano, Eichenbaum, and Evans (2005), and Smets and Wouters (2003, 2007). These real and nominal frictions can take the form of sticky prices and wages, habit formation in the consumption equation and adjustment costs in the investment equations and are included in an attempt to capture real aspects of the data, Harrison and Oomen (2010). DSGE models are built upon microeconomic foundations whereby the decision rules of economic agents are derived with respect to their preferences, technologies, and the current monetary policy regime, by solving intertemporal optimization problems. Exogenous stochastic shock processes are present in the model which cause shifts in, for example, the nominal interest rate set by the central bank, or total factor productivity. As a result, the decision rules of economic agents are subject to uncertainty. The DSGE model can be evaluated using several different methods. This can range from calibrating the model (Kydland and Prescott 1982), to Generalised Method of Moments (GMM) estimation of
equilibrium relationships (Christiano and Eichenbaum 1992), to the more popular Bayesian estimation techniques (Christiano, Eichenbaum, and Evans (2005), An and Schorfheide (2007), Smets and Wouters (2003, 2007) and, Del Negro and Schorfheide (2012)).

2.3.1 Real Business Cycle (RBC) Theory

The foundation of DSGE models lies in the Real Business Cycle (RBC) theory of Kydland and Prescott (1982) in their Nobel Prize winning paper “Time to Build and Aggregate Fluctuations”, within which fluctuations in the economy were driven by real shocks, in particular, technology shocks. These real shocks imply that shocks are non-monetary in nature. The authors introduced three novel ideas within their paper which have since shaped macroeconomic modelling: firstly, business cycles could be analysed using dynamic general equilibrium modes where agents are homogenous, markets are competitive and agents have rational expectations; secondly, business cycle models must be consistent with the empirical regularities of the long-run growth; thirdly, to move from a qualitative comparison of the model to models that can be calibrated with parameters drawn from microeconomic studies (Rebelo, 2005). Kydland and Prescott used their RBC model to replicate the key features of US business cycles by calculating the standard deviations and correlation between major macroeconomic aggregates and comparing them to their simulated data. They found the same patterns of volatility, persistence and co-movement were present.

Since the RBC model is based on the assumption of perfectly competitive markets in which the outcomes generated by the decentralised decisions of firms and households can be replicated by solving the social planner problem. The social planner problem is given as follows:

\[ E_t \left[ \sum_{i=0}^{\infty} \beta^i \left( U(C_{t+i}) - V(N_{t+i}) \right) \right] \]

(2.1)

where \( C_t \) is consumption, \( N_t \) is hours worked, and \( \beta \) is the representative households rate of time preference. The economy faces the following production constraints:

\[ Y_t = C_t + I_t = A_t K_t^{\alpha} N_t^{1-\alpha} \]

(2.2)

\[ K_t = I_t + (1 - \delta) K_{t-1} \]

(2.3)
which can be simplified into the following equation:

$$A_tK_{t-1}^\alpha N_t^{1-\alpha} = C_t + K_t - (1 - \delta)K_{t-1}$$  \hspace{1cm} (2.4)$$

where $Y_t$, $C_t$, $I_t$, $K_t$, and $A_t$ represents output, consumption, investment, capital and a technology term, respectively. The parameter $\alpha$ represents the labours share of output (as given in the Cobb Douglas production function) and $\delta$ represents depreciation. As outlined by Stadler (1994), there are five key features of RBC models which include (i) the adoption of a representative agent framework (ii) firms and households optimise objective functions that are subject to certain constraints (iii) exogenous technology shocks are the main source of economic fluctuations (iv) markets are complete, no asymmetries exist, and agents have rational expectations and finally (v) the propagation of shocks generate actual cycles. Given these restrictive features of RBC models, it is unsurprising that these models have been subject to criticisms in the literature. These criticisms stem mainly from the concept of perfect markets and rational expectations; monetary neutrality; and technology shocks as the primary source of economic fluctuations.

To deal with some of the limitations of the RBC model, the New Keynesian DSGE model was developed which allowed for the introduction of nominal rigidities in the form of sticky prices and sticky wages within the model. As outlined by Galí and Gertler (2007), new frameworks were developed that reflect a synthesis between the RBC approach, which relies on a “bottom up” analysis, and the New Keynesian approach, which attempted to include nominal price stickiness and the non-neutrality of money. Notably, this new framework includes the development of the influential Smets and Wouters (2003, 2007) model, and the Christiano, Eichenbaum and Evans – henceforth CEE - (2001, 2005) model. Central banks draw heavily on these models for policy analysis, forecasting and counterfactual analysis. This is discussed in more detail in Section 2.3.2. These frameworks are presented as an application of the RBC methodology to an economy with sticky prices and wages. This introduction of sticky prices and wages follows Erceg et al. (2000) and CEE (2001) while

---

11 These constraints include resource constraints and technology constraints as shown in equation (4)
12 Key criticisms of the RBC model were outlined by Summers (1986) and Mankiw (1989) who state that RBC theory doesn’t provide an empirically plausible explanation of economic fluctuations.
13 This “bottom up” approach refers to the model being built on microfoundations, that is, the explicit optimization behavior at the individual level (see Galí and Gertler, 2007 for a more in-depth explanation).
monopolistic competition is included as in Kollmann (1997). Sticky prices and wages represent nominal frictions in the model, which are introduced to capture the empirical features present in macroeconomic data. In addition, the model includes a number of structural shocks including supply-side shocks (such as total factor productivity shocks) and demand-side shocks (such as a government spending shock). Unlike the RBC model which is calibrated, the New Keynesian DSGE model is estimated using Bayesian estimation techniques.

2.3.2 DSGE models and Central Banks

Over the past 20 years, central banks in both developed and emerging economies have begun to rely heavily on DSGE models for macroeconomic analysis and projections, with most having developed their own DSGE specific models. For example, the New Area-Wide Model (NAWM) of the Euro Area was developed by Christoffel et al. (2008) to use in the Broad Macroeconomic Projection Exercises (BMPE) regularly undertaken by the ECB/Eurosystem staff. When developing this model, two key considerations were included: to provide a comprehensive set of core projection variables, and to allow conditioning on monetary, fiscal and external developments. This model was built on two popular DSGE models: the Smets and Wouters (2003) model and the Adolfson et al. (2007) model. Overall, Christoffel et al. (2008) note that the NAWM model has economically plausible properties particularly in the propagation of economic shocks, in the identification of the main sources of economic fluctuations and in terms of its forecasting ability. The authors therefore suggest that “…the NAWM can make potentially useful contributions to forecasting and policy analysis, including the assessment of uncertainties and risks”.

Fischer, in his August 2015 speech at the Federal Reserve Bank of Kansas City Economic Symposium discusses the SIGMA model developed by Erceg et al. (2006). This SIGMA model was designed as a quantitative tool for policy analysis in

---

14 According to ECB (2001), these projection exercises include projections for inflation, the growth of real GDP and its main expenditure components over a two-year horizon. These projections are used as an analytical tool for “helping bring together in a systematic manner a range of current and future economic developments”. The outcomes of these projection exercises are then presented to the Governing Council to be used as an input into its monetary policy deliberations.

15 This speech can be accessed at http://www.federalreserve.gov/newsevents/speech/fischer20150829a.htm
the US. As with the NAWM model of the euro area, the SIGMA model is built on the model of Smets and Wouters (2003), and also includes additional features of models developed by Christiano et al. (2005) and Obstfeld and Rogoff (1995). The SIGMA model is purported to provide a clear linkage between structural features of the economy and its response to shocks. As such, it is said to provide a theoretically consistent framework for analysing how the economy can recover following wide array of disturbances. Additionally, the Bank of England use a DSGE model known as ‘COMPASS’ as part of its suite of models used for forecasting and it is used to assist with the production of forecasts presented by the Monetary Policy Committee (MPC) in their quarterly *Inflation Reports*. This COMPASS model was developed by Burgess et al. (2013) and is described as an open-economy New Keynesian DSGE model estimated on UK data using Bayesian methods. This model is used for three main reasons: to act as the main organizing framework for constructing forecasts; to analyse and explain forecasts; and to perform sensitivity analysis on the forecast. According to Burgess et al. (2013), the COMPASS model is closest in structure to RAMSES model of Adolfson et al. (2007) and the ECB’s NAWM of Christoffel et al. (2008).

The Terms of Trade Economic Model (ToTEM) was developed by Murchison and Rennison (2006) for the Canadian economy. This ToTEM model is described as the principle projection and policy analysis model for the Canadian economy and is used to produce the Bank staff’s quarterly economic projection. As such, it represents an important input into the monetary policy decision making process and is used as a tool to examine issues relating to optimal monetary policy and the interpretation of a wide range of shocks. To examine the Swedish economy, Adolfson et al. (2007) developed the Riksbank Aggregate Macromodel for Studies of the Economy of Sweden (RAMSES) which is an open economy DSGE model. This RAMSES model

---

16 These disturbances include monetary policy shocks, government spending shocks, falling currency risk premia shocks, and reductions in capital tax rates (Erceg et al. 2005, 2006)
17 COMPASS is the Central Organising Model for Projection Analysis and Scenario Simulation
<table>
<thead>
<tr>
<th>Central bank</th>
<th>Model Name</th>
<th>Use(s)</th>
<th>Model based on:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>- Christoffel et al. (2008)</td>
<td></td>
<td>- Adolfson et al. (2007)</td>
</tr>
<tr>
<td>Federal Reserve Bank</td>
<td>SIGMA model</td>
<td>Quantitative tool for policy analysis and counterfactual analysis</td>
<td>Smets and Wouters (2003)</td>
</tr>
<tr>
<td></td>
<td>- Erceg et al. (2006)</td>
<td></td>
<td>- Christiano et al. (2005)</td>
</tr>
<tr>
<td>Bank of England</td>
<td>COMPASS model</td>
<td>Used to assist in the production of forecasts for the MPC in their quarterly Inflation Reports</td>
<td>- Christoffel et al. (2008)</td>
</tr>
<tr>
<td>Bank of Canada</td>
<td>Terms of Trade Economic Model (ToTEM)</td>
<td>Principle projection and policy analysis model for the Canadian economy</td>
<td>Smets and Wouters (2005)</td>
</tr>
<tr>
<td>Riksbank</td>
<td>Riksbank Aggregate Macromodel for Studies of the Economy of Sweden (RAMSES)</td>
<td>Used for monetary policy analysis and to produce a consistent assessment of the future path of the economy</td>
<td>Kydland and Prescott (1982)</td>
</tr>
<tr>
<td>Bank of Japan</td>
<td>Quarterly Japanese Economic Model (Q-JEM)</td>
<td>Short-to-medium term projections, macro risk assessment and scenario analysis</td>
<td>- Not specified</td>
</tr>
<tr>
<td></td>
<td>- Fukunaga et al. (2011)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
is used for producing forecasts, interpreting economic developments and calculating the effects of monetary policy interventions. As outlined above, this model has been incorporated by the ECB and the Bank of England in their respective DSGE models. Fukunaga et al. (2011) developed the Quarterly Japanese Economic Model (Q-JEM) for the Bank of Japan and this model is used for short-to-medium term projections, macroeconomic risk assessment, and scenario analysis. The output from this model is then used for analyses that are published in the Outlook for Economic Activity and Prices report. This report outlines the outlook for developments in economic activity, risk assessment and its future plan for monetary policy by policy board members. Table 2.1 above summarises this information by outlining the model, it uses and the original model on which it is based. In addition to the central bank DSGE models mentioned already, there are many additional major central banks\(^{18}\) that have developed their own DSGE models for policy analysis, counterfactual arguments and forecasts.

### 2.4 The Prototypical DSGE Model

Given its prevalence among central banks, the DSGE model used in this chapter is based on the seminal work of Smets & Wouters (2003, 2007) which is an application of a real business cycle model with nominal\(^{19}\) and real\(^{20}\) rigidities. Within this model, we have three economic agents: households, firms and a monetary authority.

#### 2.4.1 Households

The basic structure of the households within this model can be described as follows: there exists a continuum of homogeneous households who maximise their utility function over an infinite life horizon. The household derives utility

---

\(^{18}\) This includes the Central Bank of Chile (MAS), Norges Bank (NEMO), IMF (GEM, GFM, or GIMF), and the Central Bank of Ireland (EIRE). For more, see Tovar (2009)

\(^{19}\) These nominal rigidities include sticky prices and sticky wages that adjust according to the Calvo (1983) mechanism.

\(^{20}\) Real rigidities also exist in the DSGE model and include habit formation in consumption, costs of adjustment in capital formation and capacity utilisation, all of which are included to capture the empirical features of the US economy (Edge and Gurkaynak, 2011).
from consumption and disutility from working. Consumption is present within
the utility function and is subject to an external habit parameter. Additionally,
households are assumed to have monopoly power over their wages and labour is
differentiated by a union. Since households are assumed to have monopoly
power over their wages, there is a specific wage-setting equation that includes
nominal sticky prices as modelled by Calvo (1983). Households also accumulate
capital, and rent this capital to firms. This capital accumulation by households is
subject to an investment adjustment cost which allows for adjustment in the
capital utilisation as the rental price of capital changes.

The household’s objective function is expressed as:

$$E_t \sum_{s=0}^{\infty} \beta^s \left[ \frac{1}{1 - \sigma_c} \left( C_{t+s} - \lambda C_{t+s-1} \right)^{1 - \sigma_c} \right] \exp \left( \frac{\sigma_c - 1}{1 + \sigma_l} (L_{t+s})^{1 + \sigma_l} \right)$$  \hspace{1cm} (2.5)

which is subject to the following budget constraint:

$$C_{t+s} + I_{t+s} + \frac{B_t}{\varepsilon_t^i} R_{t+s} P_{t+s} - T_{t+s} \leq \frac{B_{t+s-1}}{P_{t+s}} + \frac{W_{t+s-1}}{P_{t+s}} + \frac{R_{t+s} K_{t+s} K_{t+s-1}}{P_{t+s}} - a(Z_{t+s}) - \frac{DIV_t}{P_{t+s}} \hspace{1cm} (2.6)$$

and the following capital accumulation equation:

$$K_t = (1 - \delta)_{t-1} + \varepsilon_t^i \left[ 1 - S \left( \frac{L_t}{L_{t-1}} \right) \right] L_t$$ \hspace{1cm} (2.7)

Equation (2.5) states that the household chooses consumption $C_t$, hours worked
$L_t$, bonds $B_t$, investment $I_t$ and capital utilisation $Z_t$ in order to maximise their
utility, subject to the budget constraint given in equation (2.6) and the capital
accumulation equation given in equation (2.7). Within equation (2.5),
consumption is subject to an external habit parameter $\lambda$. According to Harrison
and Oomen (2010), this habit parameter $\lambda$ is used to capture the notion that
households gain utility from keeping consumption close to previous levels, as
well as higher levels of lifetime consumption\textsuperscript{21}. Furher (2000) and Christiano,
Eichenbaum, and Evans (2005) also state that the habit parameter is included in

\textsuperscript{21} Additionally, Harrison and Oomen (2010) state that, \textit{ceteris paribus}, a higher (lower) degree
of habit persistence will reduce (increase) the interest rate elasticity of consumption for a given
elasticity of substitution.
the model to help replicate key features of consumption data\textsuperscript{22}. The parameter $\sigma_c$, is the coefficient of relative risk aversion for households and can be represented also as the inverse of the intertemporal elasticity of substitution\textsuperscript{23}. Labour, in equation (2.5), is subject to the parameter $\sigma_l$, which represents the inverse of the elasticity of work effort with respect to the real wage. Finally, the parameter $\beta$, represents the discount rate for households, where households are assumed to discount the future by $\beta < 1$.

Equation (2.6) states that the household’s objective function is subject to a budget constraint that includes their consumption, $C_t$, their investment, $I_t$, their holdings of bonds, $B_t$ and the taxes they pay, $T_t$. This is required to be less than or equal to their bond holdings (from the previous period), their real wages ($W_t$), the income they receive from renting capital $\frac{p_t^kZ_{t+s}K_{t+s-1}}{p_{t+s}}$ (which is subject to the cost of changing capital utilisation, as given by $a(Z_{t+s})K_{t+s-1}$) and finally their dividends ($DIV_t$). Within the budget constraint, the holding of bonds is subject to an exogenous shock, $\varepsilon^b_t$, that is reflective of inefficiencies in the financial sector. These inefficiencies in the financial sector could represent some premium on the deposit rate offered to households, versus the risk free interest rate set by the central bank. Smets and Wouters (2007) refer to this as “a risk premium that households require to hold the one period bond”. As with all exogenous shocks within this DSGE model, it is assumed to follow a stochastic process that will be outlined later in this section.

Equation (2.7) expresses the capital accumulation condition for households. The depreciation rate of capital is represented by $\delta$ and an adjustment cost function is provided by $S(\cdot)$ where $S'(\cdot) > 0, S''(\cdot) > 0$. Additionally, the accumulation of capital is subject to an exogenous shock process, $\varepsilon^i_t$, that is representative of a stochastic shock to the price of investment relative to the consumption of goods. The maximisation of the objective function given in equation (2.5), subject to the budget constraint in equation (2.6) and the capital accumulation equation given in equation (2.7), yields the first-order conditions for consumption. These

\textsuperscript{22} Furher (2000) describes these key features as the gradual hump-shaped response of real spending to various shocks, such as monetary policy shocks.

\textsuperscript{23} According to Hall (1988), the intertemporal elasticity of substitution is measures as the response of the rate of change of consumption to changes in the real interest rate.
derivations are outlined in detail in the Appendix provided by Smets and Wouters, 2007. As previously outlined, household labour is differentiated by a union and households have monopoly power over their wages. Households therefore act as price-setters in the labour market and the wage rate they receive is subject to nominal wage rigidities á la Calvo (1983). The labour union that households supply their labour to is an intermediate labour union, that is responsible for differentiating labour services, setting the Calvo wage and offering the labour services provided by households to intermediate ‘labour packers’

Using Calvo pricing, the optimal wage set by the union (which represents the household) that is allowed to re-optimise its wage is obtained from the following optimisation problem:

\[
\max_{L_t \epsilon L(t)} W_t L_t - \int_0^1 W_t(i) L_t(i) di
\]

(2.8)

where \( W_t \) and \( W_t(i) \) refer to the price of composite labour services and intermediate labour services respectively. This is due to labour being used by an intermediate goods producer \( L_t \), which is a composite of differentiated labour services \( L_t(i) \). Equation (2.8) is subject to the following constraint:

\[
\left[ \int_0^1 H \left( \frac{L_t(i)}{L_t}; \varepsilon_t^W \right) di \right] = 1
\]

(2.9)

where \( H(1) = 1 \). This implies that \( H \) is a strictly concave and increasing function. As with the previous equations, \( \varepsilon_t^W \) is an exogenous shock process that reflects shocks to the aggregator function that result in changes in the elasticity of demand and, therefore, the wage mark-up. The optimal wage set by the union is derived using Calvo pricing with partial indexation. In each period, a fraction of households, \( \xi_w \), will not be able to re-adjust their wages. For these households, the wage \( W_t \) will increase at a geometrically weighted average of the steady state rate increase in wages (which, according to Del Negro et al., 2007, is equal to the steady state inflation \( \pi^* \) times the growth rate of the economy \( \gamma \)). For households that can re-adjust their wages, their nominal wage is \( \tilde{W}_t(i) \). The aggregate wage index is then given as:

\[\text{According to Smets and Wouters (2007), the labour packers then buy the differentiated labour services, package it and then offer it to intermediate goods producers.}\]
\[ W_t = (1 - \xi_w)\bar{W}_t H^{t-1} \left[ \frac{\nu r^w}{W_t} \right] + \xi_w \gamma \pi_{t-1}^w \pi_s^{1-l_w} W_{t-1} H^{t-1} \left[ \frac{\gamma \pi_{t-1}^w W_{t-1} \tau^w}{W_t} \right] \tag{2.10} \]

Where \( \tau^w_t \) is \( \int_0^1 H' \left( \frac{L_t(i)}{L_t} \right) \frac{L_t(i)}{L_t} \) \( di \). Additionally, \( l_w \) and \( 1 - l_w \) are the weights associated with the weighted average rate at which wages will increase where \( \pi_s \) is the steady state inflation rate and \( \pi_{t-1} \) is the inflation rate in the previous period. According to Smets and Wouters (2007), the mark-up of the aggregate over the wage received by households is distributed to households in the form of dividends (as provided in the budget constraint of households in equation (2.6)).

### 2.4.2 Firms

There are two types of good producers within this model: final goods producers and intermediate goods producers. Intermediate good producers rent capital and labour to manufacture intermediate goods while final goods producers aggregate these intermediate goods into final goods. Both types of goods producers are outlined below.

**Final goods producers**

Starting with the final goods producer, according to Smets and Wouters (2007), the final good, \( Y_t \), is a composite made up of a continuum of intermediate goods \( Y_t(i) \). The final goods firm maximises profits according the follow optimisation problem:

\[ \max_{Y_t, Y_t(i)} P_t Y_t - \int_0^1 P_t(i) Y_t(i) \, di \tag{2.11} \]

where \( P_t \) and \( P_t(i) \) are the final and intermediary goods respectfully. The maximisation of the final goods firm’s profits is subject to the following budget constraint:

\[ \left[ \int_0^1 G \left( \frac{Y_t(i)}{Y_t}; \epsilon^P_t \right) \, di \right] = 1 \tag{2.12} \]

Where \( G \) is a strictly increasing concave function and is characterised by \( G(1) = 1 \). An exogenous shock, \( \epsilon^P_t \), is included in equation (2.12) and is used to reflect shocks that may cause changes in the elasticity of demand and therefore the price mark-up. This exogenous shock is constrained such that \( \epsilon^P_t \in (0, \infty) \).
and is assumed to follow an ARMA process (which will be discussed in more detail in section 2.4.4 below).

**Intermediate goods producers**

Intermediate goods producers rent capital and labour to manufacture intermediate goods using the following technology:

\[ Y_t(i) = \varepsilon_t^a K_t^s(i)^\alpha [\gamma_t L_t(i)]^{1-\alpha} - \gamma_t \Phi \]  

(2.13)

where \( K_t^s \) is capital services used in production, \( L_t(i) \) is a composite labour input and \( \Phi \) is a fixed cost. Additionally, \( \gamma_t \) represents the labour-augmenting deterministic growth rate in the economy and there is an exogenous shock, \( \varepsilon_t^a \), that reflects a shock to total factor productivity. The profit of the firm can be written as:

\[ P_t(i) Y_t(i) - W_t L_t(i) - R_t^k K_t^s(i) \]  

(2.14)

As before, the aggregate nominal wage is given as \( W_t \) and the rental rate on capital is given as \( R_t^k \). The first order conditions of the intermediate goods producers can then be derived and the capital-labour ratio across all firms is then given as:

\[ K_t^s = \frac{\alpha}{1-\alpha} \frac{W_t}{R_t^k} L_t \]  

(2.15)

The firms marginal cost for all firms is equal and is given as:

\[ MC_t = \alpha^{-\alpha} (1-\alpha)^{(1-\alpha)} W_t^{1-\alpha} R_t^k \alpha^{-(1-\alpha)} (\varepsilon_t^a)^{-1} \]  

(2.16)

As with the nominal wages for households, partial price indexation is present in the model due to Calvo and provides the optimal price set by the firm that is able to change its prices. Following Smets and Wouters (2007), the optimisation problem is given and the first order condition is derived. Using this, the aggregate price index for the firms can be given as:

\[ P_t = \left(1 - \xi_p\right) P_t(i) G^{t-1} \left[ \frac{P_t(i) \tau_t}{P_t} \right] + \xi_p \pi^{lp} P_{t-1} G^{t-1} \left[ \frac{\pi^{lp}_{t-1} \pi^{lp}_{t-1} P_{t-1} \tau_t}{P_t} \right] \]  

(2.17)
Similar to the aggregate wage index given in equation (2.10), $l_p$ and $1 - l_p$ are the weights associated with the weighted average rate at which prices will increase where $\pi_t$, the steady state inflation rate is and $\pi_{t-1}$ is the inflation rate in the previous period.

### 2.4.3 Monetary Authority

Finally, the central bank follows a nominal interest rate rule by adjusting its instrument in response to deviations of inflation and output from their target levels. This nominal interest rate rule is given as:

$$
\frac{R_t}{R^*} = \left(\frac{R_{t-1}}{R^*}\right)^{\rho} \left(\frac{\pi_t}{\pi^*}\right)^{r_\pi} \left(\frac{Y_t}{Y^*_t}\right)^{r_y} \left(\frac{Y_t/Y_{t-1}}{Y^*_t/Y^*_{t-1}}\right)^{r_{\Delta Y}} \epsilon_t^{r} \tag{2.18}
$$

where $R_t$ is the policy controlled interest rate, $R^*$ is the steady state nominal interest rate (the gross rate), $Y_t$ is output and $Y^*_t$ is natural output. The parameters characterising equation (2.18) above include $\rho$ which determines the degree of interest rate smoothing, $r_\pi$ which determines the long run reaction on inflation, $r_y$ which determines the long run reaction to the output gap, and $r_{\Delta Y}$ which determines the short run reaction to a change in the output gap. The nominal interest rate rule is also subject to an exogenous shock process, $\epsilon_t^{r}$ which reflects a monetary policy shock.

Equations (2.5) to (2.18) provides the basis of the Smets and Wouters (2007) DSGE model. The next step is to derive the first order conditions of the model, detrend the model and finally log-linearise the model around its steady state. These steps are outlined in detail in the Appendix provided by Smets and Wouters (2007, 2003) and the log-linearised equations of this model are provided in Appendix A2.1 to this chapter. These log-linearised equations include 14 equations that characterise the macro economy. Table 2.2 (page 43) outlines these 14 equations and their associated variables, parameters and exogenous shock processes.
2.4.4 Exogenous Shock Processes

Overall, there are seven exogenous shock processes within this model, each of which is outlined below:

1. Exogenous spending shock

\[ \varepsilon^g_t = \rho_g \varepsilon^g_{t-1} + \eta^g_t + \rho_{ga} \varepsilon^a_t \]  \hspace{1cm} (2.19)

Exogenous spending is assumed to follow a first-order autoregressive process with an IID-Normal error term. This shock is also affected by a productivity shock, to reflect net exports that may be affected by domestic productivity disturbances.

2. Risk premium shock

\[ \varepsilon^b_t = \rho_b \varepsilon^b_{t-1} + \eta^b_t \]  \hspace{1cm} (2.20)

The risk premium shock is assumed to represent a wedge between the interest rate controlled by the central bank and the return on assets held by households. This shock, according to Smet & Wouters (2007), is assumed to have similar effects as the ‘net worth’ shocks introduced by Bernanke, Gertler and Gilchrist (1999) in their financial accelerator DSGE model. As with equation (2.19), equation (2.20) follows a first-order autoregressive process with an IID-Normal error term.

3. Investment-specific technology shock

\[ \varepsilon^i_t = \rho_i \varepsilon^i_{t-1} + \eta^i_t \]  \hspace{1cm} (2.21)

The investment-specific technology shock is assumed to follow a first-order autoregressive process and an IID-Normal error term.
4. Total factor productivity shock

\[ \varepsilon_t^a = \rho_a \varepsilon_{t-1}^a + \eta_t^a \]  
(2.22)

As with the other exogenous shocks, the total factor productivity shock is assumed to follow a first-order autoregressive process with an IID-Normal error term.

5. Price mark-up shock

\[ \varepsilon_t^p = \rho_p \varepsilon_{t-1}^p + \eta_t^p - \mu_p \eta_{t-1}^p \]  
(2.23)

The price mark-up shock differs from the previous shocks as it is assumed to follow an ARMA(1,1)\(^25\) process. This is so the high-frequency fluctuations that often occur within inflation can be captured by the MA term.

6. Wage mark-up shock

\[ \varepsilon_t^w = \rho_w \varepsilon_{t-1}^w + \eta_t^w - \mu_w \eta_{t-1}^w \]  
(2.24)

As with the price mark-up shock in equation (2.21), the wage mark-up shock is also assumed to follow an ARMA(1,1) process in order to capture high frequency fluctuations in wages.

7. Monetary policy shock

\[ \varepsilon_t^r = \rho_r \varepsilon_{t-1}^r + \eta_t^r \]  
(2.25)

Finally, the monetary policy shock is assumed to follow a first-order autoregressive process with an IID-Normal error term.

---

\(^25\) ARMA(1,1) is an autoregressive moving average process with the AR element equal to one and the MA element equal to 1.
Table 2.2: Log-Linearised Equations: Variables, Parameters and Exogenous Shocks

<table>
<thead>
<tr>
<th>Log-linearised equation</th>
<th>Variables</th>
<th>Parameters</th>
<th>Exogenous shock</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aggregate resource constraint</td>
<td>1. Output</td>
<td>- Steady-state consumption, investment and capital utilisation</td>
<td>Exogenous spending shock with two components: Government spending and productivity</td>
</tr>
<tr>
<td></td>
<td>2. Consumption</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3. Investment</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>4. Capital utilisation rate</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Consumption</td>
<td>1. Current, past, and expected future consumption</td>
<td>- Habit parameter</td>
<td>Risk premium shock that determines the willingness of households to hold a one-period bond.</td>
</tr>
<tr>
<td></td>
<td>2. Hours worked</td>
<td>- Elasticity of intertemporal substitution</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3. Ex-ante real interest rate</td>
<td>- Growth rate</td>
<td></td>
</tr>
<tr>
<td>Investment</td>
<td>1. Current, past, and expected future investment</td>
<td>- elasticity of the capital adjustment cost function</td>
<td>Investment specific technology shock</td>
</tr>
<tr>
<td></td>
<td>2. Real value of existing capital stock</td>
<td>- household discount factor</td>
<td></td>
</tr>
<tr>
<td>Current value of capital stock</td>
<td>1. Expected future value of the capital stock</td>
<td>- Depreciation rate</td>
<td>Risk premium shock</td>
</tr>
<tr>
<td></td>
<td>2. Expected real rental rate on capital</td>
<td>- Household discount factor</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3. Real interest rate</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aggregate production function</td>
<td>1. Output</td>
<td>- Share of capital in production</td>
<td>Total factor productivity shock</td>
</tr>
<tr>
<td></td>
<td>2. Capital</td>
<td>- Fixed costs in production</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3. Labour</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Capital used in production</td>
<td>1. Capital installed in the previous period</td>
<td>- No parameters</td>
<td>Not directly subjected to an exogenous shock</td>
</tr>
<tr>
<td></td>
<td>2. Capital utilisation rate</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Capital utilisation</td>
<td>1. Rental rate of capital</td>
<td>- Elasticity of the capital adjustment cost function</td>
<td></td>
</tr>
</tbody>
</table>

(Table 2.2 Continued)
<table>
<thead>
<tr>
<th>Log-linearised equation</th>
<th>Variables</th>
<th>Parameters</th>
<th>Exogenous shock</th>
</tr>
</thead>
</table>
| Accumulation of capital  | 1. Past capital  
                          2. Investment | - Depreciation rate  
                          - Growth rate  
                          - Household discount rate  
                          - Elasticity of the capital adjustment cost function | Investment specific technology shock |
| Price mark-up            | 1. Marginal product of labour  
                          2. Real wage | - No parameters | Total factor productivity shock |
| Inflation (New Keynesian Phillips Curve) | 1. Current, past and expected future inflation  
                          2. Price mark-up | - Indexation to past inflation  
                          - Discount factor  
                          - Growth rate  
                          - Degree of price stickiness  
                          - Fixed costs in production | Price mark-up shock that is designed to capture high-frequency fluctuations in inflation |
| Rental rate of capital   | 1. Capital-labour ratio  
                          2. Real wage | - No parameters | Not directly subjected to an exogenous shock |
| Wage mark-up             | 1. Real wage  
                          2. Marginal rate of substitution | - Habit parameter  
                          - Elasticity of labour supply | Not directly subjected to an exogenous shock |
| Real wages               | 1. Current, past and expected future real wages  
                          2. Current, past and expected future inflation  
                          3. Wage mark-up | - Degree of wage stickiness  
                          - Discount factor  
                          - Growth rate  
                          - Indexation to past wages | Wage mark-up shock that is designed to pick up high frequency fluctuations in wages |
| Monetary policy reaction function | 1. Past interest rate  
                          2. Inflation rate  
                          3. Past and current output  
                          4. Past and current potential output | - Degree of interest rate smoothing  
                          - Long run reaction to inflation, and the output gap | Monetary policy shock |
2.5 Estimating a DSGE model using Bayesian methods

The DSGE model used in this chapter is empirically estimated using Bayesian estimation techniques. This method allows the likelihood function to transform the prior distribution for the structural parameters of the model into a posterior distribution. This posterior distribution is then used for model inference and policy decision-making (Geweke and Whiteman, 2006).

According to Bayes theorem, one can combine the prior beliefs $P(\theta)$ with the sample information contained in the likelihood function $L(Y_T|\theta)$ to obtain a new set of beliefs (posterior distribution) $P(\theta|Y_T)$, as follows:

$$P(\theta|Y_T) \propto L(Y_T|\theta)P(\theta)$$  \hspace{1cm} (2.26)

To estimate the DSGE model\textsuperscript{26}, we must first log-linearise the model equations around their steady state. In doing so, we obtain the Linear Rational Expectations (LRE) model, which is solved and written in a state space form. Once the model is written in state space form, we can compute the likelihood function. The Kalman filter\textsuperscript{27} is used to evaluate the likelihood function. The likelihood function is combined with the prior distribution on the parameters to obtain the posterior density function, which is estimated using Markov Chain Monte Carlo (MCMC) techniques. One such technique is the generic Metropolis-Hastings (MH) algorithm, by Metropolis et al. (1953) and later generalised by Hastings (1970), which generates a Markov chain such that the stationary distribution associated with the Markov chain is unique and equals the posterior distribution (Herbst and Schorfheide, 2014). One variation of the MH algorithm is the random walk MH (RWMH) algorithm.

This MH algorithm is then employed to obtain a complete picture of the posterior distribution. This algorithm generates draws from the posterior distribution of $\theta$, and requires the evaluation of $L(\theta|Y)p(\theta)$. From Schorfheide (2000), Otrok (2001) and

\textsuperscript{26}The model is estimated using Dynare 4.2. The posteriors are based on 250,000 draws of the Metropolis-Hastings algorithm
\textsuperscript{27}The Kalman filter (Kalman (1960, 1963) is an iterative algorithm, used for many computational purposes, including estimating unobserved components models
An and Schorfheide (2007), the random walk Metropolis-Hastings algorithm\(^{28}\) proceeds as follows:

1. A numerical optimization routine is used to maximize the log posterior, which is given by

\[
\ln \mathcal{L}(\theta|Y) + \ln p(\theta). \tag{2.27}
\]

Let \(\bar{\theta}\) denote the posterior mode.

2. Let \(\hat{\Sigma}\) be the inverse of the Hessian computed at the posterior mode \(\bar{\theta}\).

3. The algorithm then draws \(\theta^{(0)}\) from \(\mathcal{N}(\bar{\theta}, c^2 \hat{\Sigma})\), or directly from a specified starting value.

4. For \(s = 1, \ldots, n_{sim}\), draw \(\nu\) from the proposal distribution \(\mathcal{N}(\theta^{(s-1)}, c^2 \hat{\Sigma})\).

The jump from \(\theta^{(s-1)}\) is accepted \((\theta^{(s)} = \nu)\) with probability

\[
\min\{1, r(\theta^{(s-1)}, \nu|Y)\} \quad \text{and rejected} \quad (\theta^{(s)} = \theta^{(s-1)}) \quad \text{otherwise.}
\]

Here,

\[
r(\theta^{(s-1)}, \nu|Y) = \frac{\mathcal{L}(\nu|Y)p(\nu)}{\mathcal{L}(\theta^{(s-1)}|Y)p(\theta^{(s-1)})} \tag{2.28}
\]

From Herbst and Schorfheide (2014), the draw, \(\nu\), is accepted with probability one if the posterior \(\nu\) has a higher value than the posterior at \(\theta^{(s-1)}\).

5. The posterior expected value can then be approximated by a function \(h(\theta)\)

by \(\frac{1}{n_{sim}} \sum_{s=1}^{n_{sim}} h(\theta^{(s)})\)

In summary, the RWMH algorithm determines a new value for the parameter of interest and evaluates whether it increases the posterior. If the posterior does increase, it is accepted with a probability of one. If it does not increase, it is accepted with a probability less than one (Fernández-Villaverde, 2009).

2.5.1 Parameter Estimates

The parameter estimations for the prior distributions, the endogenous parameters and the exogenous parameters are outlined in this section.

Prior Distributions

Prior distributions\(^{29}\) allow for the inclusion of some non-sample information, gleamed from sources such as pre-sample data, the use of data from other countries (for example, a prior for a DSGE model of the euro area is specified based on US data) or from micro level data (for example, panel studies on price elasticity’s or labour supply behaviour), which does not directly enter the likelihood function. This non-sample information is independent of the sample used in the model estimation. Thus, the prior distribution adds weight to the likelihood function and can introduce curvature into the posterior density surface that facilitates the use of MCMC methods to derive the posterior distribution, An and Schorfheide (2007). In constructing the priors, the parameters may be grouped into three broad categories which include steady state parameters, endogenous parameters, and exogenous parameters. Steady state parameters tend to be calibrated in DSGE models and reflect “great ratios”, Del Negro and Schorfheide (2008).

In estimating the model, the parameters are calibrated in the same way as Smets & Wouters (2007). Taking the steady state parameters first, five parameters are calibrated. Theses include the depreciation rate which is assumed to be 10 percent annually \((\delta = 0.025)\). The degree of monopolistic competition in the goods and labour market are assumed to imply mark-ups of 10 percent respectively. For exogenous spending, GDP is set at 18 percent and the steady state mark-up in the labour market is 1.5. The list of parameters estimated in the model, including the prior mean, standard deviation, and distribution used are provided in Table 2.4 (see page 57).

---

\(^{29}\)The prior and posterior parameter graphs are provided in Appendix A2.2 of this thesis along with the Metropolis-Hastings convergence diagnostics.
Endogenous Parameters

We now turn to the endogenous parameters. As before, the parameters used are the same as those used by Smets and Wouters (2007). The prior parameters of the consumption and investment utility functions are as follows: both the elasticity of intertemporal substitution and the elasticity of the capital adjustment cost function are assumed to be normally distributed with a prior mean of 4.0. The beta distribution is defined on the interval [0, 1] and is used to model the behaviour of random variables limited to intervals of finite length. The distribution used to model the habit parameter is the beta distribution. The prior mean of the habit parameter is set at 0.7 with a standard deviation of 0.1.

Regarding the monetary policy reaction function, the interest rate in response to changes in the inflation parameter is assumed to be approximately 1.5 and normally distributed, while the degree of interest rate smoothing uses a beta distribution and is set at 0.75. The parameters representing the interest rate in response to the output gap and changes in the output gap are both set at 0.125, and are assumed to be normally distributed. The prior mean of the Calvo probabilities of price and wage stickiness are set at 0.5 each, which suggests average price and wage contracts of half a year and a standard deviation of 0.1. The Calvo probabilities use a beta distribution.

Exogenous Parameters

Finally, we turn to the exogenous parameters representing exogenous shock processes within the model, which are given in Table 2.5 (page 59). The prior mean and standard deviation are set at 0.1 and 2.0 respectively, which is seen as a relatively loose prior. The distribution used for the priors of the exogenous shock processes is an inverse gamma distribution, which restricts the parameters of the model to be positive. The persistence of the AR(1) processes are restricted to a beta distribution, with a prior mean of 0.5 and standard deviation of 0.2.
2.6 Description of the data

The model is estimated using seven key variables over the period 1947Q1 to 2007Q4. The end date was chosen so the dynamics in the lead up to the financial crisis could be captured. Quarterly data is obtained from Federal Reserve Economic Data (FRED). The seven variables used in the estimation include real GDP, consumption, investment, real wages, hours worked, the short term interest rate, and inflation. Real GDP is expressed in Billions of Chained 1996 dollars. Personal Consumption Expenditure and Fixed Private Investment are used for the consumption and investment variables. The real wage is obtained using data from the Non-Farm Business Sector (NFB): Hourly Compensation. Hours worked is determined using data on NFB: Average Hours Worked.

The aggregate real variables are expressed per capita by dividing by the total population over 16, and are then deflated using the GDP deflator. The aggregate real variables are also expressed as 100 times log. The Implicit Price Deflator is used to model inflation and the short-term interest rate is the federal funds rate. As with the aggregate real variables, the inflation rate and the interest rate are expressed quarterly. All variables are seasonally adjusted. Figure 2.2 to 2.8 illustrates each of the seven variables prior to transformation (and expressed in year on year percentage change)\textsuperscript{30}.

2.6.1 Real GDP

Real GDP, expressed as the year on year percentage change, is provided in Figure 2.2 for the period 1948Q11 to 2007Q4. This time period corresponds with approximately ten recessions (not including the Great Recession from 2008 – 2009) and Table 2.3 below summaries these recessions. The recession of 1948-1949 is due to the post WWII slump in the US which was associated with downward pressure on

\textsuperscript{30} Appendix A2.3 depicts the transformed variables used in the estimation.
prices, a decline in consumer demand, and a decline in fixed private investment after the initial post-war boom (Caplan, 1956).

![Figure 2.2: Year on Year Percentage Change in Real GDP](source)

The recession of 1953 – 1954 is attributed to a decline in house prices in the US, which bottomed out in 1952Q1, and coincided with increased government spending on national defence expenditures as a result of the Korean War (Gjerstand and Smith, 2014). The 1957-1958 recession (often referred to as the Eisenhower recession) is generally associated with the tightening of monetary policy by the Federal Reserve and, according to the NBER, lasted for 8 months. The 1960s and 1970s corresponds to three recessions in the US: the 1960-1961 recession, the 1969-1970 recession, and the 1973-1975 recession, which lasted 10 months, 11 months, and 16 months respectively. Several factors contributed to the 1973-1975 recession including the movement away from the gold standard, the OPEC oil embargo, and the introduction of wage-price controls by President Nixon. The 1980s was characterised by two recessions which took place at the beginning of the decade (1980-1982), both of which coincide with record high levels of inflation in the US as a result of the Iranian oil embargo, and the associated tight monetary policy as a result.
Table 2.3: Post WWII Recessions in the United States

<table>
<thead>
<tr>
<th>Recession</th>
<th>Duration (months)</th>
<th>Decline</th>
<th>Main cause</th>
</tr>
</thead>
<tbody>
<tr>
<td>1948.1 – 1949.4</td>
<td>11</td>
<td>-10.1%</td>
<td>Post-war slump</td>
</tr>
<tr>
<td>1953.2 – 1954.2</td>
<td>10</td>
<td>-9.5%</td>
<td>Post Korean War and housing decline</td>
</tr>
<tr>
<td>1957.3 – 1958.2</td>
<td>8</td>
<td>-13.6%</td>
<td>Tight monetary policy</td>
</tr>
<tr>
<td>1960.2 – 1961.1</td>
<td>10</td>
<td>-8.6%</td>
<td>Tight monetary policy</td>
</tr>
<tr>
<td>1969.4 – 1970.4</td>
<td>11</td>
<td>-7%</td>
<td>Bretton Woods</td>
</tr>
<tr>
<td>1973.4 – 1975.4</td>
<td>16</td>
<td>-13.1%</td>
<td>Oil prices and stagflation</td>
</tr>
<tr>
<td>1980.1 – 1980.3</td>
<td>6</td>
<td>-6.6%</td>
<td>Oil prices</td>
</tr>
<tr>
<td>1981.3 – 1982.4</td>
<td>16</td>
<td>-9.4%</td>
<td>Oil prices</td>
</tr>
<tr>
<td>1990.3 – 1991.1</td>
<td>8</td>
<td>-4.1%</td>
<td>Gulf War, oil price spike and Savings and Loan crisis</td>
</tr>
<tr>
<td>2001.1 – 2001.4</td>
<td>8</td>
<td>-6.2%</td>
<td>Dot-com bubble</td>
</tr>
</tbody>
</table>

Source: This table is complied from various sources including National Bureau of Economic Data, Romer (2008), Gjerstand and Smith (2014), Caplan (1956) and Walsh (1993).

From 1982 to 2007, the US economy experienced only two mild recessions: the 1990-1991 recession (which is generally attributed to a combination of debt accumulation from the 1980s and the jump in oil prices during the Gulf War, amongst others31) and the 2000-2001 dot-com recession. This period of stability for the US marks the ‘Great Moderation’ period32.

2.6.2 Consumption and Investment

Personal consumption expenditure and fixed private investment are illustrated in Figure 2.3 and Figure 2.4. According to the Bureau of Economic Analysis (BEA), personal consumption expenditure represents a measure of the types of goods and services purchased by households in the US, while fixed private investment represents the spending by private firms, non-profit institutions and households on fixed assets in the US.

31 Walsh (1993) states that there are several factors that contributed to the mild recession during the 1990-1991 period. Besides the two factors mentioned, a credit crunch by bankers and monetary policy in the US are also considered key.

32 According to Romer (2008), this Great Moderation period is due to several factors: improvements in monetary policy, the increasing importance of the services sector, and a decline in supply side shocks (such as oil price shocks).
Consumption accounts for approximately 70 percent of GDP in the US, compared with investment, which accounts for approximately 15 percent. Unsurprisingly, both consumption and investment move together with one another and with periods of expansion and recession in the US. For example, the 1950s represents a period of prosperity for the US, during which consumption and investment increased significantly. On the other hand, the 1990-1991 recession, which is attributed in part to the Gulf War and oil price increases, resulted in a considerable decline in consumption and investment.
2.6.3 Hours worked and Real Wages

Figure 2.5 and Figure 2.6 below depict the average weekly hours worked and hourly compensation by the nonfarm business sector.

Figure 2.5: Year on Year Percentage Change in Weekly Hours Worked in Nonfarm Business Sector

Source: Federal Reserve Economic Databank

Figure 2.6: Year on Year Percentage Change in Hourly Compensation in Nonfarm Business Sector

Source: Federal Reserve Economic Databank
According to the Bureau of Labor Statistics (BLS), the nonfarm business sector is a subset of the domestic economy that excludes the economic activities of government, private households and non-profit organisations serving individuals and farms. Figure 2.5 shows that weekly hours worked in the nonfarm business sector displays persistent volatility, but the magnitude of this volatility is small, with the biggest movements coinciding with a 2 percent increase or decrease. Nominal hourly compensation in the nonfarm business sector is also illustrated in Figure 2.6. The period between the late 1960s and early 1980s shows considerable wage inflation in the US, which also coincides with a period of increased price inflation. During the early to mid 2000s, nominal wage inflation remains quite low and stable.

2.6.4 Inflation and the Short Term Interest Rate

The GDP implicit price deflator and the federal funds rate are given in Figure 2.7 and Figure 2.8 below. Examining the inflation rate, periods of high inflation are exhibited in the early 1950s (after the Korean War) and during the Great Inflation period from the late 1970s to the early 1980s.

Source: Federal Reserve Economic Databank

Figure 2.7: GDP Implicit Price Deflator

33 Inflation as measured by the annual growth rate of the GDP implicit deflator shows the rate of price change in the economy as a whole. The GDP implicit deflator is the ratio of GDP in current local currency to GDP in constant local currency’s
This high inflation period coincides with tight monetary policy in the US, when the federal funds rate increased significantly in an attempt to curb inflation. Over the Great Moderation period, inflation became more stable and the federal funds rate decreased significantly.

### 2.6.5 Data Transformation

Measurement equations are added to the model to allow one to link model variables with observable quarterly time series. This is done using the Kalman filter\(^{34}\). The measurement equations used in this model follow Smets and Wouters (2007) and are given as follows:

\[
Y_t = \begin{bmatrix} dlGDP_t \\ dlCONS_t \\ dlINVE_t \\ dlWAGE_t \\ IHOURS_t \\ dlINF_t \\ FEDFUNDS_t \end{bmatrix} = \begin{bmatrix} \tilde{y} \\ \tilde{\gamma} \\ \tilde{\eta} \\ \tilde{l} \end{bmatrix} = \begin{bmatrix} y_t - y_{t-1} \\ c_t - c_{t-1} \\ i_t - i_{t-1} \\ w_t - w_{t-1} \end{bmatrix}
\]

where \( l \) and \( dl \) represent log and log difference respectively. \( \tilde{y} = 100(\gamma - 1) \) represents the common quarterly growth rate to real GDP, consumption, investment

\(^{34}\) For details on this and the use of the measurement equation see Cuthbertson et al (1993), Kim & Nelson (1999) & Commandeur & Koopman (2007).
and wages. The quarterly steady-state inflation rate is given as $\bar{\pi} = 100(\pi_* - 1)$ and the steady-state nominal interest rate is given as $\bar{r} = 100(\beta^{-1}\gamma^\sigma\pi_* - 1)$. Finally, $\bar{l}$ represents the steady-state hours worked, which is normalised to zero.

2.7 **Estimations & Results**

2.7.1 **Prior and Posterior Distributions**

The prior and posterior parameters estimated by the model are given in Table 2.4. The parameters characterising output are the steady state growth rate and the exogenous spending shock. In the model, the prior mean is 0.4. The posterior mean estimated by the model is 0.49. The parameters characterising consumption are the elasticity of intertemporal substitution and the habit parameter. The elasticity of intertemporal substitution represents the degree to which people prefer a stable rate of consumption relative to a higher rate of consumption in the future.

It can be measured by the response of the rate of change in consumption to changes in the expected real interest rate. When the elasticity of intertemporal substitution is lower than the prior mean, it is assumed that there is a lower sensitivity of consumption to changes in the real interest rate. In the model, the prior mean is set at 1.5. The resulting posterior mean is 1.28. The prior mean for the habit parameter is 0.7. The posterior mean is estimated to be higher at 0.81. According to Harrison and Oomen (2010), households derive utility from keeping consumption close to its previous aggregate level as well as higher levels of lifetime consumption. A higher degree of habit persistence will reduce the interest rate elasticity of consumption for a given elasticity of substitution. The rate of consumption is therefore more greatly affected by consumer’s habits than movements in the real interest rate.

The parameters characterising investment are the elasticity of the capital adjustment cost function and the discount factor. From Groth (2008), the capital adjustment cost function represents the cost of changing the level of investment. Investment adjustment costs induce inertia in investment causing it to adjust slowly to shocks. As in Christiano, Eichenbaum and Evans (2005), a higher elasticity of the cost of adjusting capital reduces the sensitivity of investment to the real value of capital stock. In our model, the prior mean is 4. The posterior mean is higher at 7.19.
## Table 2.4: Prior and Posterior Distribution

<table>
<thead>
<tr>
<th></th>
<th>Prior Distribution</th>
<th>Posterior Distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Distribution</td>
<td>Mean</td>
</tr>
<tr>
<td>Elasticity of capital adjustment</td>
<td>Normal</td>
<td>4.00</td>
</tr>
<tr>
<td>Elasticity of intertemporal substitution</td>
<td>Normal</td>
<td>1.50</td>
</tr>
<tr>
<td>Habit Parameter</td>
<td>Beta</td>
<td>0.70</td>
</tr>
<tr>
<td>Degree of Wage Stickiness</td>
<td>Beta</td>
<td>0.50</td>
</tr>
<tr>
<td>Elasticity of Labour Supply</td>
<td>Normal</td>
<td>2.00</td>
</tr>
<tr>
<td>Degree of Price Stickiness</td>
<td>Beta</td>
<td>0.50</td>
</tr>
<tr>
<td>Wage Indexation</td>
<td>Beta</td>
<td>0.50</td>
</tr>
<tr>
<td>Inflation Indexation</td>
<td>Beta</td>
<td>0.50</td>
</tr>
<tr>
<td>Elasticity of Capital Utilisation Adjustment Cost Function</td>
<td>Beta</td>
<td>0.50</td>
</tr>
<tr>
<td>Share of Fixed Costs in Production</td>
<td>Normal</td>
<td>1.25</td>
</tr>
<tr>
<td>Interest rate Response to Inflation</td>
<td>Normal</td>
<td>1.50</td>
</tr>
<tr>
<td>Degree of Interest Rate Smoothing</td>
<td>Beta</td>
<td>0.75</td>
</tr>
<tr>
<td>Interest Rate Response to Output</td>
<td>Normal</td>
<td>0.125</td>
</tr>
<tr>
<td>Interest Rate Response to Output Gap</td>
<td>Normal</td>
<td>0.125</td>
</tr>
</tbody>
</table>
Investment is therefore less sensitive to changes in the real value of capital stock.

The prior and posterior mean on the discount factor are similar at 0.25 and 0.23, respectively. Next, examining the parameters regarding nominal rigidities, the prior mean on both price and wage stickiness is 0.5. The posterior mean for the wage stickiness is higher at 0.78, while the posterior mean for the price stickiness is only marginally higher than the prior at 0.54. This suggests that wages are reset less frequently than initially assumed. The posterior mean for the degree of price indexation and wage indexation is 0.25, and 0.53, respectively. Finally, we examine the parameters related to the monetary policy reaction function. According to the Taylor (1995) rule, monetary authorities adjust the policy controlled interest rate in response to inflation and the output gap. The posterior mean of the long-run reaction coefficient to inflation is estimated to be relatively high at 1.80. There is also considerable degree of interest rate smoothing as the mean of the coefficient on the lagged interest rate is estimated to be 0.88. Policy does not appear to react very strongly to the output gap or changes in the output gap at 0.12 and 0.10, respectively.
Table 2.5:
Prior and Posterior Distributions of the Shock Processes

<table>
<thead>
<tr>
<th>Shock Processes</th>
<th>Prior Distribution</th>
<th>Mean</th>
<th>Standard Deviation</th>
<th>Mean</th>
<th>5% CI</th>
<th>95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>TFP</td>
<td>Inverse Gamma</td>
<td>0.10</td>
<td>2.00</td>
<td>0.5552</td>
<td>0.5062</td>
<td>0.6049</td>
</tr>
<tr>
<td>Investment</td>
<td>Inverse Gamma</td>
<td>0.10</td>
<td>2.00</td>
<td>0.5499</td>
<td>0.4687</td>
<td>0.6297</td>
</tr>
<tr>
<td>Risk Premium</td>
<td>Inverse Gamma</td>
<td>0.10</td>
<td>2.00</td>
<td>0.3624</td>
<td>0.3145</td>
<td>0.4112</td>
</tr>
<tr>
<td>Exogenous Spending</td>
<td>Inverse Gamma</td>
<td>0.10</td>
<td>2.00</td>
<td>0.6627</td>
<td>0.6127</td>
<td>0.712</td>
</tr>
<tr>
<td>Price Mark-Up</td>
<td>Inverse Gamma</td>
<td>0.10</td>
<td>2.00</td>
<td>0.2145</td>
<td>0.1812</td>
<td>0.2494</td>
</tr>
<tr>
<td>Wage Mark-Up</td>
<td>Inverse Gamma</td>
<td>0.10</td>
<td>2.00</td>
<td>0.2457</td>
<td>0.2172</td>
<td>0.2737</td>
</tr>
<tr>
<td>Monetary Policy</td>
<td>Inverse Gamma</td>
<td>0.10</td>
<td>2.00</td>
<td>0.2274</td>
<td>0.2082</td>
<td>0.2461</td>
</tr>
</tbody>
</table>

Autoregressive Parameters of the Shock Processes

<table>
<thead>
<tr>
<th>Shock Processes</th>
<th>Distribution</th>
<th>Mean</th>
<th>Standard Deviation</th>
<th>Mean</th>
<th>5% CI</th>
<th>95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>TFP</td>
<td>Beta</td>
<td>0.50</td>
<td>0.20</td>
<td>0.976</td>
<td>0.9666</td>
<td>0.9858</td>
</tr>
<tr>
<td>Risk Premium</td>
<td>Beta</td>
<td>0.50</td>
<td>0.20</td>
<td>0.1587</td>
<td>0.0489</td>
<td>0.262</td>
</tr>
<tr>
<td>Exogenous Spending</td>
<td>Beta</td>
<td>0.50</td>
<td>0.20</td>
<td>0.958</td>
<td>-0.9422</td>
<td>0.9741</td>
</tr>
<tr>
<td>Investment Specific</td>
<td>Beta</td>
<td>0.50</td>
<td>0.20</td>
<td>0.6553</td>
<td>0.5759</td>
<td>0.7298</td>
</tr>
<tr>
<td>Monetary Policy</td>
<td>Beta</td>
<td>0.50</td>
<td>0.20</td>
<td>0.2188</td>
<td>0.1257</td>
<td>0.3114</td>
</tr>
<tr>
<td>Price Mark-Up</td>
<td>Beta</td>
<td>0.50</td>
<td>0.20</td>
<td>0.9773</td>
<td>0.9609</td>
<td>0.9946</td>
</tr>
<tr>
<td>Wage Mark-Up</td>
<td>Beta</td>
<td>0.50</td>
<td>0.20</td>
<td>0.9656</td>
<td>0.9459</td>
<td>0.9865</td>
</tr>
</tbody>
</table>
In Table 2.5, the prior and posterior distributions for the shock processes are presented. The autoregressive coefficients on the shock parameters suggest that productivity shocks, exogenous spending shocks and price and wage mark-up shocks are highly correlated, with all coefficients over 0.95. Monetary policy shocks and risk premium shocks are the least persistent, with values of 0.21 and 0.15, respectively.

### 2.7.2 Model Evaluation

To evaluate the DSGE model, the variance decomposition, impulse response functions and model forecasts are provided in the following sections.

**Variance Decomposition**

The variance decomposition allows us to identify the contribution each shock has in generating fluctuations in endogenous variables. The results are given in Table 2.6 below.

<table>
<thead>
<tr>
<th>Variable</th>
<th>TFP</th>
<th>Risk Premium</th>
<th>Exogenous spending</th>
<th>Investment specific</th>
<th>Monetary policy</th>
<th>Price mark-up</th>
<th>Wage mark-up</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output</td>
<td>15.85</td>
<td>26.61</td>
<td>25.49</td>
<td>19.7</td>
<td>6.52</td>
<td>2.89</td>
<td>2.94</td>
</tr>
<tr>
<td>Consumption</td>
<td>7.47</td>
<td>71.48</td>
<td>0.95</td>
<td>0.98</td>
<td>10.81</td>
<td>2.49</td>
<td>5.82</td>
</tr>
<tr>
<td>Investment</td>
<td>4.95</td>
<td>6.08</td>
<td>1.59</td>
<td>78.27</td>
<td>4.31</td>
<td>3.15</td>
<td>1.65</td>
</tr>
<tr>
<td>Inflation</td>
<td>4.61</td>
<td>0.59</td>
<td>0.86</td>
<td>2.39</td>
<td>6.88</td>
<td>46.27</td>
<td>38.4</td>
</tr>
<tr>
<td>Interest rate</td>
<td>7.06</td>
<td>5.02</td>
<td>3.35</td>
<td>10.94</td>
<td>12.25</td>
<td>29.71</td>
<td>31.67</td>
</tr>
<tr>
<td>Hours worked</td>
<td>6.36</td>
<td>6.03</td>
<td>10.31</td>
<td>15.11</td>
<td>7.15</td>
<td>13.75</td>
<td>41.29</td>
</tr>
<tr>
<td>Real wage</td>
<td>11.28</td>
<td>0.71</td>
<td>0.13</td>
<td>1.77</td>
<td>1.01</td>
<td>42.66</td>
<td>42.44</td>
</tr>
</tbody>
</table>

It is clear that price and wage mark-up shocks are the biggest determinants of fluctuations in inflation, the interest rate and the real wage, which on aggregate account for 84.7 percent, 61.4 percent, and 85 percent respectively, over the sample period. Risk premium shocks are the main drivers of fluctuations in consumption (70 percent) and to a lesser extent output (26 percent), which is equally affected by exogenous spending shocks (25 percent). Not surprisingly, investment specific
shocks cause the biggest movements to investment at 78 percent. Monetary policy shocks do not appear to be an important source of business cycle fluctuation.

**Historical Shock Decomposition**

To further assess the importance of various shocks at particular points in time during the sample period, we can estimate the historical shock decomposition for each of the variables, and are illustrated in Figures 2.9 to 2.15.

Risk premium shocks and exogenous spending shocks are the key driver of fluctuations in output for the US economy. Negative productivity shocks from 2006Q3 onwards coincide with a (small) decline in output. Price mark up shocks turn negative between (2000Q3 and 2003Q3) and continue to do so over the remaining sample period. The decline in output just before 2007Q4 is driven by negative investment shocks. Overall, output appears to be driven by a combination of many different shocks.

![Figure 2.9: Historical Shock Decomposition: Output](image-url)

61
Figure 2.10: Historical Shock Decomposition: Consumption

Figure 2.11: Historical Shock Decomposition: Investment
The decline in consumption prior to 2000Q3 was a result of negative risk premium shocks. Positive price mark up shocks offset the decline. Their impact is small however. Again, the decline in consumption in the period preceding 2003Q3 was due to negative risk premium shocks. Positive productivity and monetary policy shocks are small. Positive risk premium shocks allow for the increase in consumption preceding the decline. Prior to 2007Q4, consumption is marginally below the steady state, where monetary policy and productivity shocks are becoming more important.

Investment specific shocks result in fluctuations in investment. An analysis of the historical shock decomposition shows that negative investment shocks caused a decline in investment prior to 2003Q3. Positive monetary policy shocks were too small to offset the decline, which continues for some time. It is only when investment shocks turn positive that we see an increase in investment. This is consistent over the entire sample examined. Analysis of the historical shock decomposition shows that negative wage mark up shocks keep inflation below the steady state level. While positive price mark up shocks are large, they do little in causing a change in inflation.

![Figure 2.12: Historical Shock Decomposition: Federal Funds Rate](image)
Figure 2.13: Historical Shock Decomposition: Inflation Rate

Fluctuations in the real wage are directly as a result of both positive and negative wage and price mark-up shocks. Movements in the hours worked variable are driven positively by wage mark-up shocks and negatively by a combination of exogenous spending, and price mark-up shocks. Monetary policy and productivity shocks become more influential towards the end of the sample, but still have little impact.

Figure 2.14: Historical Shock Decomposition: Real Wage
The decline in the interest rate from 2001 to 2007 coincides with negative wage mark up shocks and investment shocks. Price mark-up shocks contribute positively to the interest rate, over the sample shown. The increase in the interest rate prior to 2007Q4 is as a result of both positive monetary policy shocks and price mark-up shocks.

**Impulse Response Functions**

The impulse response functions are given in Figures (A.2.4.1-A2.4.7) in the appendix of this thesis. The risk premium shock causes an increase in all variables over the short to medium term, however the impact is less pronounced for the real wage, inflation and interest rate variables. The productivity shock causes an increase in output, consumption, investment, and the real wage, which lasts into the short-to-medium term. A decline in hours worked and inflation is observed, which lasts for the short term. The negative impact on the interest rate lasts into the medium term. Exogenous spending shocks cause a decline in consumption and investment, which lasts into the short-to-medium term. The positive impact on the real wage turns negative after one year and does not return to the steady state in the medium-to-long term. Output and hours worked increase, as does inflation and the interest rate, but
only marginally. A monetary policy shock causes a decline in all variables considered, with the exception of the interest rate, which increases by 0.2. The impact of the shock lasts for the short to medium term.

A price mark-up shock results in a 0.3 increase in inflation, which lasts into the medium-to-long term. The interest rate also increases as a result of the shock. All other variables decline with the real wage variable experiencing the biggest fall. This effect dissipates quickly and the real wage returns to its steady state. The decline in hours worked becomes more pronounced in the medium term and does not return to its steady state. An investment specific shock causes an increase in all variables considered, with the impact on investment being the most significant. Inflation increases slightly initially, however this increase turns negative over the medium term. The wage mark-up shock causes the real wage, inflation and interest rate variables to increase. It causes very small declines in the remaining variables.

**Forecasting performance**

The model is forecast for horizons \( h \in \{0, 1, 2, 3, 4\} \), thereby providing a four quarter ahead forecast. Figure 2.16 shows the forecasts of the key endogenous variables in the model along with the 90 percent confidence bands. The variables are as expressed in the model, i.e. subject to the measurement equations and in terms of their deviation from the steady state. The dashed line represents the forecast made by the DSGE model and the solid line represents the observed time series. The green lines represent the 90% confidence interval. As is apparent in the graphs, DSGE models were unable to foresee a downturn in the economy. The model predicts a steady to slight increase in output over the next four quarters. In fact, what we observe is a steady decline in output. The observed data falls outside the 90% confidence interval, as given by the model. Consumption is also forecast to remain steady over the coming quarters, when the observed data shows a significant decline in consumption. The steep decline in investment is apparent from the graphs; however, the DSGE model forecasts an expected increase in investment over the next four quarters. As with output, both consumption and investment data are outside the 90 percent confidence intervals. Forecast predictions of inflation are good, for the short term at least, and are almost in line with observed inflation. In forecasting the
interest rate the model does well in foreseeing an interest rate cut, however the magnitude is less that what the model expected. It is however, within the 90 percent confidence interval. The DSGE model does not do well in forecasting the sharp decline and subsequent increase in the real wage, which it forecasts to decrease slightly and then remain steady over the next year.

![Figure 2.16: DSGE Model Forecast](image)

The *solid* line represents the actual time series observed and the *dashed* line is the DSGE model forecast. The green lines represent the 90% confidence intervals. The *x*-axis is the forecast horizon.

In a bid to assess the forecasting performance of the DSGE model with other model based forecasts, a Bayesian VAR (BVAR) model is estimated. The forecasts made by the BVAR model are provided in Figure 2.17 along with the DSGE model forecasts and the observed data. The blue line is the actual time series observed. The green line is the BVAR model forecast and the red line is the DSGE model forecast. The BVAR model does a better job of forecasting output, consumption and investment. We see that the BVAR model picks up a decline in output; however it does not accurately forecast the magnitude of the decline. Unlike the DSGE model which predicts an increase in investments, the BVAR forecasts a small decline in investment over the next year. As with the DSGE model, the BVAR model does well in predicting inflation. It over-predicts the increase in hours worked, and under-
predicts the interest rate forecast, however it does a better job of forecasting the decline in the real wage.

![Figure 2.17: BVAR & DSGE Model Forecast](image)

The blue line is the actual time series observed. The green line is the BVAR model forecast and the red line is the DSGE model forecast.

To evaluate the forecast accuracy of the models, the root mean squared error (RMSE) of the DSGE model and the BVAR model is computed and reported in Table 2.7. The RMSEs are reported for each variable.

The reported output, consumption, investment and real wage RMSE’s are smaller in the BVAR model. There is considerable difference between the RMSE reported for the investment variable in both models. The BVAR model estimates an RMSE of 2.68 percent, while the DSGE model reports a RMSE of 4.39 percent. However, the DSGE model does a better job of forecasting the interest rate and hours worked. Both the DSGE model and the BVAR model have a very similar RMSE for inflation.
Table 2.7: RMSE for DSGE & BVAR Models

<table>
<thead>
<tr>
<th>Variable</th>
<th>DSGE Model</th>
<th>BVAR Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output</td>
<td>1.9798</td>
<td>1.22</td>
</tr>
<tr>
<td>Consumption</td>
<td>1.9927</td>
<td>1.6814</td>
</tr>
<tr>
<td>Investment</td>
<td>4.3921</td>
<td>2.6827</td>
</tr>
<tr>
<td>Inflation</td>
<td>0.2755</td>
<td>0.2652</td>
</tr>
<tr>
<td>Interest Rate</td>
<td>0.518</td>
<td>1.6587</td>
</tr>
<tr>
<td>Real Wage</td>
<td>0.8427</td>
<td>0.5783</td>
</tr>
<tr>
<td>Hours Worked</td>
<td>0.8897</td>
<td>1.8134</td>
</tr>
</tbody>
</table>

These findings are consistent with those of Edge and Gurkaynak (2010), Del Negro and Schorfheide (2012) and Wickens (2014). These authors compare model based forecasts of the DSGE model and a BVAR model with those made by the Federal Reserve Board of Governors ‘Greenbook’ forecasts and Blue Chip consensus forecasts. They find that short run forecasts of DSGE models are not as good as those of professional forecasts, however Del Negro and Schorfheide (2012) argue that over the medium to long term, forecasts of output and inflation become more competitive with the professional forecasts.

35 Greenbook projections contain variables forecast by the the Federal Reserve Bank of Philadelphia’s Survey of Profession Forecasters (SPF). These variables include real GDP and its components, nominal GDP, five measures of inflation, unemployment, industrial production, and housing starts. The Greenbook is produced before each meeting of the Federal Open Market Committee (FOMC). Using an assumption about monetary policy, the Research staff at the Board of Governors prepares projections about how the economy will fare in the future. More information is available at https://www.philadelphiafed.org/research-and-data/real-time-center/greenbook-data

36 Blue chip consensus forecast, or blue chip economic indicators, are survey poll from top business economists in the US with their macroeconomic forecasts of the US economy. These forecasts include inflation, interest rate, economic growth, and other critical indicators of future business activity
2.8 Limitations of DSGE Models

The global financial crisis has sparked renewed debate over the state of macroeconomic modelling, particularly in the lead up to the 2008/2009 Great Recession. Given the foundations upon which DSGE models are built, it should come as no surprise that DSGE models have been heavily criticised in the literature. Within the prototypical framework, agents are assumed to be homogenous and optimizing with rational expectations. No endogenous instability exists in the model. Perturbations in the economy are the result of exogenous shocks which cause the economy to deviate from its steady state. Moreover, money within the model is merely a unit of account and there is no role for financial intermediaries, since financial markets are assumed to be complete and perfectly frictionless. Perfectly frictionless markets assume that agents can borrow or lend at the risk free interest rate and there is no risk that they will default on their loan. As discussed by Goodhart and Tsomocos (2011), if everyone always repaid their debts with certainty, then there would be no need for money, financial instruments, or financial intermediaries such as banks, since agents would fully repay their debt on time and in full.

This assumption of perfectly frictionless financial markets within DSGE models has been the subject of much debate within the literature. For example, Curdia & Woodford (2009) state that a single interest rate is sufficient within the DSGE model framework to represent the policy rate used as the operating target for central banks, the rate of return on savings for households and firms, and to represent the rate at which anyone can borrow against future income. As such, the DSGE model does not include the concept on interest rate spreads that exist in the real economy since frictionless financial markets exist and all interest rates are assumed equal. In addition, Gertler & Karadi (2009) note the credit market interventions undertaken by the Federal Reserve since the onset of the Great Recession, where the quantity of assets held increased from approximately eight hundred billion to over two trillion after the collapse of Lehmann Brothers. Since DSGE models assume frictionless financial markets, they are not in a position to account for central bank interventions that often occur after financial market disruptions.
The inclusion of debt within a DSGE model in its current form however is not possible due to the addition of the transversality condition, which ensures that money, bonds and capital do not grow too quickly:

\[
\lim_{t \to \infty} \beta^t \lambda_t \frac{M_t}{P_t} = 0 \tag{2.30}
\]

\[
\lim_{t \to \infty} \beta^t \lambda_t \frac{B_t}{P_t} = 0 \tag{2.31}
\]

\[
\lim_{t \to \infty} \beta^t \lambda_t K_{t+1} = 0 \tag{2.32}
\]

As such, the transversality condition within the DSGE model does not allow for endogenous asset price bubbles to exist. As noted by Vleck and Roger (2012), deviations of relative asset prices from their fundamental values are therefore modelled as exogenous shocks with high persistence. Indeed Motto and Rostagno (2009) contend that, if general equilibrium models are to be useful, then liquidity conditions that are relevant for both economic and financial decisions must be included. This concept of perfectly frictionless financial markets is clearly at odds with what we observe occurring in the real economy, particularly given the financial nature of the Great Recession, as outlined in Chapter 1 of this thesis.

2.9 Conclusions

As stated in the introduction of this chapter, DSGE models are used by academics and policy-makers alike for many different reasons; policy analysis, to identify the source of business cycle fluctuations, for counterfactual analysis, and forecasting. The objective of this chapter was to critically assess the empirical properties of the prototypical macroeconomic model used by central banks and policy makers in the run up to the Great Recession. Given this objective, a DSGE model is estimated for the pre-crisis period up to 2007Q4. The results of this indicate that the output given by the model provides little evidence for policy makers that a recession is imminent.

We suggest that the foundations of DSGE models, in their current form, are too simplistic to cope with assessing the onset of economic crisis periods since they omit the financial side of the economy. In order to account for the real and financial interlinkages which we observe in the economy, the new class of DSGE model must
incorporate a role for financial frictions if they are to be useful for both policymakers and academics alike. Given the financial nature of the Great Recession, it is imperative that the new generation of DSGE models includes financial frictions within their models, and allows a clear role for money, debt, and the possibility of default, if these models are to be useful for policy analysis and forecasting.

Two conclusions are therefore uncovered in this chapter. The first conclusion is methodological in nature and shows that linearised models, such as the DSGE model, cannot capture adequately the nonlinear dynamics, such as regime changes and asymmetries that are inherent in macroeconomic data. These nonlinear features arise as a result of complex interlinkages within the macroeconomy. The second conclusion is substantive in nature. This chapter shows that a DSGE model, without financial variables, cannot represent the true nature of the complex macroeconomy. This is particularly notable when one considers the impact of the tranversality condition on general equilibrium models, whereby bubble formation, and debt accumulation, are not possible. Given the nature of the Great Recession, the omission of this salient feature is likely to have tremendous impacts on the policy decisions, particularly given their prevalence among central banks.

Given the main findings of this chapter, the next chapter will establish the empirical properties of macroeconomic and financial data. Following this, Chapter 4 will examine monetary policy transmission in the US and will include a role for the financial economy, through the addition of house prices and credit to the nonfinancial private sector. The model used will be the nonlinear Markov switching model, which will allow for regime changes and asymmetries.
CHAPTER 3

EMPIRICAL PROPERTIES OF MACROECONOMIC DATA

3.1 Introduction

Methodologically, Chapter 2 noted that linearised models of the complex macroeconomy cannot appropriately capture the key dynamics of most macroeconomic and financial data, and ultimately, the types of interactions that occur between them. These interactions can include asymmetries, regime change, and as such, nonlinear behaviours. Given this, the objective of this chapter is to examine the nonlinear properties of both macroeconomic and financial variables. While linear models can have many advantages over their nonlinear counterparts: they are parsimonious, easily comparable, and allow for regression analysis, they do however assume that any irregularity in the model is due to some random element, rather than representing a key feature of the underlying system (Kantz and Schreiber, 2003). Scheinkman (1990) notes that, within the context of business cycle modelling, the reliance on linear models occurs for two reasons. Firstly, nonlinear systems seemed incapable of replicating the key statistical aspects of economic data. For example, the explanation of economic fluctuations had to rely solely on the inclusion of exogenous shock processes that could recreate the randomness observed in general equilibrium models (this is still prevalent in more up-to-date macroeconomic general equilibrium models, such as the DSGE model estimated in Chapter 2). Secondly, linear models could empirically capture key features of aggregate time series. For example, low order autoregressive models (AR(1)) models could, in principal, results from an economy with complete markets where production was subject to some exogenous shock. Given both these features, Scheinkman (1990) states that there was no obvious gain in introducing nonlinearity, and as a result, they fell out of favour within macroeconomics.

The main concept behind theoretical linear models is that the series is independently and identically distributed (i.i.d.). From Granger and Teräsvirta (1993), a series \( \varepsilon_t \)
t = 1, . . . , T is i.i.d. if all the terms are independent of each other and all have the same distribution. If \( x_t \) is the probability density function of \( \varepsilon_t \) then, \( p_t(x) = p(x) \) for all \( t \) and the joint distribution of any set of \( n \) components of \( \varepsilon_i \) is the product of the marginal distributions. If the sequence up to time \( T \) is observed, then the value taken at time \( T + 1 \) will be in no way affected by the earlier values and will be drawn from the same distribution.

Since strong restrictions are required for a process to be i.i.d., it may be sufficient to consider a simpler, ‘white noise’ process, particularly when linear models are used. A white noise process is one with no identifiable structure, where the mean and the variance are constant and where there is zero autocovariances, except at lag zero:

\[
E(y_t) = \mu \tag{3.1}
\]

\[
\text{var}(y_t) = \sigma^2 \tag{3.2}
\]

\[
y_{t-r} = \begin{cases} 
\sigma^2 & \text{if } t = r \\
0 & \text{otherwise} 
\end{cases} \tag{3.3}
\]

If these three conditions hold, the process is known as zero mean white noise (Brooks, 2014). One of the simplest classes of linear time series models used in macroeconomic analysis is the autoregressive moving average (ARMA) model. The ARMA model contains two key class of model: the autoregressive process and the moving average process.

### 3.2 Linear Macroeconomic Model: ARMA

An autoregressive process is one in which the current value of a variable, \( y_t \), depends only on the values that the variable has taken in previous periods, plus an error term. An autoregressive model of order \( p \) can be expressed as:

\[
y_t = \mu + \phi_1 y_{t-1} + \phi_2 y_{t-2} + \cdots + \phi_p y_{t-p} + u_t \tag{3.4}
\]

where \( \mu \) is the constant term, and \( u_t \) is a white noise disturbance term that follows the properties outlined in equation (3.1-3.3) above. Equation (3.4) therefore refers to an AR(\( p \)) model, where the order of the model is given by \( p \).
A moving average process is a linear combination of white noise processes, so that \( y_t \) depends on the current and previous values of a white noise disturbance term, \( u_t \). A moving average model of order \( q \) can be expressed as:

\[
y_t = \mu + u_t + \phi_1 u_{t-1} + \phi_2 u_{t-2} + \cdots + \phi_q u_{t-q}
\]  

Equation (3.5) refers to an \( \text{MA}(q) \) model, where the order of the model is given by \( q \). The combination of the \( \text{AR}(p) \) and \( \text{MA}(q) \) models results in an \( \text{ARMA}(p, q) \) model, whereby the values of \( p \) and \( q \) determine the length of the linear models memory. In addition to the \( \text{ARMA}(p,q) \) model is the \( \text{ARIMA}(p,d,q) \) model which refers to an integrated \( \text{ARMA}(p,q) \) model. An integrated autoregressive model is one whose characteristic equation has a root on the unit circle, thereby implying that the data is non-stationary. In order to remove the non-stationary component of the time series, the data is differenced, or integrated, by order \( d \).

### 3.3 Nonlinear Dependence

Brock, Dechert, and Scheinkman (1996), henceforth BDS, present a test of independence that can be applied to the estimated residuals of any time series model. The idea is that a proposed model (for example, an \( \text{ARIMA} \) model, or a \( \text{GARCH} \) model) is estimated, and the BDS test is applied to the residuals to determine if any remaining structure is present. This is a pure hypothesis test whereby the null hypothesis is that the time series sample comes from a data generating process that is independently and identically distributed (i.i.d). If the proposed model is adequate, the residuals of the model should be white noise (i.i.d). If the null hypothesis is rejected, then the proposed model is insufficient to capture all of the relevant features of the data, and the BDS test statistic will be statistically significant.

The concepts of the correlation integral and correlation dimension are important in the BDS test. The correlation integral, as introduced by Grassberger and Procaccia (1983), sought to measure the fractal dimension of deterministic data. The correlation integral is defined by Brock et al. (1996) as a measure of the frequency with which temporal patterns are repeated in the data. The correlation dimension can be estimated using the correlation integral and measures the dimensionality of the fractal.
From Diks (2003), let \( \{X_t\}_{t=1}^N \) denote a sequence of length \( N \) of scalar observations from a stationary time series process. For a selected value of \( m \), the time series is embedded into an \( m \) dimensional vectors where the \( m \)-histories \( X_t^m \) are defined as \( \left( X_t, \cdots, X_{t+m-1} \right)^T \). The correlation integral at embedding dimension \( m \) is given by

\[
C_{m,n}(\epsilon) = \frac{2}{n(n-1)} \sum_t \sum_{s,s<t} I_{[0,\epsilon]} \left( \| x_t^m - x_s^m \| \right)
\]

(3.6)

where \( I(.) \) is an indicator function that takes a value of either 0 or 1 according to:

\[
I_{[0,\epsilon]}(s) = \begin{cases} 
1 & \text{if } S \in [0,\epsilon] \\
0 & \text{if } S \notin [0,\epsilon] 
\end{cases}
\]

(3.7)

and \( \| \cdot \| \) denotes the supremum norm, given by:

\[
\| u \| = \sup_{i=1, \cdots, m} |u_i|
\]

(3.8)

The correlation integral counts the number of points that are within a distance, \( \epsilon \), of each other in an \( m \)-dimensional space. If the data is generated by a strictly stationary stochastic process which is absolutely regular, then the following limit exists:

\[
\lim_{n \to \infty} C_{m,n}(\epsilon) = C_m(\epsilon)
\]

(3.9)

If the data is independent then this implies that:

\[
C_m(\epsilon) = [C_1(\epsilon)]^m
\]

(3.10)

The standarised BDS test statistic is given as:

\[
T = \frac{\sqrt{n}(C_m(\epsilon)-C_1(\epsilon)^m)}{\sigma_m(\epsilon)}
\]

(3.11)

which is shown by Brock et al. (1996) to be normally distributed with \( N(0,1) \).

Barnett et al. (1997) designed a single-blind controlled competition among five highly regarded tests for nonlinearity or chaos with ten simulated data series. Five generating models were used to produce both large and small sample sizes. The models included a fully deterministic, chaotic Feigenbaum recursion, a generalised autoregressive conditional heteroskedasticity (GARCH) process, a nonlinear moving average process, an autoregressive conditional heteroskedasticity (ARCH) process
and an autoregressive moving average (ARMA) process. Therefore, two of the data sets were purely deterministic and chaotic, while eight of the data sets were stochastic processes in which Monte Carlo simulations were used to produce randomness. Their results indicate that, within large samples, the BDS test successfully detected nonlinearity in all the data sets. The results are similar with a smaller sample size particularly in the two extreme cases of linearity and chaos. If linearity is rejected with the BDS test, it becomes reasonable to attempt to distinguish among the possible forms of nonlinearity.

3.4 Testing for Independence in Macroeconomic Data

The BDS test is carried out on a range of macroeconomic data for the United States and includes: real GDP, consumption, investment, federal funds rate, inflation, credit, house prices, and the unemployment rate. The data considered is over the period 1976Q1 to 2014Q3 and is obtained from the Federal Reserve Economic Databank. Credit to the nonfinancial private sector is obtained from the Bank for International Settlements37. With the exception of the federal funds rate, all variables are expressed as the year on year percentage change. The summary statistics for each of the variables is provided in Table 3.1 below. The first and second moments of the data are provided in the second and third columns of Table 3.1. If the data follow a normal distribution, then these two moments (mean and variance) should be sufficient to describe the entire series. However, it is often necessary, particularly with financial and economic time series, to examine the higher moments of the data (i.e. the skewness and kurtosis) to fully characterise the series. If the data are normally distributed, then skewness should be zero and kurtosis should be equal to three. It is clear that the variables are characterised by both positive and negative skewness. For example, the skewness for the inflation rate and consumption is 1.60 and -0.65 respectively. Examining kurtosis reveals all series, with the exception of credit and the unemployment rate, are leptokurtic. Leptokurtic distributions are those which have fatter tails and are more peaked at the mean than a normally distributed random variable (Brooks, 2014).

37 Credit to the nonfinancial private sector can be obtained from http://www.bis.org/statistics/totcredit.htm
Table 3.1: Descriptive Statistics and Selection of an ARIMA($p,d,q$) Model for a Sample of Macroeconomic Data

<table>
<thead>
<tr>
<th>Variable</th>
<th>Mean</th>
<th>Standard Deviation</th>
<th>Skewness</th>
<th>Kurtosis</th>
<th>Jarque-Bera</th>
<th>ARIMA ($p,d,q$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Real GDP</td>
<td>2.78</td>
<td>2.15</td>
<td>-0.58</td>
<td>4.21</td>
<td>17.69***</td>
<td>(1,0,3)</td>
</tr>
<tr>
<td>Consumption</td>
<td>2.97</td>
<td>1.79</td>
<td>-0.65</td>
<td>3.52</td>
<td>12.47**</td>
<td>(5,1,0)</td>
</tr>
<tr>
<td>Investment</td>
<td>6.25</td>
<td>7.69</td>
<td>-0.47</td>
<td>4.47</td>
<td>19.22***</td>
<td>(2,0,3)</td>
</tr>
<tr>
<td>Federal funds rate</td>
<td>5.45</td>
<td>4.03</td>
<td>0.73</td>
<td>3.47</td>
<td>14.67***</td>
<td>(1,1,1)</td>
</tr>
<tr>
<td>Inflation</td>
<td>3.22</td>
<td>2.17</td>
<td>1.60</td>
<td>4.75</td>
<td>83.81***</td>
<td>(1,1,3)</td>
</tr>
<tr>
<td>Credit</td>
<td>7.48</td>
<td>4.37</td>
<td>-0.49</td>
<td>2.87</td>
<td>6.28**</td>
<td>(1,1,3)</td>
</tr>
<tr>
<td>House prices</td>
<td>4.53</td>
<td>4.55</td>
<td>-0.24</td>
<td>3.58</td>
<td>3.51</td>
<td>(5,0,0)</td>
</tr>
<tr>
<td>Unemployment rate</td>
<td>6.44</td>
<td>1.58</td>
<td>0.63</td>
<td>2.76</td>
<td>10.41***</td>
<td>(2,0,0)</td>
</tr>
</tbody>
</table>

***, **, * denotes acceptance at the 1%, 5%, and 10% significance level respectively

To formally test for normality, the Jarque-Bera (1981) test can be applied, which tests the property that the entire distribution can be characterised by the first and second moments of the distribution. In doing so, the Jarque-Bera (1981) tests whether the coefficient of skewness and excess kurtosis are jointly zero. The null hypothesis of the Jarque-Bera (1981) test is of normality. Examining Table 3.1 shows that all variables, with the exception of house prices, reject the null hypothesis of normality at either the 1 percent or 5 percent significance levels. This implies that the underlying data is not normally distributed.

To undertake the BDS test, the best fitting linear model should be applied to the data to remove any linear serial dependence. Accordingly, the BDS test is carried out on the residuals of the linear model. Given that the BDS test works under the assumption that the series considered is an i.i.d. process, any serial dependence remaining should reflect the non-linear structure of the data set. The linear model applied in this instance is the ARMA ($p,q$) model. Prior to the application of the ARMA($p,q$) model, each of the variables are tested for stationarity using the Augmented Dickey Fuller (ADF) test. Consumption, the federal funds rate, inflation, inflation,

---

38 The kurtosis of the normal distribution is three, so excess kurtosis is zero, as given by (kurt – 3), Brooks (2014)
and credit to the nonfinancial private sector data were found to be non-stationary and first differences were taken accordingly. As such, an ARIMA\((p,d,q)\) model is estimated for those variables. In accordance with the literature, the most parsimonious linear model is determined using the Box-Jenkins (1970) selection criteria. The Box-Jenkins selection criteria involve three necessary steps to estimate an ARMA model. This includes (i) Identification of the order of the model to capture the key features of the data (ii) Estimation of the parameters of the model and (iii) Diagnostic checking to determine if the model specified and estimated is adequate. The models were chosen based on the lowest Akaike Information Criteria and Schwartz Bayesian Criteria and the highest Adjusted \(R^2\) value and the model chosen is provided in the final column of Table 3.1. For example, an ARIMA\((1,0,3)\) model is chosen for real GDP and an ARIMA\((1,1,1)\) is chosen for the federal funds rate. As stated above, the BDS test is then carried out on the residuals of the linear model. Therefore, for each of the ARIMA\((p,d,q)\) models applied to each of the eight variables, given in Table 3.1, the BDS test is estimated using their residuals.

Since the BDS statistic is a function of the embedding dimension \(m\) and the distance \(\epsilon\), careful consideration must be given when deciding on each respective value. For a given \(m\), \(\epsilon\) must not be too small because \(C_{m,n}(\epsilon)\) will capture too few points, nor should \(\epsilon\) be too large so that \(C_{m,n}(\epsilon)\) involves too many data points. Hsieh and LeBaron (1988a,b,c) choose \(\epsilon\) to optimise the size and power performance on their experimental design. They recommend choosing \(\epsilon\) between 0.5 and 1.5 standard deviations of the data. The choice of \(m\) depends upon which lag the investigator wishes to test for dependence. Embedding dimensions between 2 and 6 are the commonly applied in the literature. Once the optimal embedding dimension and distance values are decided, the BDS test can be computed. For the purpose of this analysis, \(\epsilon\) was chosen to be equal to 0.7 standard deviations, and the embedding dimension, \(m\), was allowed to vary from 2 to 6. Additionally, since the sample size of the variables are small (n=155), the BDS statistic is bootstrapped\(^{39}\) to ensure accurate results.

---

\(^{39}\) Brock and Sayers (1988) note the BDS statistic no longer follows a standard normal distribution when the sample size is small. Since the sample size is small, bootstrapping techniques can be applied to the probability estimates.
Table 3.2: BDS Test with $\varepsilon/\sigma = 0.7$ for a Sample of Macroeconomic Data

<table>
<thead>
<tr>
<th>Embedding Dimension ($m$)</th>
<th>Real GDP</th>
<th>Consumption</th>
<th>Investment</th>
<th>Federal Funds Rate</th>
<th>Inflation</th>
<th>Credit</th>
<th>House Prices</th>
<th>Unemployment</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>3.26**</td>
<td>1.06</td>
<td>1.72</td>
<td>5.13***</td>
<td>1.84</td>
<td>1.41</td>
<td>2.58**</td>
<td>3.73***</td>
</tr>
<tr>
<td>3</td>
<td>4.30***</td>
<td>2.71**</td>
<td>1.91</td>
<td>7.76***</td>
<td>2.65*</td>
<td>2.47**</td>
<td>4.61***</td>
<td>4.55***</td>
</tr>
<tr>
<td>4</td>
<td>3.60**</td>
<td>4.66***</td>
<td>1.49</td>
<td>9.09***</td>
<td>3.87**</td>
<td>3.55**</td>
<td>6.20***</td>
<td>5.42***</td>
</tr>
<tr>
<td>5</td>
<td>4.05**</td>
<td>5.26***</td>
<td>0.96</td>
<td>10.21***</td>
<td>3.89**</td>
<td>4.21**</td>
<td>9.05***</td>
<td>6.20***</td>
</tr>
<tr>
<td>6</td>
<td>4.66**</td>
<td>5.56***</td>
<td>0.91</td>
<td>11.51***</td>
<td>2.83</td>
<td>4.68**</td>
<td>12.95***</td>
<td>6.90***</td>
</tr>
</tbody>
</table>

***, **, * denotes acceptance at the 1%, 5%, and 10% significance level respectively
3.5 Discussion of the Results

The results of these estimations are provided in Table 3.2 above. As stated previously, the null hypothesis is that the time series sample comes from a data generating process that is independently and identically distributed (i.i.d). With the exception of investment, the null hypothesis is rejected for all other variables tested. For real GDP and credit, the results are significant at the 5 percent significance level. Consumption and inflation reject the null hypothesis at dimensions greater than 2, while the results for the federal funds rate and the unemployment rate are highly statistically significant with the null hypothesis rejected at the 1 percent significance level.

Similar results have been found in the literature. For example, Henry and Shields (2003) find strong evidence of nonlinearities in inflation rate data for the UK, Japan and the US. Additionally, Altavilla and Ladolfo (2005) study the application of the BDS test to the inflation rate for the Euro Area and the UK and find all tests reject the null hypothesis of a linear generating mechanism for the residuals of a linear model. Several authors, including Ho and Tsui (2003), Bodman and Crosby (2000) and Cancelo and Mourelle (2005) use the BDS test to examine nonlinearities in real GDP growth rates for a range of countries, including the US, and all, unequivocally, reject the hypothesis that all real GDP growth rate series are i.i.d. at the 1 percent significance level.

Finally, Brock and Sayer (1998) and Panagiotidis and Pelloni (2001) found strong evidence of nonlinearity in the US unemployment rate, along with Peel and Speight (1998) who found evidence of nonlinear structure in the residuals of the ARMA models for Germany, UK and the US. The evidence which emerges from this analysis is in agreement with some the current literature. With the exception of investment, all other variables exhibit significant nonlinearities, which cannot be captured successfully through the implementation of a linear model. One significant limitation of the BDS test, however, is that the source and structure of the nonlinearity in the data is not provided. For example, it does not distinguish between nonlinear stochastic processes and nonlinear deterministic processes, which if known, would improve economic and financial modelling. As such, additional tests would therefore be required to determine additional nonlinear features of the data.
For example, to determine if the data is chaotic, the Lyapunov exponent can be calculated which measures the sensitivity of the data to its initial conditions. To determine if the data is from a nonlinear deterministic process, or a nonlinear stochastic process, time delay embedding and the calculation of the correlation dimension can be undertaken to further assess the empirical properties of macroeconomic data.

3.6 Conclusions

The aim of this chapter was to examine the methodological issues arising from the DSGE model estimated in Chapter 2. Specifically, this chapter examines the empirical properties of macroeconomic time series to establish key its characteristics and features. This is particularly important when one considers the interaction between the real and financial economy, where regime change, asymmetries, and ultimately, nonlinearities arise. This analysis is therefore particularly important when understanding the transmission of monetary policy under financialisation, where the financial economy plays a pivotal role.

To achieve this aim, this chapter first set out the summary statistics of the main US macroeconomic and financial variables\(^{40}\) used in the thesis, along with the most parsimoniously chosen linear model – the ARIMA \((p,d,q)\) model. Firstly, examining the third and fourth moments of the distributions provides evidence of non-normality in the data: skewness is both positive and negative, and excess kurtosis is present. Using the Jarque-Bera test for normality, the null hypothesis is rejected at both the 5 percent and 1 percent significance levels for all variables, with the exception of house prices. Finally, four of the eight variables examined, contained unit roots and are therefore nonstationary; a feature typical of economic data.

Given the evidence of non-normality in the summary statistics of the variables examined, the BDS test is applied to the residuals of the fitted linear ARIMA model to determine if the residuals are independently and identically distributed. If the linear model fitted is appropriate, then no nonlinear dependence should remain in the residuals of the model. Instead, the residuals should be simply white noise. The results of this exercise found that, with the exception of investment, nonlinear

---

\(^{40}\) It excludes two variables from the analysis: hours worked and the real wage, neither of which feature in the following chapters of this thesis. It does, however, include the unemployment rate.
dependence was discovered in the residuals of the model variables. As such, this finding provides evidence that a fitted linear model, such as the ARIMA model, is insufficient in capturing all the relevant features of the data. Given this finding, the use of a linear model to examine the interaction between the real and financial economy, would be not be appropriate. Instead a nonlinear model, which allows for a wide variety of possible forms of nonlinearity, should be used.
CHAPTER 4

MONETARY POLICY TRANSMISSION IN THE US: A MARKOV SWITCHING APPROACH

4.1 Introduction

The objective of this Chapter is to examine the transmission mechanism of monetary policy under financialisation, particularly in light of the existence of the IS puzzle in the US. The crisis of 2008-09 that gripped the global economy has reignited interest in understanding the crucial roles of money, credit, and asset price fluctuations within the macroeconomy in an effort to understand their influence on the amplification, propagation, and generation of shocks both in normal times and, even more so, in times of financial distress (Schularick and Taylor, 2012). Within the current suite of popular macroeconomic models, the risk free short-term interest rate is sufficient to model the monetary side of the economy (Goodhart and Hofmann, 2008). As such, money, credit and asset prices do not interact within the standard versions of these models. Borio (2014) argues that the suitability of these models come under criticism when one considers the financial boom and subsequent bust phases experienced within the United States: credit and property prices surged for several years against the backdrop of strong financial innovation and an accommodative monetary policy.

The New Keynesian Model (NKM) of monetary policy has become the standard tool for the analysis of monetary policy transmission. This NK model consists of a Phillips curve, an Investment-Saving (IS) curve and a monetary policy rule. According to Goodhart and Hofmann (2005), the IS Curve represents the intertemporal Euler consumption equation that relates the output gap to the expected future output gap and the real interest rate, where an inverse relationship

41 For example, the DSGE models of Smets and Wouters (2003, 2007), and Christiano Eichenbaum and Evans (2005)
42 See for example, Clarida, Gali and Gertler (1999) and Walsh (2003)
43 For an outline of the derivation of the intertemporal Euler consumption equation, please refer to Appendix A4.1
between the two variables exists. In their highly influential 1992 paper “The Federal Funds Rate and Monetary Policy Transmission”, Bernanke and Blinder ask two questions; firstly, does monetary policy affect the real economy and secondly, if it does, what is the transmission through which these effects occur. Using a structural vector autoregressive model, the relationship between money, credit and income on the real economy are examined. Their findings suggest that monetary policy does have an impact on the real economy and that monetary policy transmission works through bank loans (credit) and deposits (money). Blanchard (1990) and Friedman (1995) find similar results, albeit, without the addition of credit and money. There is, however, a separate branch of research that suggests monetary policy has a diminishing impact on the real economy, for example Goodhart and Hofmann (2005) who suggest an ‘IS puzzle’ exists. This IS puzzle implies that central banks cannot stabilize the real economy. In this study of monetary policy transmission in G7 economies, the authors find that the standard specification of the IS curve is insufficient to capture the effects of the interest rate on aggregate demand.

Therefore, a broader framework that can account for the demand effects of other variables, especially property prices, is suggested as an improvement upon the current framework. There is little consensus however within the literature on the interaction of the financial economy, and financial imbalances, within the study of the transmission of monetary policy. Evidence of this IS puzzle is shown to exist in the US over the period 1976Q1 to 2014Q1 and is provided in Chapter 1 of this thesis (see page 10).

Recent research by Borio and Disyatat (2011) and Borio (2014) focus, in particular, on the inability of financial and monetary regimes to constrain what they refer to as financial imbalances. They use the term “excess financial elasticity” to denote the property of an economic system that generates the build-up of financial imbalances. The build-up of such financial imbalances gives rise to endogenous boom-bust processes, or “financial cycles” (Borio, 2013). These cycles are characterised by the surge and collapse in credit expansion (see for example Drehmann et al. (2011), Haldane et al. (2011), Jordá et al. (2011a), Drehmann and Tsatsaronis (2014)).

44 The term ‘excess financial elasticity’ was coined by Borio and Disyatat (2011) and refers to the build-up of financial imbalances that can lead to financial crises and macroeconomic fluctuations. This view includes a role for the capital account rather than the current account.
which typically works alongside equivalent fluctuations in asset prices, especially property prices (Drehmann et al. (2012)). This has led to some re-evaluation of the current thinking about the state of macroeconomic modelling and the role of the financial economy. Borio (2012) argues that it is not possible to understand business cycle fluctuations without understanding the role of the financial cycle. The financial cycle, according to Drehmann et al. (2012) is the combination of credit and property prices. These variables tend to co-vary with one other at low frequencies and so illustrate the importance of their interactions with one another. For example, credit is necessary for purchasing property and financing constructing. As such, by combining credit and property prices, the core features of the link between the financial cycle, the business cycle, and financial crises can be established.

In this chapter, we examine the relationship between monetary policy, aggregate demand and the financial cycle, which is a proxied by the inclusion of credit and property prices as established by Drehmann et al. (2012). We examine to what extent changes in the US financial system have impacted on the transmission of the Federal Reserve’s conduct of monetary policy. This will be achieved by estimating a Markov switching IS curve including both property prices and credit, since both variables are taken to be the most “parsimonious representation of the financial cycle”. We then examine if monetary policy has asymmetric effects: that is, does monetary policy have a bigger impact during expansions or recessions. This will be achieved by modelling the nonlinear transmission of monetary policy that can arise as a result of the interaction between the real and financial economy.

4.2 Monetary Policy Transmission Theory

Given the nature of the global financial crisis that began in mid-2007, the interaction between the financial economy and real economy is more important than ever. Within this section, the channels of monetary policy transmission are first outlined and the role of the financial economy in monetary policy transmission is then discussed.
4.2.1 Channels of Monetary Policy Transmission

Within the literature, the mechanism of monetary policy transmission works via three channels: the interest rate channel, the asset price channel, and the credit channel. Both the interest rate channel and the asset price channels are traditionally referred to as the neoclassical channels of monetary policy transmission in which financial markets are assumed frictionless and perfect. The credit channel belongs to the non-neoclassical channel of monetary policy whereby financial markets are imperfect and contain asymmetric information (see for example, Mishkin (1995) (2001); Bernanke and Gertler (1995); and Ireland (2005)).

The Interest Rate Channel

The interest rate channel is the main monetary policy transmission mechanism for the standard Keynesian IS-LM model of Hicks (1937). According to this interest rate channel, an inverse relationship exists between the real interest rate and aggregate demand. Expansionary monetary policy leads to a fall in the nominal interest rate that translates into a fall in the real interest rate. This lowers the cost of capital, thereby causing a rise in investment and consumption spending, which leads to an increase in aggregate demand (Mishkin, 1996). This mechanism is contained within the conventional ‘IS’ curve of the IS-LM model. In addition to its inclusion within the standard IS-LM model, this interest rate channel also lies at the heart of more recent prominent New Keynesian DSGE models where the short-term interest rate is sufficient to model the monetary side of the economy (Goodhart and Hofmann, 2008).

The Asset Price Channel

The second monetary policy transmission mechanism is the asset price channel, which is an alternative to the interest rate channel. This channel includes Tobin’s $q$ theory of investment and wealth effects on consumption due to Ando and

---

45 Examples of these New Keynesian DSGE models include Smets and Wouters (2003, 2007); Christiano et al. (2005); in addition to a wide variety of DSGE models for Central Banks including the Bank of England, Federal Reserve, the ECB, the Bank of Japan and so on.
Modigliani’s life-cycle theory of consumption (1963). Tobin’s q is defined as the ratio between the market value of firm and the firm’s replacement cost of capital. If monetary policy is contractionary, debt instruments become more attractive to investors than equities, which results in a fall in equity prices and therefore a fall in the value of a firm’s q. To finance new investment projects, firms must issue more shares of stock, thereby making investment more costly for firms. This leads to, on aggregate, a decline in output as investment spending declines. Alternatively, expansionary monetary policy makes equities more attractive to investors, which leads to an increase in equity prices, a subsequent increase in the value of the firm’s q and as a result, an increase in the firm’s investment spending. This increase in investment spending by firms is said to lead to an increase in aggregate output (Ireland, 2005).

In addition to Tobin’s q theory is the wealth channel which arises from the life-cycle model of consumption by Ando and Modigliani (1963). This model purports that a household’s consumption spending is not determined solely by their income, but also by their financial wealth. Financial wealth (for example, holding stocks, bonds, or housing) is a key component of the life-course resources of a consumer. According to this life-cycle theory of consumption, a positive relationship exists between a household’s financial wealth and the stance of monetary policy. Expansionary (contractionary) monetary policy will lead to an increase (decrease) in the value of household’s assets. Since consumers hold their assets as part of their financial wealth, an increase (decrease) in the value of these assets will result in an increase (decrease) in consumer’s wealth. This will cause an increase (decrease) in consumption spending by households, which in turn, will lead to an increase (decrease) in aggregate demand. Empirical research on the relationship between monetary policy and house prices are broadly in agreement with the wealth channel of monetary policy transmission (see for example Iacoviello, 2005; Del Negro and Otrok, 2007; Musso et al., 2010; Iacoviello and Neri, 2009; Calza et al., 2009). In addition to the inclusion of house prices, some studies use a combination of house prices and stock prices, for example, Chrinko et al., 2004; and Bjornland and Jacobsen, 2013; and find that asset prices, through either wealth or balance sheet channels, have real effects on the economy.
The Credit Channel

The third monetary policy transmission mechanism is the credit channel. The credit channel includes a bank lending channel and a balance sheet channel. Both of these channels include a role for asymmetric information within financial markets (Mishkin, 1996). The bank lending channel of Roosa (1951) has been incorporated by Blinder and Stiglitz (1983), Bernanke and Blinder (1988) and more recently by Baum et al. (2013), Brady (2011) and Ciccarelli et al. (2010) in their analysis of the impacts of monetary policy on the real economy. According to the bank lending channel, there is a special role for banks in the economy since they perform a dual purpose; they issue liabilities (bank deposits) that contribute to broad monetary aggregates and they hold assets (bank loans) for which there are few substitutes for firms to obtain sources of funding for investment purposes (Ireland, 2005). The bank lending channel is therefore sensitive to the stance of monetary policy: expansionary monetary policy should result in an increase in the supply of banks reserves, bank deposits and ultimately bank loans to lenders which leads to an increase in investment spending, whilst contractionary monetary policy should have the opposite effect.

Though the bank lending channel has been supported in empirical work (for example, Gertler and Gilchrist, 1993, 1994, Kashyap and Stein, 1995), other research has raised doubts about it (see Romer and Romer, 1989, and Ramey, 1993). The balance sheet channel is based on the strength of the firm’s financial position, which is measured by their net worth. For households, their net worth is derived from holding assets such as housing, which is used as collateral for obtaining loans. As in the bank lending channel, the balance sheet channel is subject to asymmetric information problems within credit markets where adverse selection and moral hazard issues are said to persist (Boivin, 2010). According to this view, the greater the borrower’s (firm or household) net worth, the lower their external premium should be. This is based on the premise that borrowers with a strong net worth have less potential conflict with lenders since they can offer more collateral to guarantee their liabilities. Therefore, the terms of credit facing borrowers are dependent upon their financial position (Gertler and Bernanke, 1995). The availability of collateral by borrowers facilitates credit extension within the economy (Bernanke, 2007). This has given rise to the ‘financial accelerator’ view of Bernanke and Gertler (1989) and
Bernanke, Gertler and Gilchrist (1999) which argues that endogenous pro-cyclical movements in a borrower’s balance sheet can amplify and propagate business cycles. Given this, what is the impact of changes in monetary policy? When there is expansionary (contractionary) monetary policy, debt repayments, cash-flows and assets prices will increase (decrease). This leads to an increase (decrease) in a firm or household’s level of collateral, thereby influencing their financial position and therefore their ability to finance investment activities. This results in an increase (decrease) in credit growth and an increase (decrease) in output and aggregate demand.

Some empirical studies for firms have implemented the balance sheet channel via the BGG (1999) model of the financial accelerator within a VAR or DSGE model framework. Other empirical studies use a two-step regression. For example, Kashyap and Stein (2000) examine the impact of monetary policy on the lending behaviour of a wide variety of banks with varying levels of balance sheet liquidity using a two-step regression approach. Their results find that the impact of monetary policy on lending is stronger for banks with less liquid balance sheets. Using firm level data for the UK, Angelopoulou and Gibson (2009) construct a monetary tightness indicator to study the sensitivity of investment to cash flow during periods of monetary tightness. They find that the balance sheet channel is important for transmitting the impact of monetary policy to the real sector and that financial accelerator effects are a determining characteristic of UK business cycles. Iacoviello and Minetti (2008) test for the presence of a credit channel in four European housing markets using a VAR approach. Evidence of a bank lending channel for Finland and UK is found and evidence of a balance sheet channel is found for Germany. In comparison, Musso et al. (2010) examine the role of the housing market in the macroeconomy for the US and the Euro Area using a structural VAR approach. The results suggest that the transmission of monetary policy shocks to the housing market is stronger in the US than the Euro Area, however, they do not find evidence of a balance sheet channel of monetary policy transmission.

---

46 (See for example Hafstead and Smith (2012); Gertler and Kiyotaki (2009); Curdia and Woodford (2010); Del Negro et al. (2010); Dib (2010), Christensen and Dib (2008); Christiano et al. (2009)).
Goodhart and Hofmann (2008) assess the link between money, credit, house prices and the macroeconomy using a fixed-effects panel VAR for 17 industrialised countries. They find evidence of a significant multidirectional link between house prices, broad money, private credit and the macroeconomy. Furthermore, shocks to house prices, credit and money are found to have significant impacts on aggregate demand and these shocks are stronger when house prices are booming. Boivin et al. (2010), using vector autoregressive (VAR) models and DSGE models, find that developments in financial markets have changed the traditional transmission of monetary policy. In particular, the removal of restrictive regulations in credit markets in the 1980s and the growth of securitization in the mortgage market are found to have altered the monetary policy transmission mechanism. This growth in securitization is found to have two major impacts; firstly, borrowers can now bypass banks to obtain credit, and secondly it had led to the “democratization of credit” whereby a larger percentage of the population have access to credit. This democratization of credit could suggest an increasing role of the balance sheet channel for households and an increased responsiveness of consumer spending to changes in house prices (Aoki, Proudman, and Vlieghe, 2002).

4.2.2 The Role of Credit and Property Prices

The recent literature highlighted above gives rise to the inclusion of property prices and credit within the macroeconomic modelling framework.

There has been a surge in the recent literature establishing the important role of the credit in the transmission of monetary policy. For example, Gertler and Karadi (2015) examine how monetary policy actions influence the real economy through the cost of credit using VAR analysis. Their findings illustrate a need to incorporate credit spreads in modelling monetary policy transmission since small increases in the short-term interest rate was found to lead to significant contractions in output. Jannsen et al. (2015) examine the transmission of monetary policy in financial and

---

47 The 17 industrialised countries include the US, Japan, Germany, France, Italy, UK, Canada, Switzerland, Sweden, Norway, Finland, Denmark, Spain, the Netherlands, Belgium, Ireland and Australia over the period 1973 – 2006.

48 Money growth is found to have a significant effect on house prices and credit, credit influences money and house prices, and house prices influence both credit and money.
non-financial crises to establish if any difference exists. Using data on 21 advanced economies in an interacted panel VAR model, they find that monetary policy was faster to react and had a larger effect on GDP during financial crises. Like Jannsen et al. (2015), Bech et al. (2014) study the impact of monetary policy in periods following a financial crisis, to determine if its impact is different. Their results indicate that if monetary policy is accommodative during a non-financial crisis, then the recovery should be strong, however, the same result is not found for recessions that are associated with financial crises. In addition, the distinction between non-financial and financial crises is important when establishing the role of deleveraging. That is, in non-financial recessions, deleveraging produces no significant benefit to the recovery, whilst deleveraging during a financial recession helps the economy recover. The importance of credit in the conduct of monetary policy is further emphasized by Schularick and Taylor, 2010a, 2010b; Goodhart and Hofmann, 2008; Borio, 2013a, 2013b, 2014a, 2014b; and Hendricks and Kempa, 2009, 2010.

To understand the interaction between the financial and real economy, Drehmann et al. (2012) and Borio (2012), first identify what is known as the financial cycle. The financial cycle is said to be determined by the combination of credit and property prices, which are found to co-vary closely with each other at low frequencies. This implies that credit is important in the purchasing of property and the financing of construction (see for example, Aikaman et al., 2010; Schularick and Taylor, 2009, 2012; Jordá et al., 2011), while other studies examine the behaviour of credit and property prices individually, for example Claessens et al., 2011a, 2011b. The financial cycle, which is illustrated in Figure 4.1 below, is said to observe the following properties (see Borio 2012 and Drehmann et al., 2012 for a more detailed discussion): first, the financial cycle is best captured by the joint behaviour of credit and property prices; second, the financial cycle is much longer, and has a much larger amplitude than the traditional business cycle; third, it is closely associated with systemic banking crises, which tend to occur close to its peak; fourth, it permits the identification of the risks of future financial crises in real time and with a good lead; and finally, it is highly dependent on the financial, monetary and real-economy policy regimes in place. Most macroeconomic policy is concerned with the business cycle, however, the financial cycle is an important propagator of instability in the
macroeconomy, and should be modelled accordingly to aid policymaking (Borio, 2013).

\[ \text{Source: The Financial and Business Cycle in the US in Drehmann et al., (2012)} \]

\[ \text{Figure 4.1: Characterising the Financial Cycle} \]

In Figure 4.1, the orange and green bars represent the peaks and troughs of the financial cycle, which is measured by the combined behaviour of the component series (credit, credit to GDP ratio, and house prices) using turning point methods. The blue line illustrates the financial cycle which is measured as the average of the medium term cycle in the component series using frequency-based filters. Finally, the red line illustrates the GDP cycle identified by the traditional shorter-term filter used to measure the business cycle (Drehmann et al., 2012). Credit is vital for economic activity and private sector borrowing has important implications for monetary policy. History shows that financial crises tend to be preceded by unusually large build-ups of credit in the private sector (Mendoza and Terrones, 2008, 2012; Claessens and Kose, 2013; and Dembiermont et al., 2013). As such, credit has an important influence on the monetary transmission mechanism and is a major determinant of financial stability. In this chapter, the interaction between the real economy (as represented by the output gap), the financial economy (as represented by property prices and credit), and monetary policy (as represented by the short term real interest rate) is examined in an effort to understand the boom bust nature of the economy and the role of monetary policy.
4.3. Methodology

4.3.1. The IS Curve

The three-equation New Keynesian Model (NKM) has become a standard tool used in the analysis of monetary macroeconomics (Carlin and Soskice, 2005) and is used by several highly influential macroeconomists as the basis for their macroeconomic modelling (see for example, Woodford, 2003; Clarida, Gali and Gertler, 1999; Goodfriend and King, 1997). The NKM typically consists of a Phillips curve that determines inflation, an IS curve that determines the level of output, and a monetary policy rule that determines the short term interest rate set by the central bank or the monetary authority. A key component of this canonical model is the IS curve which describes the transmission of monetary policy to the real economy. This equation is obtained by log linearizing the consumption Euler equation and substituting it into the economy’s aggregate resource constraint. From Clarida et al. (1999), this yields the following IS curve equation:

$$\bar{y}_t = \bar{y}_{t+1} - \alpha (i_t - \pi_t) + e_t$$  \hspace{1cm} (4.1)

In this equation, $\bar{y}_t$ is the output gap i.e. the deviation of output from its natural level, $(i_t - \pi_t)$ is the short term real interest rate and $e_t$ is a demand shock. The parameter $\alpha$ is key to the specification of this equation since it expresses the relationship between changes in the output gap and changes in the short term real interest rate. In other words, it describes the responsiveness of the real economy to changes in the central bank’s monetary policy stance.

The specification of equation (4.1) is purely forward looking: it relates the output gap to the expected future output gap, the short term real interest rate and an external demand shock. However, in empirical applications, purely forward looking models have been found to be inconsistent with the short run dynamics of aggregate demand (Clarida et al., 1999; Estrella & Furher, 1999, 2000; Linde, 2001). Therefore, a backward looking specification is often preferred in order to match the lagged and persistent responses of output to monetary policy measures which are found in the data (Rudebusch, 2002). Even with this modification, many empirical papers of the US and UK economy have found little evidence of a negative relationship between the real interest rate and the level of output. For example, Nelson (2001, 2002)
estimates a backward looking IS curve for the US and UK over the period 1982-1999 and fails to find a significant relationship between the real interest rate and aggregate demand, which he famously refers to as the “IS puzzle”. Goodhart and Hofmann (2003), using data on G7 countries for the period 1982-1998, make similar findings to those of Nelson (2001, 2002): no statistically significant relationship exists between the real interest rate and output. This implies that the central bank cannot stabilise the economy through changes in the interest rate. Alternatively, Rudebusch and Svensson (1999) estimate a backward looking IS curve for the US and find a statistically significant relationship between the two variables. Similar results are found by Peersman and Smets (1999) for the Euro Area.

As initially outlined in the introduction to this chapter, Goodhart and Hoffman (2005), in their analysis of the IS curve for the US and as outlined above, find that including asset prices appears to be hugely important for the real interest rate to enter the IS curve with the expected negative sign. The authors argue that an extension of the IS curve may be in order to examine the transmission of monetary policy. As such, the real effective exchange rate, nominal short term interest rate, real residential property prices, real share prices and broad monetary aggregates are included in their specification since they may also affect aggregate demand via wealth effects. A change in perceived lifetime wealth, caused by a change in asset prices or broad money, may induce consumers to change their consumption plans (Modigliani, 1971). Their findings suggest that “the standard specification of the IS curve is not sufficient to properly identify the effect of interest rates on aggregate demand and that a broader framework, also taking into account the demand effects of other variables, especially property prices, might be more appropriate” (Goodhart and Hofmann, 2005 p. 15).

In addition to the inclusion of property prices within the IS curve, and as discussed by Drehmann et al. (2012) and Borio (2012, 2013), credit is included within the specification of this IS curve as a means of modelling the financial side of the economy. Therefore, the linear benchmark model used in this chapter is described by the following equation:

\[ \ddot{y}_t = \ddot{y}_{t-1} - \alpha(i_t - \pi_t) + \Delta\text{rrp}_t + \Delta c_t + e_t \]  

(4.2)
The specification of equation (4.2) includes a role for property prices, as denoted by $\Delta r_{tp}$, and a role for credit, as denoted by $\Delta c_t$.

**4.3.2 Asymmetries in the transmission of monetary policy**

For decades macroeconomists have debated the asymmetric effect of monetary policy: for example, does monetary policy have the same effect on real output in expansions and recessions (Garcia and Schaller, 1999; Weise, 1999; Lo and Piger, 2005; Tenreyro and Thwaites, 2013). There has been very little agreement in the mainstream literature regarding the asymmetric effect of monetary policy. The US economy has changed substantially over the past number of decades. These changes not only include the conduct of monetary policy towards an increasing focus on achieving price stability, but also changes in the way financial markets operate (Boivin et al., 2010). The implications of structural change for the conduct of monetary policy has attracted increased attention from researchers and policymakers.

The magnitude of macroeconomic fluctuations has declined dramatically (Williams, 2004). During the late 60’s and throughout the 70’s, inflation was high, volatile and persistent and periods of recessions were common. This period, known as the Great Inflation, was followed by a period beginning in the early 1980’s where the level, variance and persistence of inflation and the volatility of output decreased significantly (Bilbiie and Straub, 2012). This period is known as the Great Moderation. These changes make it difficult to explain macroeconomic dynamics in the US over the last 40 years within a linear homoskedastic framework. There is still no consensus on whether the Great Moderation represents a structural break or rather a persistent but temporary change in regime. Additionally, the causes also remain the subject of much debate within the literature (Baele et al., 2011). With this in mind, we will estimate our IS curve and examine the effect of monetary policy on the level of output by using a linear model with multiple structural breaks. This will allow us to establish the IS curve in the presence of a structural break. A non-linear Markov switching (MS) model is then estimated to examine the transmission process of monetary policy and will allow us to establish if any asymmetries exist.
4.3.3 Multiple Breakpoint Model

The standard linear regression model assumes that the parameters of the model do not vary across observations. Despite this assumption, structural change, the changing of parameters at dates in the sample periods, plays an empirically relevant role in applied time series analysis\(^{49}\). The seminal work of Chow (1960) and Quandt (1960) developed the testing procedure for structural changes in a time series at a single specified (hence known) break date. This work was closely followed by Andrews (1993), Andrews and Ploberger (1994), Andrews et al. (1996), Liu et al. (1997), and Bai and Perron (1998, 2003) who attempted to develop methods that allow for the estimation and testing of structural change at unknown break dates. Andrews et al. (1996) considers multiple structural changes but requires a known variance. Liu et al. (1997) also test for multiple unknown change points but consider only the pure structural change case where all parameters are subject to shifts. Therefore, the procedure hypothesised by Bai-Perron (1998, 2003) is adopted.

It is a logical conclusion to suggest that changes in monetary policy regimes will cause linear estimations of the monetary policy transmission channel to provide misleading dynamics between monetary policy and the real economy. This will be due to the presence of breakpoints or structural breaks in the time series associated with these changes in policy. Clarida, Galí, and Gertler (2000), Lubik and Schorfheide (2004) and Boivin and Giannoni (2006) have all carried out studies on the effects of different policy regimes, corresponding to the pre-Volcker regime and the post-Volcker regime. By studying the two subsample periods separately, they reach a conclusion that changes in monetary policy help explain the substantial decline in macroeconomic volatility observed in the post-war U.S. economy. The Bai–Perron (BP) procedure seems like a useful tool in carrying out similar research in the US economy as it allows the researcher to find the number of breaks implied by the data, as well as estimating the timing of the breaks and the parameters of the processes between breaks. The methodology can be used to estimate multiple structural changes in a linear model estimated by least squares. It treats the number of breakpoints and their locations as unknown.

If we apply the linear benchmark IS curve model outlined in equation (4.2) to this framework with $m$ breaks we get:

$$y_t = A_1 + B_1 y_{t-1} - \alpha_1 (i_t - \pi_t) + C_1 r r p_t + D_1 c_t + e_t, \quad t = 1, \ldots, T_1$$ (4.3)

$$y_t = A_m + B_m y_{t-1} - \alpha_m (i_t - \pi_t) + C_m r r p_t + D_m c_t + e_t, \quad t = T_{m+1}, \ldots, T$$ (4.4)

Where the breakpoints $(T_1, \ldots, T_{m+1})$ are treated as unknown. The Bai-Perron estimation is based upon least square estimates of $A_i, B_i, C_i$ & $D_i$ and are obtained by minimizing the sum of squared of residuals

$$\sum_{i=1}^{m+1} \sum_{t=T_{i-1}+1}^{T_i} (y_t - A_i - B_i y_{t-1} - \alpha_i (i_t - \pi_t) + C_i r r p_t + D_i c_t)^2$$ (4.5)

The number of breakpoints is determined by a “sequential process” suggested by Bai-Perron. According to this sequential process, the null hypothesis that there are $l = 0$ structural breaks is first tested using the SupF test. If the null hypothesis of $l$ breaks is rejected in favour of the $l + 1$ breaks alternative, then the test is applied to each subsequent sub-sample, until rejection fails. Before the Bai and Perron (1998, 2003) procedure is implemented, an initial trimming region needs to be specified to ensure that there is a reasonable number of degrees of freedom to calculate an initial error sum of squares. The trimming specification will also determine the maximum number of breaks and minimum state or regime size. The trimming imposed in this model is 15 percent and allows the procedure to search for a maximum of five breaks. This is standard specification for a sample size similar to the sample used in this empirical estimation.

### 4.3.4 Markov Switching Model

As mentioned, changes in the monetary policy transmission and the size of monetary policy shocks are often considered as an explanation for the reduction in volatility of key US macroeconomic aggregates during the period referred to as “The Great
Moderation” (Galvao & Marcellino, 2012). Econometrically, these changes have often been dealt with in the literature by the inclusion of abruptly changing parameters whose evolution is determined by an unobservable Markov chain. This Markov switching (MS) specification has been adopted for this purpose by Sims & Zha (2006), Davig & Doh (2009) and Bianchi (2009). The MS model, developed by Hamilton (1989), provides a platform in which to model the dynamics of macroeconomic variables in an economy which has been subjected to dramatic and substantial structural change. The advantage of this non-linear model over the standard linear favourites such as AR, MA and ARMA models is that it is able to represent more dynamic patterns such as asymmetry. Many economic time series occasionally exhibit dramatic breaks in their behaviour associated with events such as financial crises or abrupt changes in government policy (Hamilton 2005). It is widely accepted in the literature that both US macroeconomic performance and the behaviour of the Federal Reserve has gone through substantial change over recent decades. The U.S. financial system has also changed significantly in recent years. As discussed by Fischer (2015) in his speech at the ‘Debt and Financial Stability – Regulatory Challenges’ conference in Germany, changes in the US financial system have meant there is “...increased market liquidity, greater diversity of funding sources, and--it is often claimed--a more efficient allocation of risk among investors”. These changes mean the standard linear models may under or overestimate the transmission of monetary policy to the real economy.

The MS model is so called because the switching mechanism is controlled by an unobserved state variable $s_t$ that follows a first order Markov chain process. A Markov process is one where the probability of being in a particular state is only dependent upon the state taken in the previous period. The model involves multiple structures that can characterise the time series behaviour in different states. By permitting switching between these structures, the model is able to capture more complex dynamic patterns. The state switches between different regimes according to its previous value and transition probabilities. The MS model differs from models of multiple breakpoints as it allows for frequent changes of random time points. It is therefore argued that the MS framework is more suitable for describing correlated

---

30 This has been well documented in the literature with Boivin et al (2010) providing a comprehensive survey.
data that exhibit distinct dynamic patterns during different time periods (Kuan, 2002). An interesting feature of the MS model is that the filtered probabilities can be interpreted as the agent’s belief that the economy is in one of the possible states that describe the economy, Demers (2003).

By fitting the linear benchmark equation to the MS framework, we get the following specification:

\[ y_t = A_{st} + B_{st}y_{t-1} - \alpha_{st}(i_t - \pi_t) + C_{st}rrp_t + D_{st}c_t + e_t \]  \hspace{1cm} (4.6)

Where \( e_t \sim i.i.d. N(0, \sigma_{e, st}^2) \) and with unobserved state \( s_t \), which is assumed to follow a Markov chain of order 1 with transition probabilities \( p_{ij} \). The transition probability \( p_{ij} \) gives the probability that state \( i \) will be followed by state \( j \):

\[ P_{ij} = \Pr[s_t = j \mid s_{t-1} = i], \quad \sum_{i=1}^{M} p_{ij} = 1, \quad \forall i, j = 1, \ldots, M \]  \hspace{1cm} (4.7)

It is often convenient to collect the transition probabilities in an \((M \times M)\) matrix \( P \) known as the transition matrix:

\[
P = \begin{bmatrix}
p_{11} & p_{21} & \cdots & p_{M1} \\
p_{12} & p_{22} & \cdots & p_{M2} \\
\vdots & \vdots & \ddots & \vdots \\
p_{1M} & p_{2M} & \cdots & p_{MM}
\end{bmatrix}
\]  \hspace{1cm} (4.8)

Estimating a Markov switching specification of the IS curve in this manner will allow us to examine a number of key considerations. Firstly, we can examine to what extent changes in the US financial system have impacted on the transmission of the Federal Reserve’s conduct of monetary policy. This will achieved by including both property prices and credit within the specification of the IS curve, since both variables are taken to be the most “parsimonious representation of the financial cycle”. Secondly, it will allow us to examine if monetary policy has asymmetric effects: that is, does monetary policy have a bigger impact during expansions or recessions. This will be achieved by examining the parameters relating to monetary policy, property prices and credit over the different regimes picked up by the Markov switching model.

This research will draw on the quite small and recent literature that utilises the Markov switching framework to establish the transmission of monetary policy. For
example, Hendricks and Kempa (2009) use a Markov switching model to investigate how the credit channel depends on the business cycle and the stance of monetary policy, along with developments in financial markets. Lo and Piger (2005) and Ravn and Sola (2004) use a regime switching coefficients model to examine if the response of output to monetary policy is asymmetric within the US. Sims and Zha (2006) examine if there were regime switches in monetary policy in the US using monthly data from 1959 to 2003, although their model is not specifically a Markov switching model. Finally, Basistha and Startz (2004) use a Markov switching model to examine why changes in the federal funds rate were smaller in the 1990s.

4.4 Data

In this chapter, quarterly data for the period 1977Q1 to 2014Q3 are obtained for real GDP, the consumer price index, the federal funds rate, total credit to the non-financial private sector, and real residential property prices.

4.4.1. Real GDP and the Derivation of the Output Gap

Real GDP is expressed in billions of chained\(^{51}\) 2009 dollars and is obtained from the Federal Reserve Economic Databank (FRED). The annual growth rate is obtained by taking logs of the data and calculating the percent change from the previous period. Figure 4.2 below illustrates real GDP over the sample period 1977Q1 to 2014Q3.

As illustrated in Figure 4.2, and in accordance with NBER recession dating periods, over the sample period, the US has experienced recessionary periods during 1980, 1981, 1990, 2001 and 2007. The recession of 1980 lasted for 6 months and is generally referred to as the “Energy Crisis” recession where energy prices were high, inflation was over 13 percent and GDP declined 1.1 percent. The recession of 1981 lasted 16 months and GDP declined approximately 3.6 percent. This recession was closely associated with the overthrow on the Shah of Iran which led to increases in oil prices.

\(^{51}\) Chained dollars are those that have been adjusted for inflation
Figure 4.2: Year on Year Percentage Change in Real GDP

Both the 1980 and 1981 recession’s take place during the period of the ‘Great Inflation’ and correspond to a period of time in the US where monetary policy was very tight. The 1990 and the 2001 recessions were relatively mild with GDP declining 1.5 percent and 0.3 percent, respectively. Finally, the 2008-2009 Great Recession, which lasted 18 months was associated with a decline in GDP of 4.3 percent.

Using the real GDP data obtained from FRED, the output gap is derived. The output gap represents the difference between actual GDP and potential GDP in the economy. Potential GDP, which is often referred to as the production capacity of the economy, is achieved when the economy efficiently produces the maximum amount of goods and services required in the long run (Jahan and Mahmud, 2015). Although potential GDP is not directly observable, there are several methodologies available to estimate it, including estimating the production function or using statistical techniques such as the Hodrick Prescott filter. Central to these methodologies is the assumption that output can be divided into two components: a trend component (which is used as the estimate of potential GDP) and the cyclical component (which is used as the measure of the output gap). In line with the literature, potential output
is estimated using the Hodrick-Prescott filter\textsuperscript{52}. The output gap is then derived by subtracting potential output from actual output and the result is illustrated in Figure 4.3 below.

![Figure 4.3: The Estimated Output Gap](image)

\textit{Source: Author’s Calculations}

As illustrated in Figure 4.3 above, there are clear periods of instability over the sample examined where the output moves between being positive and negative. The two main recessions over the sample period (the 1981 recession and the 2008-2009 recession) correspond to periods when the output gap is the most negative, that is; there is substantial slack in the economy as a result of weak demand.

\textbf{4.4.2 Real Interest Rate}

The ex-ante real interest rate is obtained by adjusting the nominal interest rate for inflation. The nominal interest rate used in this chapter is the federal funds rate. The inflation rate is the year on year percentage change in the consumer price index. Both the federal funds rate and the consumer price index are obtained from FRED.

\footnote{Potential output is derived using the Hodrick-Prescott filter with lambda equal to 1600, as is usual with quarterly data.}
Figure 4.4 illustrated below depicts the ex-ante real interest rate for the US over the sample considered.

The sharp increase in the real interest rate is notable during the early 1980s which corresponds to the Great Inflation period in the US. During the second half of 1979, the federal funds rate was held between 10 percent and 10.5 percent. Prices, however, were still increasing and policies to curb inflation and strengthen the dollar were not succeeding. In August 1979, Paul Volcker replaced William Miller as chairman of the Federal Reserve marking the movement to a more monetarist approach. They imposed new reserve requirements and a new operating procedure for monetary policy was announced. The new operating procedure targeted monetary aggregates instead of directly targeting a specific interest rate and by the end of March 1980 the federal funds rate was 19.4 percent.

![Figure 4.4: The Ex-Ante Real Interest Rate](image)

*Source: Federal Reserve Economic Databank (FRED)*

Despite the very tight monetary policy, inflation continued to increase during the first quarter of 1980. In an effort to combat rising inflation, President Carter announced a package of budget proposals to cut the projected federal deficit and authorized the imposition of controls on consumer credit by the Federal Reserve. The impact of credit controls combined with very tight monetary policy pushed the
economy into recession. The federal funds rate fell to 9.4 percent in June, a fall of 10 percent over a three-month period⁵³. By the mid-1980s inflation fell to around 4 percent. The Federal Reserve’s interest rate policy during this period focused on stabilising inflation and their response to the output gap decreased considerably. Kim and Nelson (2006) argue that this shift in policy may have actually stabilised inflation at a lower level. Once inflation had been stabilised at this lower level, the Fed could pay more attention to stabilizing real economic activity in the 1990’s. Figure 4.4 shows that movements in the real interest rate became remarkably smoother than in the previous decades (Basista and Startz, 2004).

What is interesting is that in the 1990-1994 period, the federal funds rate matched the Taylor rule theory rate closer than any previous time period. After this period, inflation remained low but economic growth continued into the late 1990’s. Inflationary pressure did start to build in the late 1999 and 2000. The federal funds rate was raised from 4.5 percent in late 1998 to 6.5 percent in June 2000. The recession in 2001 meant that inflation was no longer a concern. With high unemployment and low growth, the federal funds rate was cut to as low as 1 percent in 2003. As the economy began to recover, the rate was gradually raised back to 5 percent in 2007.

### 4.4.3 Real Residential Property Prices

Data on real residential property prices are obtained from the Bank for International Settlements (BIS) Statistics and represents all types of existing dwellings in the US⁵⁴. It is adjusted for inflation using the consumer price index and the percentage change from the previous period is calculated.

As evidenced from the Figure 4.5 below, there have been two large boom periods for property prices over the sample period considered; the boom during the late 1970s and the boom during the late 1990s and early 2000s. Beginning with the boom

---

⁵³ For a comprehensive review of monetary policy during this period, see Friedman (1988); Mussa (1994); Goodfriend (2002).
⁵⁴ This data was sourced from the Federal Reserve by the Bank for International Settlements
during the late 1970s, property prices increased significantly as a result of changes in demographics: the so-called aging of the ‘baby-boom’ from the 1950s drove housing
demand in the US (Mankiw and Weil, 1989). In the late 1990s, house prices in many industrial countries, including the US, increased significantly. A boom in property prices is said to have taken place in 1998Q1 and this boom continued to grow until the bust in 2006Q2. This increase in house prices is said to have been driven by several factors; low and accommodative monetary policy; increased liquidity; and stable economic activity (Ahearne et al., 2005).

### 4.4.4 Credit to the Non-Financial Private Sector

Data on credit to the non-financial private sector is also obtained from the BIS Statistics. Credit to the non-financial private sector includes non-financial corporations (both private-owned and public-owned), households and non-profit institutions serving households and represents the outstanding amount of credit at the end of the reference quarter (Dembiermont et al., 2013). In terms of financial instruments, credit covers loans and debt securities such as bonds and short term
paper. Figure 4.6 below plots the year on year percentage change in total credit to the non-financial private sector.

![Graph showing year on year percentage change in total credit to the non-financial private sector](image)

*Source: Bank for International Settlements (BIS) Statistics*

**Figure 4.6: Year on Year Percentage Change in Total Credit to the Non-Financial Private Sector**

As illustrated in Figure 4.6 above, the growth in total credit to the non-financial sector has remained positive for the entire sample period, with the exception of the 2009Q2 to 2011Q3 period. During this period, total credit to the non-financial private sector fell 3.4 percent. The period covering the 1990s shows a sustained increase, with credit growing from 1.3 percent in 1992Q2 to 11 percent in 2006Q2. This period of growth is in line with the period of growth experienced in the housing sector. There is a well-established link between these variables which occurs via housing wealth and collateral effects on credit demand and credit supply (Goodhart and Hofmann, 2008). Higher house prices induce households to spend and borrow more, as house price collateral increases making it easier to enhance their borrowing capacity (see for example Goodhart and Hofmann, 2008; Aoki *et al.*, 2004; and Iacoviello, 2004, 2005).
4.5. Results

The results from the following three models are outlined in this section. First, the results from the linear OLS estimation are outlined and discussed. Second, the breakpoint model is estimated in line with the Bai-Perron methodology outlined in section 4.3 and the results are interpreted. Finally, the Markov Switching model results are presented and examined.

Prior to the estimation of the three models, each of the variables underwent stationarity testing using the Augmented Dickey Fuller unit root test. The results of this unit root test are provided in Table 4.1 below.

**Table 4.1: Augmented Dickey Fuller Unit Root Test**

<table>
<thead>
<tr>
<th></th>
<th>Output gap</th>
<th>Real interest rate</th>
<th>Real residential property prices</th>
<th>Total credit to the non-financial private sector</th>
</tr>
</thead>
<tbody>
<tr>
<td>t-statistic</td>
<td>-3.99***</td>
<td>-4.17***</td>
<td>-3.45***</td>
<td>-2.92</td>
</tr>
</tbody>
</table>

Note: The 1%, 5% and 10% significance levels are denoted by ***, **, and * respectively.

Given the results in Table 4.1, all variables with the exception of total credit to the non-financial private sector, were found to be stationary. First differences of the total credit to the non-financial private sector were therefore taken which rendered the variable stationary.

4.5.1 Linear OLS Estimation

The results of the linear OLS estimation are provided below in Table 4.2 and clearly show that the expected negative relationship between the real interest rate and the output gap is not present. While the coefficient takes the expected negative sign, the result is not statistically significant. Both the total credit to the nonfinancial private sector and real residential property prices are correctly signed and statistically significant. This implies that changes in property prices and credit have an impact of
the output gap within the economy. The coefficient on total credit to the nonfinancial private sector is 0.22. This implies that a 1 percent standard deviation in this credit variable leads to a 0.67 percent change in the output gap. The coefficient on real residential property prices is smaller at 0.02 and implies that a 1 percent standard deviation in property prices leads to a 0.09 percent change in the output gap. The lagged output gap variable is highly persistent and statistically significant, as expected.

Table 4.2: Results from the Linear OLS Estimation
1977Q1 – 2014Q3

<table>
<thead>
<tr>
<th>Variable</th>
<th>Coefficient</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>0.01</td>
<td>(0.06)</td>
</tr>
<tr>
<td>Output gap (-1)</td>
<td>0.84***</td>
<td>(0.04)</td>
</tr>
<tr>
<td>Real interest rate</td>
<td>-0.01</td>
<td>(0.02)</td>
</tr>
<tr>
<td>Δ Real residential property prices</td>
<td>0.02**</td>
<td>(0.01)</td>
</tr>
<tr>
<td>Δ Credit to the non-financial private sector</td>
<td>0.22***</td>
<td>(0.07)</td>
</tr>
<tr>
<td>Sup F. Test</td>
<td>3.81**</td>
<td>1983Q3</td>
</tr>
</tbody>
</table>

Note: The standard errors are given in parenthesis. The 1%, 5% and 10% significance levels are denoted by ***, **, and * respectively.

Finally, the Quandt-Andrews breakpoint test is applied to the linear OLS results which tests for the presence of structural breaks within the data. The Sup F test result is provided in Table 4.2 above and is statistically significant at the 5 percent level. This test indicates that a structural break took place in the US economy in 1983Q3. It is widely regarded that the US economy moved from the Great Inflation phase to
the Great Moderation phase in 1984. During this period, economic stability prevailed. Early findings of a discrete break in volatility around 1984 (Kim and Nelson, 1999; McConnell and Perez-Quiros, 2000) encouraged a focus on comparisons before and after 1984. Given the results of the Quandt-Andrews breakpoint test, a new model is estimated to examine if there are key differences between the results before and after the specific breakpoint is said to have occurred.

4.5.2 Multiple Breakpoint Estimation

Given the results of the Quandt-Andrews structural break test in the linear OLS estimation, the breakpoint model is used. By using the breakpoint model we can establish the difference in results between the period prior to the structural break and after the structural break. A key component of this test is that we do not specify when the breakpoint occurs; the breakpoint is simply picked up by the data and many breakpoints can occur. The results of the breakpoint model are provided in Table 4.3 below.

The estimation results from this model indicate two things; firstly, there is a single breakpoint identified within the data; and secondly, this breakpoint occurs in 1983. The estimation results are therefore broken down into two sub-sample periods. The first sub-sample period is from 1977Q3 to 1982Q4 and the second sub-sample period is from 1983Q1 to 2014Q3. As with the linear OLS model estimation, the real interest rate is not statistically significant in either sub-sample. The only statistically significant variables in the first period (1977Q3 to 1982Q4) is the change in real residential property prices, which is statistically significant at the 10 percent level and the lag of the output gap, which is significant, as expected. The size of coefficient on property prices is small at 0.09. This coefficient implies that a 1 percent standard deviation in property prices leads to a 0.23 percent change in the output gap.

Within the second sub-sample, which covers the period 1983Q1 to 2014Q3, only the change in the total credit to the non-financial private sector is statistically significant (at the 1 percent significance level), along with the lag of the output gap. The
coefficient on credit is 0.24, which implies that a 1 percent standard deviation in credit leads to a 0.83 percent change in the output gap.

Table 4.3: Breakpoint Model Estimation Results

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>-0.22</td>
<td>-0.02</td>
</tr>
<tr>
<td></td>
<td>(0.34)</td>
<td>(0.07)</td>
</tr>
<tr>
<td>Output gap(-1)</td>
<td>0.80***</td>
<td>0.82***</td>
</tr>
<tr>
<td></td>
<td>(0.08)</td>
<td>(0.04)</td>
</tr>
<tr>
<td>Real interest rate</td>
<td>-0.07</td>
<td>0.03</td>
</tr>
<tr>
<td></td>
<td>(0.08)</td>
<td>(0.02)</td>
</tr>
<tr>
<td>∆ Real residential property prices</td>
<td>0.09*</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td>(0.04)</td>
<td>(0.01)</td>
</tr>
<tr>
<td>∆ Credit to the non-financial private sector</td>
<td>0.05</td>
<td>0.24***</td>
</tr>
<tr>
<td></td>
<td>(0.23)</td>
<td>(0.08)</td>
</tr>
</tbody>
</table>

Note: The standard errors are given in parenthesis. The 1%, 5% and 10% significance levels are denoted by ***, **, and * respectively.

In addition to the analysis of the breakpoint estimation, Table 4.4 below provides the summary statistics for each of the variables during the two sub-sample periods; 1977Q3 to 1982Q4 and 1983Q1 to 2014Q3. It is clear from the summary statistics that the first sub-sample represents the period when all variables had a higher mean value; the output gap is positive with a mean of 0.31 percent and the mean of the real interest rate is 1.8 percent. In comparison to the second sub-sample, both the change in real residential property prices and the change in total credit to the non-financial private sector are higher with means of 2.9 percent and 11.88 percent, respectively. Interestingly, the volatility of these two variables is higher in sub-sample two with a standard deviation of 6.55 percent and 4.12 percent respectively.
The overarching conclusion from the estimation of this breakpoint model is simple: even when accounting for a structural break within the US economy, monetary policy has no statistically significant influence on output. Prior to the structural break, only the change in real residential property prices had a statistically significant impact on output. After the structural break, only the change in total credit to the non-financial private sector has a statistically significant impact on output.

Table 4.4: Summary Statistics using the Breakpoint Dates

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Output Gap</td>
<td>Real Interest Rate</td>
<td>Real Residential Property Prices</td>
</tr>
<tr>
<td>Mean</td>
<td>0.31</td>
<td>1.8</td>
<td>2.90</td>
</tr>
<tr>
<td>S.D.</td>
<td>2.29</td>
<td>3.23</td>
<td>5.86</td>
</tr>
<tr>
<td></td>
<td>Output Gap</td>
<td>Real Interest Rate</td>
<td>Real Residential Property Prices</td>
</tr>
<tr>
<td>Mean</td>
<td>-0.02</td>
<td>1.52</td>
<td>1.54</td>
</tr>
<tr>
<td>S.D.</td>
<td>1.18</td>
<td>2.47</td>
<td>6.55</td>
</tr>
</tbody>
</table>

As discussed in Brooks (2014), this type of piecewise regression has major limitations. First, this type of method is subject to some efficiency loss since there are fewer observations in each of the two sub-samples than if all of the observations were collected together. Indeed, the first sub-sample within this analysis (for the period 1977Q3 to 1982Q4) contains \( n = 22 \) observations. Second, it may be the case that only one property of the series has changed, for example the unconditional mean of the real interest rate, while the remaining properties of this series remains unchanged. As such, as an alternative to piecewise models, is a model that allows all of the observations of the series to be estimated together, but also that the model is
sufficiently flexible to allow for different type of behaviour at different points in time. One such model is the nonlinear Markov switching model.

### 4.5.3 Markov Switching Estimation

The Markov switching model is estimated over the entire sample period from 1977Q1 to 2014Q3. Table 4.5 provides the output from the Markov switching estimation. We can clearly see that the duration of state 1, at 7.6 quarters, is much lower than the duration of state 2, which lasts for 27.2 quarters. During state 1 all variables included in the estimation are highly statistically significant and correctly signed. The real interest rate has the correct negative sign and is statistically significant at the 1 percent level. The coefficient on the real interest rate is -0.30, implying that monetary policy has an impact on aggregate demand during this period. Real residential property prices are significant at the 1 percent level and credit is significant at the 5 percent level. Interestingly, the coefficient on credit is high at 0.50. This implies that credit has a bigger impact on aggregate demand than the real interest rate. During state 2, only the lag of the output gap and credit are statistically significant. Credit is statistically significant at the 1 percent level and has a coefficient value of 0.15. The real interest rate is incorrectly signed and has no impact on aggregate demand. This implies that credit is the only variable which has an impact on aggregate demand.

The results indicate that state 1 can be characterised as the contractionary regime and state 2 as the expansionary regime, as illustrated in Figure 4.7 below. Within Figure 4.7, state 1 is represented by the blue shaded area, while state 2 is represented by the white shaded area. The regimes in state 1 correspond to the recessions experienced in the early 1980s, the 1990-1992 period and finally the 2008-2009 period, where GDP growth fell 3 percent, 1 percent, and 5 percent, respectively. The regimes in state 2 represent periods of sustained growth in GDP in the late 1980s, the early 1990s to late 2000s and finally the post Great Recession phase from late 2009 to present.
Table 4.5: Markov Switching Estimation Results

<table>
<thead>
<tr>
<th></th>
<th>State 1</th>
<th>State 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>0.74***</td>
<td>0.04</td>
</tr>
<tr>
<td></td>
<td>(0.21)</td>
<td>(0.06)</td>
</tr>
<tr>
<td>Output Gap (-1)</td>
<td>0.48***</td>
<td>0.85***</td>
</tr>
<tr>
<td></td>
<td>(0.06)</td>
<td>(0.05)</td>
</tr>
<tr>
<td>Real Interest Rate</td>
<td>-0.30***</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>(0.04)</td>
<td>(0.02)</td>
</tr>
<tr>
<td>Δ Real Residential Property Prices</td>
<td>0.13***</td>
<td>-0.01</td>
</tr>
<tr>
<td></td>
<td>(0.02)</td>
<td>(0.01)</td>
</tr>
<tr>
<td>Δ Credit to the Non-Financial Private Sector</td>
<td>0.50**</td>
<td>0.15**</td>
</tr>
<tr>
<td></td>
<td>(0.20)</td>
<td>(0.07)</td>
</tr>
<tr>
<td><strong>Duration</strong></td>
<td>7.6 quarters</td>
<td>27.2 quarters</td>
</tr>
<tr>
<td>$p_{11}$</td>
<td>0.87</td>
<td></td>
</tr>
<tr>
<td>$p_{12}$</td>
<td>0.13</td>
<td></td>
</tr>
<tr>
<td>$p_{21}$</td>
<td>0.04</td>
<td></td>
</tr>
<tr>
<td>$p_{22}$</td>
<td>0.96</td>
<td></td>
</tr>
</tbody>
</table>

Note: The standard errors are given in parenthesis. The 1%, 5% and 10% significance levels are denoted by ***, **, and * respectively.
Figure 4.7: Markov Switching Regimes and Real GDP

Note: The blue shaded area of Figure 4.7 represents state 1 (the contractionary regime).
The white shaded area represents state 2 (the expansionary regime)

The contractionary regime

To understand these results in more detail, first let’s examine the contractionary periods picked up by the Markov switching model. The period of the late 1970s and early 1980s is often referred to as the ‘Great Inflation’. During this period, inflationary pressures in the US were significantly increasing, while real economy activity was erratic. World oil prices increased sharply following the overthrow of the Shah of Iran, and policies to curb inflation and strengthen a continually weakening dollar were not succeeding. Following the appointment of Paul Volcker as chairman of the Federal Reserve in October 1979, the FOMC adopted a new operating procedure for the conduct on monetary policy and this marked the movement of the Federal Reserve to a more ‘monetarist’ approach. As part of this new operating procedure, new reserve requirements were imposed on certain liabilities and the Federal Reserve, instead of targeting particular federal funds rates, set about supplying ‘a volume of bank reserves consistent with desired rates of growth of monetary aggregates prescribed by the FOMC’. As such, the Federal
Reserve moved from targeting the Federal Funds Rate to targeting non-borrowed reserves, a policy which remained in place until 1984. Additionally, President Carter, in an effort to combat rising inflation, authorized the imposition of controls on consumer credit by the Federal Reserve. The objective of this control on consumer credit was to reduce pressure on, already very high, interest rates and to limit the growth of consumer credit that appeared to be fuelling the inflationary process. According to Mussa (1994), the response to the credit controls, combined with very tight monetary policy, was virtually instantaneous. The economy moved into recession but only for a very brief period of time. This period of very tight monetary policy remained until mid-1982, when monetary policy begins to loosen and the volatility of output began to decrease significantly (Bilbie & Straub, 2012).

Unlike the recessions of the early 1980s, the causes of the mild 1990-1991 recession have been attributed to many different factors including pessimistic consumers, debt accumulation from the 1980s, increases in oil prices, and a credit crunch. Using an IS-LM-AS model with impulse response functions, Walsh (1993) finds the downturn in the economy was as a result of two factors; a crisis in consumer and business sentiment at the time of the Gulf War; and restrictive monetary policy which lead to overall weakness in the economy. The Federal Reserve reacted by steadily reducing the federal funds rate from 6 percent in mid-1991 to 3 percent in October 1992. Inflation fell to approximately 3 percent by 1992, bringing the real interest rate to approximately zero. This zero real interest rate remained in place until 1994 (Goodfriend, 2002). The response of the Federal Reserve to the Great Recession included a combination of aggressive monetary and fiscal policy. The government essentially set out to accomplish two goals: to stabilise a weak financial system, and to restart economic growth (Blinder, 2010). The Federal Reserve aggressively lowered the interest rate and by the end of 2008, a zero-interest rate policy was in operation.

These three contractionary periods detected by the Markov switching model correspond to the aggressive use of monetary policy to stabilise the economy. Monetary policy in the late 1970s and early 1980s was used to reduce inflationary pressure. In the early 1990s, the Federal Reserve adopted a zero real interest rate policy to ensure recovery from the brief recession during the Gulf War, and finally during the Great Recession to stabilise a weak financial system and restart economic
growth. The summary statistics provided in Table 4.6 below support the concept that state 1 is reflective of the contractionary regime. The output gap is negative in this regime suggesting that there is some slack in the US economy and real GDP growth is low at 0.95 percent. Property prices experience negative growth in this regime and are highly volatile, with a standard deviation of 6.15 percent.

Table 4.6: Summary Statistics

<table>
<thead>
<tr>
<th>Variable</th>
<th>Mean</th>
<th>S.D.</th>
<th>Skewness</th>
<th>Kurtosis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output gap</td>
<td>-0.46%</td>
<td>2.48%</td>
<td>0.03</td>
<td>-1.25</td>
</tr>
<tr>
<td>Real interest rate</td>
<td>2.48%</td>
<td>3.04%</td>
<td>0.28</td>
<td>-1.10</td>
</tr>
<tr>
<td>Δ property prices</td>
<td>-2.11%</td>
<td>6.15%</td>
<td>-0.06</td>
<td>0.74</td>
</tr>
<tr>
<td>Δ credit</td>
<td>8.75%</td>
<td>4.91%</td>
<td>-0.60</td>
<td>-0.33</td>
</tr>
<tr>
<td>Δ real GDP</td>
<td>0.95%</td>
<td>3.11%</td>
<td>0.23</td>
<td>-0.97</td>
</tr>
</tbody>
</table>

Figure 4.8: The IS curve for the US in a Recessionary Regime

Interestingly, credit growth in the contractionary regime is higher than credit growth in the expansionary regime. As illustrated in Figure 4.12 (page 122), the contractionary regime includes the 1970s and 1980s period when credit expansion was the highest over the entire sample period.

55 Interestingly, credit growth in the contractionary regime is higher than credit growth in the expansionary regime. As illustrated in Figure 4.12 (page 122), the contractionary regime includes the 1970s and 1980s period when credit expansion was the highest over the entire sample period.
Given that state 1 is assumed to be representative of the contractionary regime, Figure 4.8 above illustrates the contractionary regime IS curve for the US economy. The IS curve is clearly downward sloping, as theory suggests it should be. This implies that, in contractionary periods, the real interest rate has an important impact on the output gap. However, as provided in Table 4.5, the real interest rate does not work in isolation. Additional credit market factors and housing related factors also have a statistically significant impact on the output gap.

*The expansionary regime*

Next, let’s examine the expansionary regime of the model; the period 1984 to 1991; 1992 to 2008; and 2009 to present. As described by the output in Table 4.5, during the expansionary regime only the lag of the output gap and total credit to the non-financial private sector are statistically significant. Monetary policy is found to have no statistically significant impact on aggregate demand during this period. The period after 1984 is generally regarded as the starting point of increased stability in the US economy and represents a period often referred to as the ‘Great Moderation’. There has been much research on why volatility declined during this period, with many pointing to improved monetary policy (Clarida et al., 2000), the introduction of financial innovation (Dynan et al., 2006), to more micro level reasons, such as better inventory control methods (Kahn et al., 2002). Some simply attribute it to ‘good luck’ as a result of smaller exogenous shocks over the period (Stock and Watson, 2002) while others, such as Gali and Gambetti (2009), attribute it to changes in the patterns of co-movements among output, hours and labor productivity. Here we examine the role of two of these factors: monetary policy during the Great Moderation period and the role of financial innovation.

According to Taylor (2007, 2009, 2014) monetary policy, along with fiscal and regulatory policy, became more discretionary in the Great Moderation period. In particular, there was a significant shift in monetary policy between 2002 and 2006 when the Federal Reserve held interest rates unusually low at 1 percent when the inflation rate was 2 percent. Jarocinski and Smets (2008) use vector autoregressive equations to analyse the interest rate environment in the US over this period and find similar results. This low interest rate environment is found to have exacerbated the housing boom and subsequent bust by allowing excessive risk taking (Bekaert,
Hoerova, and Lo Duca, 2013). The demand for housing depends partly on the long-term fixed mortgage rate which is related to short-term interest rate. As such, a lower short-term interest rate will reduce the mortgage interest rate on adjustable rate mortgages (Bordo and Landon-Lane, 2013).

Dynan et al. (2006) finds that financial innovation, in the form of improved assessment and pricing of risk, has increased lending to households with little collateral and has allowed households and firms to access many forms of credit in which to borrow. Additionally, securitization has led to the enormous expansion of the so-called “shadow banking system,” in which bank lending has been replaced by lending via the securities market. According to Boivin et al. (2010), shadow banking has had two major impacts: firstly, it has enabled borrowers to bypass banks to get credit; and secondly, shadow banking has led to wider access to credit by a larger percentage of the population, a process known as the “democratization of credit.” Over the period of the Great Moderation, the appetite of households and firms to obtain credit changed substantially. Figure 4.9 below shows the ratio of household debt to disposable income over the past 30+ years.

![Figure 4.9: Ratio of Household Debt to Disposable Income in the US](image)

Here we can see that the ratio of household debt to disposable personal income rose from 61 percent in 1977Q1 to a high of 130 percent by 2007Q4. From the period 1984Q1 to its peak in 2007Q4, this ratio increased 67 percent.
These increases seem likely to stem from the increase in the credit supply, as illustrated in Figure 4.10, and from an increased willingness to borrow (Dynan et al. 2006). Gross and Souleles (1999) suggest this is as a result of a greater understanding of obtaining credit and also the reduced stigma associated with being in debt.

**Table 4.7: Summary statistics**

**State 2 (Expansionary Regime)**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Mean</th>
<th>S.D.</th>
<th>Skewness</th>
<th>Kurtosis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output gap</td>
<td>0.17</td>
<td>0.99</td>
<td>0.02</td>
<td>-0.49</td>
</tr>
<tr>
<td>Real interest rate</td>
<td>1.41</td>
<td>2.44</td>
<td>-0.05</td>
<td>-0.94</td>
</tr>
<tr>
<td>∆ property prices</td>
<td>2.55</td>
<td>6.16</td>
<td>-0.73</td>
<td>1.18</td>
</tr>
<tr>
<td>∆ credit</td>
<td>7.01</td>
<td>4.14</td>
<td>-0.56</td>
<td>0.06</td>
</tr>
<tr>
<td>∆ real GDP</td>
<td>3.13</td>
<td>1.47</td>
<td>0.48</td>
<td>1.54</td>
</tr>
</tbody>
</table>
Figure 4.11: The IS Curve for the US in an Expansionary Regime

The summary statistics for state 2 are provided in Table 4.7 above and are consistent with the notion that state 2 is reflective of the expansionary regime. Here real GDP growth is high at 3.13 percent and stable, with a small standard deviation of 1.47 percent. The growth in house prices is positive at 2.55 percent and the real interest rate is lower during this period at 1.41 percent (compared to an average of 2.48 percent in state 1). As in state 1, the growth in credit to the non-financial private sector is high at 7.01 percent but the standard deviation and hence volatility of this series is slightly lower during this period, at 4.14 percent (compared to a standard deviation of 4.91 percent in the contractionary regime). The IS curve for the US when in an expansionary regime, as identified by the Markov switching model, is illustrated in Figure 4.11 above. Clearly, an upward sloping IS curve exists during expansionary periods, and underlies the concept of this ‘IS puzzle’
Figure 4.12 below illustrates total credit to the non-financial private sector growth and property price growth within the two distinct regimes.

Source: Federal Reserve Economic Databank and author’s calculations

Figure 4.12: Credit and Property Prices during Expansionary and Contractionary Regimes

Note: The blue shaded area of Figure 4.12 represents state 1 (the contractionary regime). The white shaded area represents state 2 (the expansionary regime)
4.6. Conclusions

The objective of this chapter was to examine the transmission mechanism of monetary policy under financialisation. This objective is achieved in two ways: (i) by introducing the financial economy through the incorporation of house prices and credit, and (ii) by modelling the nonlinear transmission of monetary policy that can arise as a result of the interaction between the real and financial economy. Regarding the first objective, it is clear that property prices and credit are important determinants of aggregate demand within the economy. This is reflected in the results of the estimation of three separate models: the simple linear OLS estimation, the breakpoint model estimation, and finally the Markov switching estimation, were both variables are statistically significant. As outlined by Bordo and Landon-Lane (2013), asset price booms are important and potentially dangerous to the real economy and should therefore be monitored closely by monetary policymakers. In addition to the inclusion of asset prices, and in line with research by Drehmann et al. (2012) and Borio (2013, 2014), the interaction between credit and asset prices is important since they tend to co-vary with one another at low frequencies.

Regarding the second objective of this chapter; the results of the Markov switching model indicate that monetary policy is asymmetric in the US. During an expansionary regime, monetary policy has no influence on aggregate demand. Aggregate demand is driven by credit to the non-financial private sector. However, during a contractionary regime, all variables included in the estimation (output gap, the real interest rate, real residential property prices and total credit to the non-financial private sector) become statistically significant and are correctly signed. The results during the contractionary regime indicate that monetary policy can influence the real economy, but that it is important that the real interest rate does not act in isolation. The financial economy variables remain important during this period, suggesting a dual role for the real interest rate and the financial cycle within the transmission of monetary policy to the real economy.
CHAPTER 5

EXAMINING THE INTERACTION BETWEEN THE BUSINESS AND FINANCIAL CYCLE USING RECURRENTANCE ANALYSIS

5.1 Introduction

The objective of this chapter is to study the nature of the business cycle, the financial cycle, and their interaction using nonparametric methods, with a view to informing the development of alternative macroeconomic theory and policy. Examining the interaction between the business and financial cycle in the US using nonparametric techniques will help to understand how these cycles interact with each other. This objective is achieved through the use of recurrence plots (RPs) and recurrence quantification analysis (RQA), which are techniques used in the study of nonlinear dynamics. Although there are several methodologies prevalent in the literature to achieve this objective, these models typically rely on linear techniques and therefore have limited capacity to detect and characterise nonlinearities inherent in a system as complex as the macroeconomy (Crowley and Schultz, 2010). These linear models assume that the data is stationary, the parameters are constant, and that all irregularity must be as a result of some random element in the model (Kantz and Schreiber 2003, Patterson 2000).

Recurrence plots, as popularised by Eckmann et al., 1987, and recurrence quantification analysis, as introduced by Zbilut and Webber (1992), are nonlinear time series analysis techniques that can be used to detect deterministic dependencies in time series data. Recurrence plots are graphical tools that provide a visual representation of recurrences by providing information on the time evolution of trajectories in some phase space as given by some small and large scale patterns. These patterns can reveal complex deterministic patterns in dynamical systems. The quantification of these recurrence plots, as provided by recurrence quantification analysis, allows for analysis of a range of typical dynamical features of the system, such as predictability or laminarity (Marwan and Kurths, 2004).”

This nonparametric approach is particularly interesting in economics and finance since it deals with many of the limitations of linear models: it requires no
assumptions on stationarity, statistical distributions, and observation size (Bastos and Caiado, 2011). Moreover, their ability to work with nonlinearity and testing for chaos or noise, detecting changes in data behaviour, detecting breaks, like phase transitions, and in informing about other dynamic properties of a time series has allowed for their successful implementation in a number of scientific fields, and more recently, in economics and finance (Fabretti and Ausloos, 2004). As noted by Caraiani and Haven (2013), recurrence analysis is particularly useful when examining transitions during recessions, or for understanding the complexity that exists between macroeconomic and financial variables (Karagianni and Kyrtou, 2011).

As outlined by Sinai (2010), business cycle analysis was developed over 80 years ago by Burns and Mitchell (1946) in an effort to describe the economy at the time, which was quite different to the one we have today, where the financial sector constitutes a large part of the economy. According to Borio (2014), the notion of the financial cycle actually predates the notion of the business cycle, but fell out of favour during the post-war period. Notably, financial variables were largely either ignored in business cycles (for example, Woodford, 2003) or modelled as exogenous frictions in the system (for example, Bernanke et al., 1999). According to economic theory, and as outlined by Cochrane (2006), when there are no financial frictions, the macroeconomy and financial economy interact closely with one another via wealth and substitution effects. If financial frictions do exist, then the interaction between the macroeconomy and the financial economy is amplified via various channels. These financial frictions are often modelled in the form of a financial accelerator.

The Great Recession period was marked by a financial crisis and panic which illustrated, according to Sinai (2010), the so-called ‘financial factor’ in the business cycle. This ‘financial factor’ encompasses the financial system in terms of its interactions with the real economy. However, while research on the interaction between the real and financial economy has increased over recent years, the empirical link between the two has not been established as an empirical fact (Avouyi-Dovi and Matheron, 2003). Indeed, Claessens et al., (2011), states that ‘the

56 With the exception of Minksy (1982) and Kindleberger (2000)
current theoretical literature appears far from either being able to explain the linkages between the real economy and financial sector or from capturing them in models useful for policy making”. With this in mind, Drehmann et al. (2012), Borio et al. (2014) and others\textsuperscript{58} focused their attention on the financial cycle. Their classification of the financial cycle noted five key features: first, it can be most parsimoniously described in terms of credit and property prices; second, it has a lower frequency than the traditional business cycle (the business cycle is found to be between one – eight years, while the financial cycle is found to be approximately 16 years); third, its peaks are closely associated with financial crises; fourth, it is possible to measure the buildup of risk of financial crises in real-time; and finally, its length and amplitude depends on policy regimes\textsuperscript{59}.

Given the importance of the financial sector to the propagation of the business cycle, this chapter takes a nonparametric view of the business cycle, the financial cycle and finally the interaction between business and financial cycles. The aim is to observe the key features present in both cycles to aid our understanding of the complex macroeconomic system. Additionally, the interaction between the business and financial cycle is undertaken to determine their convergence and synchronicity. This is important in determining lead-lag relationships and critical transitions. Recent research has relied on turning point methodologies and frequency based filters to characterise the financial cycle, along with the concordance index to determine synchronicity. The research in this chapter, to our knowledge, is the first to use recurrence analysis to study the interaction between the business and financial cycle.

5.2 Review of the Literature

The following section outlines the literature relating to the interaction between the business and financial cycle, the literature relating to the identification of variables representing the financial cycle and finally the current literature that utilises recurrence analysis using financial and economic data.

\textsuperscript{58} Additionally, Claessens et al. (2011a,b), Aikman et al. (2011), Goodhart and Hofmann (2008), Alessi and Detken (2009), Gerdesmeier et al. (2010) amongst others. Drehmann et al. (2012) provides a list of recent research exploring this.

\textsuperscript{59} According to Borio and Lowe (2002), the three regimes include the financial regime, the monetary regime, and the real economy regime.
5.2.1 The Interaction between the Real and Financial Economy

As noted by Gertler (1988), the classic business cycle theory holds that the financial system is irrelevant to the real economy. Indeed, economic theory in general has been divided about this issue. After the collapse of the financial system during the Great Depression, Fisher (1933) argued that there was a link between the real and financial economy: the high level of debt among the borrowing classes was sufficient, in his view, to “not only rock the boat, but to start it capsizing”. From this, Fisher put forward his debt-deflation theory. While the financial system did form an important part of Keynes’ General Theory, it did not play a central role in his theory of output determination either and, as discussed by Gertler (1988), macroeconomists following the General Theory largely ignored the link between the real and financial economy. The exception was Hicks (1937) and Modigliani (1944) who focused on Keynes’ theory of liquidity preference which would link money to real economic activity.

Sinai (1992) noted that the macroeconomic tradition stressed that fluctuations in real variables, such as output and employment, took precedent over fluctuations in money and financial assets. Given the financial nature of the 1990 and 1991 recessions in the US, Sinai (1992) challenged this approach and developed a large scale structural macroeconomic model (Sinai-Boston Model of the US Economy) to examine the presence of financial business cycles in the US over the period 1980 to 1990. This Sinai-Boston Model is a flow-of-funds type model, with households, business, financial intermediaries, government, and the rest of the world acting as sectors within the economy. The results indicated that both real and financial variables matter for growth, employment, inflation, interest rates, financial flows, debt and balance sheet behavior and can provide a useful framework for analyzing the characteristics of actual economic behavior.

Regardless of the research developed by Sinai (1992), econometric models of the macroeconomy continued to ignore the role financial side of the economy in the propagation of real side fluctuations. The financial nature of the Great Recession, however, made it difficult to ignore, and consequently research began to examine the interaction between the business and financial cycle. One such examination by
Claessens et al. (2011), found that interactions between business and financial cycles play an important role in shaping recessions and recoveries. In particular, recessions associated with financial disruption such as house price busts, are often longer and deeper than other recessions, while recoveries associated with rapid growth of credit and house prices tend to be more robust. Additionally, there is a high degree of synchronisation between business cycles and cycles in credit and house prices, but less synchronisation when associated with cycles in equity prices. The equity prices finding is in line with research by Avoui-Dovi and Matheron (2003) who found no evidence of dependence in their analysis of the interaction between business cycles and stock market cycles.

5.2.2 Defining the Financial Cycle

While GDP has been the most common variable used to measure the business cycle, the consensus on the appropriate variable required to represent the financial cycle is less established. For example, Claessens et al., (2011), use output to represent the business cycle and three different individual market segments are used to represent the financial cycle. These market segments include credit, housing and equity markets. Drehmann et al. (2012) use five financial variables: credit to the non-financial private sector, the ratio of credit-to-GDP, equity prices, residential property prices, and an index of aggregate asset prices combining residential property, commercial property and equity prices. The joint behaviour of credit and property prices is used by Borio et al. (2013) to represent the financial cycle, while other studies focus either exclusively on credit (see for example, Aikman et al., 2010; Schularick and Taylor, 2009; and Jordá et al. (2011) or exclusively on property prices (IMF, 2003).

For the purposes of this study, the System of National Accounts (2008) is analysed to determine the variable that could best represent the financial cycle. The System of National Accounts (SNA) is presented within an accounting framework which provides a detailed account of the complex activities being undertaken by different economic agents. This allows for the analysis of economic interactions taking place within the different sectors of the macroeconomy. The production account, capital account and financial account are detailed below.
The production account

The production account displays the generation, distribution and use of income within the economy. According to item 6.2, production “...uses inputs of labour, capital, and goods and services to produce outputs of goods and services”. The production boundary defines what constitutes production within the SNA. Accordingly, item 6.27 of the SNA outlines the production boundary by the following activities:

1. The production of all goods and services that are used up in the process of producing goods and services
2. Production of goods for own final consumption or gross capital formation
3. Production of knowledge capturing products for own final consumption or gross capital formation, but excluding products produced by households for their own use
4. Production of housing services by owner occupiers
5. Production of domestic and personal services by employing paid domestic staff

The capital account

The capital account deals with changes in the value of assets held by institutional units, and records transactions in non-financial assets. Non-financial assets include produced assets and non-produced assets. Produced assets are “non-financial assets that come into existence as outputs from production processes that fall within the production boundary of the SNA” while non-produced assets are “non-financial assets that have come into existence in ways other than through processes of production”. These produced assets include fixed assets, inventories and valuables. Regarding fixed assets, item 10.33 states that “all goods and services supplied to the economy by means of production, imports, or the disposal of produced assets must be used for exports, consumption or as part of capital formation”. Consumer durables, such as washing machines, should not be treated as fixed assets since they produce services outside the production boundary. Non-produced assets include natural resources, contracts, leases and licenses, purchased goodwill and marketing assets.
The financial account

Item 11.8 of the System of National Accounts states that “financial assets consist of all financial claims, shares or other equity in corporations plus gold bullion held by monetary authorities as a reserve asset”. The financial instruments provided by the System of National Accounts 2008 include the following: monetary gold and Special Drawing Rights (SDRs); currency and deposits; debt securities; loans; equity and investment fund shares; insurance, pension and standardised guarantee schemes; financial derivatives and employee stock options; other accounts receivable or payable; and memorandum items, each of which are explained in more detail below.

Monetary gold and Special Drawing Rights (SDRs): According to item 11.44 of the SNA, “monetary gold is gold to which the monetary authorities have title and is held as a reserve asset”. This monetary gold is issued by the IMF, and with the exception of limited institutional circumstances, can only be a financial asset for the central bank or central government. Currency and deposits: Item 11.52 of the SNA states that currency “consists of notes and coins that are of fixed nominal values and issued or authorised by the central bank or government”. Currency may be held as assets by all sectors of the economy. Debt securities include bills (such as Treasury bills), bonds, certificates of deposit, commercial paper, debentures, asset-backed securities and other instruments traded in the financial markets. According to item 11.64 “debt securities are negotiable instruments serving as evidence of a debt”. The updated 2008 SNA included asset-backed securities and collateral debt obligations (CDOs) within their definition of the financial account. These are defined as “arrangements under which payments of interest and principal are backed by payments on specified assets or income streams”. Asset-backed securities are backed by a variety of different financial assets, including mortgages and credit cards.

Loans include overdrafts, instalment loans, hire-purchase credit and loans to finance trade credit. According to item 11.72 loans are defined as “financial assets that are created when a creditor lends funds directly to a debtor, and are evidence by documents that are not negotiable”. In addition, securities, repurchase agreements, gold swaps and financing using a financing lease are also considered under the broad loan heading. Equity and investment fund shares: Item 11.83 states that equity “comprises all instruments and records acknowledging claims on the residual value
of a corporation or quasi-corporation after all the claims of all creditors have been met”. Types of equity include shares, stocks, depository receipts, participations, or similar documents and are used to indicate evidence of ownership on the assets of corporations. Within insurance, pension and standardised guarantee schemes are five different reserves applicable. These include non-life insurance technical reserves, life insurance and annuities entitlements, pension entitlements, pension fund claims and provisional calls on standardised guarantees. Financial derivatives and employee stock options: Item 11.111 states that “financial derivatives are financial instruments that are linked to a specific financial instrument or indicator or commodity, through which specific financial risks can be traded in financial markets in their own right”. Two types of financial derivatives exist: option contracts and forward-type contracts.

Based on the SNA (2008), this chapter will examine the interaction between the production account and the capital account, which is represented by property prices. Property prices represent unproductive capital that yields a rate of return and there is a growing body of literature that outlines the importance of housing to the business cycle (see for example, Helbing and Terrones, 2003; Van den Noord, 2004, 2006; Ahearne et al. 2005; Hoeller and Rae, 2007; and Leamer, 2007) with housing representing a large share of wealth for households. As a result, price adjustments affect consumption and output more than say equity movements or restrictions in credit (Claessens et al., 2011). The importance of housing also extends to changes in the key components of output, since consumption and investment account for approximately 68 percent and 19 percent\(^{60}\) of GDP respectively in the US. A decline in the housing wealth of consumers is likely to affect household consumption and hence impact on output. Additionally, Cecchetti (2006) found that housing bubbles can change the entire distribution of macroeconomic outcomes. Further research will allow for additional variables from the financial account to be analysed. This will include in particular credit spreads between US Treasury bonds and Baa corporate bonds. For the purpose of this study however, house prices will be used as the variable representing the financial cycle.

\(^{60}\) See World Bank databank which is available at http://data.worldbank.org/indicator/NE.GDI.TOTL.ZS
5.2.3 Recurrence Analysis in the Economic Literature

Recurrence plots and recurrence quantification analysis, for the most part, has been applied mainly in the sciences, for example physics, astronomy, physiology, ecology and is a relatively new approach in the finance and economics literature. There have been, however, several papers which have used this approach (see for example Strozzi et al. 2007; Crowley 2007; Belaire-Franch et al. 2002; Marwan et al. 2007; Fabretti and Ausloo 2005). Goswami et al. (2012) examine the interrelations of recurrences and connectivity trends between nine stock market indices from around the world. This includes stock market indices from Asia, Europe and the US over a twenty year period (1990 to 2010). Using recurrence plots, their findings show that markets have moved in and out of highly connected periods. This is particularly evident when studying the behaviour of these indices during bubbles, when they are found to share similar dynamics.

Similarly, Bastos and Caiado (2011) examine stock indices from developed and emerging market economies. Instead of examining how connected these stock indices are, the authors test for the presence of deterministic dependencies using both recurrence plots and recurrence quantification analysis. Using recurrence plots, their findings suggest that stock markets in countries with strong economic interdependence tend to display similar features in recurrence plots. Karagianni and Kyrtsou (2011) study the dynamic relationship that exists between inflation in the US and stock returns from the Dow Jones Industrial Average (DJIA) index from 1960 to 2010. Both series are found to co-move according to the specific time period and display evidence of negative nonlinear linkages. This nonlinearity implies that small changes in the fundamentals can lead to unexpected changes in the financial system. Guhathakurta et al. (2010) use recurrence plot analysis to distinguish between endogenous and exogenous crashes in the stock market. Three stock market indices are used: the Indian stock market index NIFTY 100, the Hong Kong AOI index and the DJIA. This analysis is used to detect critical regimes preceding endogenous and exogenous crashes in the stock market which is used to estimate of the timing of the bubble formation. In the case of endogenous crashes, the RP and

---

61 See Zbilut and Webber (2006) for a more detailed discussion of the the application of recurrence plots and their quantification within many different fields.
RQA tools are able to identify patterns that indicate the formation of a bubble, while in the case of an exogenous crash, no notable pattern emerges.

This methodology has also been applied to macroeconomic data. For example Caraiani and Haven (2013) use recurrence plots to characterise Okun’s law, that is, the relationship between output and unemployment using data from the US between 1949 and 2010. Their findings show nonlinearities, state switching and dynamics relations characterises this relationship. Additionally, a degree of predictability is found, with periods of discontinuity corresponding to large recessions. Chen (2011) uses a combination of recurrence plots and recurrence quantification analysis to examine the dynamics of the unemployment rate in Taiwan over the period 1978 to 2010. The findings of this research show that the unemployment rate in Taiwan shows cyclically different periodic-chaos-laminar-chaos regimes.

Recurrence plots and recurrence quantification analysis have also been used to examine business cycle synchronisation and convergence. Crowley and Schultz (2010), Crowley (2008) and Crowley (2007) test for convergence and synchronisation of both business cycles and growth cycles between a euro area growth aggregate and European member states to examine the optimal application of a single monetary policy using recurrence plots. Their findings show that, among the core members, synchronicity and convergence is high. This suggests that monetary policy has similar effects on core members of the Euro Area. As such, these members are suited to being part of a monetary union. However, outside the core members, there is no consistency regarding their convergence and synchronicity with the euro area growth rate.

5.3 Nonlinear Dynamics Methodology

Marwan et al. (2007) gives a very comprehensive overview of recurrence plot and recurrence quantification analysis, within which it outlines the concept of dynamical systems. Two facts are said to characterise dynamical systems: first, systems of very different kinds can be modelled by deterministic differential equations, and second, recurrences are a fundamental characteristic of many dynamical systems. Recurrence refers to the process of a system returning or recurring to a former state and implies that the system has some memory. The concept of recurrence was first introduced by Poincaré in 1890 and was further developed by Eckmann et al. in 1987 in which the
concept of recurrence plots was introduced. Recurrence plots were developed to
visualise the recurrences of dynamical systems. The recurrence plot is based on the
recurrence matrix provided in equation (5.1) below:

$$R_{i,j} = \begin{cases} 
1: \vec{x}_i \approx \vec{x}_j \\
0: \vec{x}_i \neq \vec{x}_j
\end{cases} \quad i,j = 1, ..., N, \quad (5.1)$$

Where \( N \) is the number of considered states, and \( \vec{x}_i \approx \vec{x}_j \) means equality up to a
distance \( \varepsilon \) with \( i \) indicating time on the x-axis and \( j \) indicating time on the y-axis.
Systems will not recur at exactly the same point as before and as a result, this
distance parameter \( \varepsilon \) is important. It will tell us when a system recurs approximately
to a previous state. The recurrence matrix compares the states of the system at times
\( i \) and \( j \). If the states are similar, then this is recorded as a value of one in the matrix
(i.e. \( R_{i,j} = 1 \)). If the states are not similar, then this is recorded as a value of zero (i.e.
\( R_{i,j} = 0 \)). This recurrence matrix therefore tells us when the similar states occur.

**A simple example of recurrence analysis**

To best illustrate the concepts underlying recurrence analysis, three simple examples
of well-known processes are outlined. These examples include a recurrence plot of
periodic motion as illustrated by a sine wave (Figure 5.1A), uniform white noise
(Figure 5.1B), and a chaotic Rössler system (Figure 5.1C). The left hand side of
Figure 5.1A shows the thresholded recurrence plot. It is a highly structured system
with a lattice (or checkerboard) shaped recurrence plot. This is indicative of a system
whose state doesn’t change much or changes very slowly and can indicate that the
series exhibits determinism or periodicity. Diagonal lines indicate trajectories that
pass through the same region of the phase space at different times (Fabretti and
Ausloos, 2004). Therefore the lattice shape of the recurrence plot for the sine wave
and the long and uninterrupted diagonals display periodic motion (Marwan *et al.*
2007).
Figure 5.1 Threshold and Unthresholded Recurrence Plots of (A) Periodic Motion, (B) Uniformly Distributed White Noise and (C) the Chaotic Rössler System

Source: Author's estimations
The right hand side of Figure 5.1A shows an unthresholded (or distance) recurrence plot. An unthresholded recurrence plot doesn’t use specific criteria to determine whether a point is similar (i.e. a distance $\varepsilon$), it simply measures the distances between the points (Crowley and Schultz, 2010). The unthresholded recurrence plot will display red dots when the points are close to one another, blue dots when the points are very different and white dots for all points in-between.

The recurrence plot of uniformly distributed white noise is provided in Figure 5.1B. Here the distribution of the points in the recurrence plots shows no structure and no diagonal lines have formed. Since by definition $R_{ij} = R_{ji}$, the recurrence plot has a black main diagonal line called the line of identity (LOI). This LOI doesn’t contain any information about the actual states of the system at times $i$ and $j$ in the phase space (Marwan and Kurths, 2005). Finally, Figure 5.1C shows the recurrence plot of chaotic Rössler system $^{62}$ The thresholded RP of the chaotic Rossler system shows black areas when the trajectories of the system are close to one another. After point 200, the Rossler system becomes (nearly) periodic and this is illustrated in both the thresholded and unthresholded RP.

5.3.1 Reconstructing the Phase Space

Following Kantz and Schreiber (2003), the theory of dynamical systems, from which recurrence analysis is built, is based on the premise that time evolution can be defined in some phase space. A phase space can be defined as a finite dimensional vector space $\mathbb{R}^m$ where a specific state is specified by a vector $x \in \mathbb{R}^m$. The dynamics of the vector can then be described by either an $m$-dimensional map (for which time is a discrete variable), or by a system of $m$ first order ordinary differential equations (for which time is a continuous variable). Given that we are using economic and financial time series, the vector can be described by an $m$-dimensional map as follows:

---

$^{62}$ The Rössler system is a system of three non-linear ordinary differential equations that exhibit chaotic dynamics.
\[ x_{n+1} = F(x_n) \quad n \in \mathbb{Z} \] (5.2)

In order to convert the time series into a phase space object, the observations need to be converted into state vectors. This is referred to as phase space reconstruction. To reconstruct the phase space, two key elements are required: an embedding dimension, \( m \), within which the attractor of the system can fully unfold and a time delay, \( \tau \), to represent the dynamics of the underlying system. Both are outlined next.

**Determining the Embedding Dimension (m)**

According to Kantz and Schreiber (2003), there exists a dimension such that the vectors \( s_n \) are equivalent to phase space vectors. The embedding dimension, \( m \), is the minimum number of time-delay coordinates needed so the trajectories of a phase space do not intersect in \( m \) dimensions. If the true dimension of the system is less than the specified \( m \), trajectories can intersect because they are projected into too few dimensions. If the true dimension of the system is greater than the specified \( m \), noise may corrupt the calculations. Therefore, to find the true embedding dimension of a system, we can employ the False Nearest Neighbours methodology of Kennel et al., 1992. The false nearest neighbour method measures the distances between a point and its nearest neighbour. As the dimension increases, this distance should not change if the points are really nearest neighbours. When the number of false nearest neighbours drops to zero, the attractor has unfolded and has been embedded in an \( m \)-dimensional Euclidean space. Figure 5.2 below illustrates the Hénon map\(^{63}\) in different dimensions. The first graph is a 1-dimensional Hénon map. Here, a green and blue dot is clearly visible and the two points appear close together. When the Hénon map is plotted in a 2-dimensional space, it is clear that there are three dots: a green dot, a blue dot, and a red dot. Not only that, when then the Hénon map is plotted in the 2-dimensional space, one can see that the green and blue dots are not actually close together, they simply look close together in the 1-dimension space (i.e. they are false neighbours). Finally, when the Hénon map is plotted in 3-dimensional space, the dynamics of the attractor can be more clearly seen as it unfolds.

---

\(^{63}\) The Hénon map is a discrete-time dynamical system that exhibits chaotic behavior.
Figure 5.2: An Illustration of the Chaotic Hénon Map in Different Dimensions: A 1D Hénon Map, a 2D Hénon Map and a 3D Hénon Map
According to Webber and Zbilut (2005), this false nearest neighbours methodology works well on stable and low noise systems, often found in mathematical examples such as the Lorenz attractor. Real world data, such as economic and financial time series, however tends to be characterised by noise and nonstationarity which can inflation the dimension of the system and serves as one limitation of the false nearest neighbour methodology. Embedding theorems by Takens (1981) and Sauer et al. (1991) indicate that the lower bound for the embedding dimension is given as $d \geq 2m+1$, where $d$ is the embedding dimension and $m$ is the dimension of the unknown system. There is no upper bound for the embedding dimension. In biological systems, the embedding dimension can be as high as between 10 and 20 (Webber and Zbilut, 2005).

**Determining the Lag Length ($\tau$)**

The second parameter required for reconstructing the phase space is the time delay $\tau$. As discussed in Webber and Zbilut (2005), the time delay should be chosen so as to minimise the interaction between points of the measured time series. If the time delay chosen is too small, successive elements of the delay vectors may be strongly correlated which can lead to redundancy (Casdagli et al. 1991a; Gibson et al. 1992). Alternatively, if it is too large, successive elements of the delay vectors will be independent causing the reconstructed attractor to become very complicated when the underlying ‘true’ attractor is in fact simple (Kantz and Schreiber, 2003). To determine the time delay $\tau$ required to reconstruct the phase space, two popular approaches can be used. The first is the autocorrelation function (ACF) where the time delay is chosen to be the first minimum of the ACF. The second approach implements the methodology of Fraser and Swinney (1986) called time delay mutual information which measures the dependence between two variables. This methodology states that the first minimum of the mutual information of the reconstructed state should be taken as the appropriate time delay $\tau$. The mutual information approach is generally preferred to the ACF approach since it measures general dependence, whilst the ACF only measures linear dependence (Li, 1990). For discrete time series such as economic and financial data, a time delay $\tau$ of 1 is
usually appropriate (Zbilut, 2005) and is therefore chosen as the time delay in this chapter.

5.3.2 Recurrence Plot Typology

To analyse recurrence plots, Eckmann et al. (1987) distinguishes between two key features: large scale typology and small scale texture. The typology of the recurrence plot can be classified by four main patterns: homogenous, periodic, drift and disrupted patterns. Homogenous patterns typically describe stationary systems such as uniform white noise as shown in Figure 5.1A. Here the overall pattern is made up of single black and white dots with no lines formed. This indicates short relaxation times in comparison with the time spanned by the recurrence plot (Marwan et al. 2007). Periodic patterns usually describe recurrence plots with lattice (or checkerboard) structures and diagonal lines, as shown in Figure 5.1B (which illustrates the recurrence plot of a sine wave). A drift typology is used to describe systems that have slowly varying parameters that make the plot ‘pale away’ from the diagonal and become darker when near it. This can be indicative of a non-stationary system. Finally, the disrupted typology of a recurrence plot is illustrated by white areas or bands. Typically, these white bands describe abrupt changes / rare events occurring in the dynamics of the system and reveal some transition may have taken place. Marwan et al. (2007) shows this using the example of disrupted Brownian motion. In addition to the large scale structures, referred to as the typology of the recurrence plot, Eckmann et al. (1987) also outlines the small scale textures within the recurrence plot. These small scale textures include single isolated recurrence points, diagonal lines, vertical (or horizontal) lines, and bowed line structures and their meanings are provided in Table 5.1 below.

An extension of the recurrence plot, referred to as the cross recurrence plot (CRP), was introduced as a means of analysing the recurrence between different time series. This method was introduced initially into the physics literature by Marwan, Thiel and Nowaczyk (2002) and Ramono et al. (2005) and has been used in the economics literature by Crowley (2005, 2007) and Crowley and Schultz (2010) in their analysis of the synchronicity of business cycles in the Euro Area.
Table 5.1
Small Scale Patterns in Recurrence Plots

<table>
<thead>
<tr>
<th>Small scale patterns (texture)</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Single isolated points</td>
<td>Single isolated points can be indicative of rare states or heavy fluctuations.</td>
</tr>
<tr>
<td>2. Diagonal lines (parallel to the LOI)</td>
<td>Diagonal lines parallel to the LOI, as observed in the example of periodic motion, can characterise deterministic structure. According to Marwan et al. (2007), if the diagonal lines occur beside single isolated points, then the process could be chaotic. The length of these lines are an indication of the duration of the ‘visits’ and are related to the Lyapunov exponents of the system.</td>
</tr>
<tr>
<td>3. Diagonal line (orthogonal to the LOI)</td>
<td>This can be an indication of an insufficient embedding dimension.</td>
</tr>
<tr>
<td>4. Vertical / Horizontal lines</td>
<td>Vertical and horizontal lines within the recurrence plot can indicate the presence of laminar states. This implies that the system remains stable or exhibits slow dynamics. The length of these lines can indicate how long a system remains in a particular state.</td>
</tr>
<tr>
<td>5. Bowed lines</td>
<td>The evolution of states is similar at different epochs but exhibits different velocity. This can indicate that the system could be changing</td>
</tr>
</tbody>
</table>

Source: This information has been sourced from Marwan et al. (2005, 2007) and Diebolt and Kyrtsou (2005)

Following Marwan et al. (2002) and Ramono et al. (2005), the cross recurrence plot can be expressed by equation (5.3) below:

$$CR_{i,j}(\varepsilon) = \Theta(\varepsilon - \| \tilde{x}_i - \tilde{y}_j \|), \quad i = 1, \ldots, N, \quad j = 1, \ldots, M, \quad (5.3)$$

where $\tilde{x}_i - \tilde{y}_j$ are two embedded time series, $\varepsilon$ is the predefined threshold (as in the recurrence plot given in equation (5.1)), $\| \|$ is the norm (for example, the Euclidean
norm) and $\Theta$ is the Heaviside function which gives a recurrence matrix $CR_{i,j}$ that contains either 0’s or 1’s. The white areas of the cross recurrence plot correspond to the 0’s and the black areas of the plots correspond to the 1’s. As such, the cross recurrence matrix is very similar to the recurrence matrix and both systems are represented in the same phase space. The cross recurrence plot searches for those periods of time when a state of the first system recurs to one of the other system.

One difference between the recurrence plot and the cross recurrence plot is the existence of the line of identity (LOI). In the RP, the LOI is always present (since $R_{i,j} = R_{j,i}$). In the CRP, if this line is present, then the two series are identical, which will obviously be very rare. Rather, the line of synchronisation (LOS) can be computed for CRPs to reveal the relationship between both systems in the same time domain. Apart from this key difference, the typology and small scale patterns given for the RP apply to the case of CRPs.

5.3.3 Recurrence Quantification Analysis

Recurrence quantification analysis (RQA) is a relatively new approach developed by Zbilut et al. (1991), Zbilut and Webber (1992) and Webber and Zbilut (1994) to quantify the small scale structures present in recurrence plots and cross recurrence plots. These measures examine the density of the recurrence points and the vertical and horizontal lines of the RP and CRP. A study by Trulla et al. (1996) found that RQA measures could identify chaos-order transitions and bifurcation points in the logistic equation. Additionally, Marwan et al. (2002) used RQA measures to detect chaos – chaos transitions in heart rate variability data.

The first RQA measure usually examined is the *recurrence rate*. This is a measure based on the density of the recurrence points and is given as:

$$RR(\varepsilon) = \frac{1}{N^2} \sum_{i,j=1}^{N} R_{i,j}(\varepsilon)$$  \hspace{1cm} (5.4)
In the limit $N \to \infty$, the recurrence rate is the probability that a state recurs to its $\varepsilon$-neighbourhood in the phase space and therefore represents that percentage of recurrence points in a RP.

The following measures are based on the diagonal lines present in the recurrence plot. The first of these measures is a measure of determinism which calculates the ratio of recurrence points that form diagonal structures to all recurrence points.

$$ DET = \frac{\sum_{l=i_{\min}}^NP(l)}{\sum_{l=1}^NP(l)} $$

The measure $P(l)$ is based on the histogram of diagonal lines of length $l$. As outlined by Marwan (2010), the length of the diagonal line in the RP indicates the time evolution according to a state very similar to another state. If the system is deterministic, then it is characterised by a repeated similar state evolution that yields a large number of diagonal lines in the RP. On the other hand, sequences with independent subsequent values have RPs with mostly single white points, like white noise. Therefore, if the system is deterministic, the DET value of the RQA will be high. However, care needs to be taken when interpreting the DET value. While a high DET is an indication of determinism, it is not sufficient to characterise the system as deterministic.\textsuperscript{64}

Next, the length of the longest diagonal line found in the RP can be calculated to determine the maximum length of time that similar dynamics occur. This is given as:

$$ L_{\text{max}} = \max(l_{i}^{N_{i}}) $$

where $N_{i} = \Sigma_{l \geq l_{\min}}P(l)$ is the total number of diagonal lines in the RP. Taking the inverse of $L_{\text{max}}$ will provide an indication of the exponential divergence of the phase space trajectory. This can be written as:

$$ \text{DIV} = \frac{1}{L_{\text{max}}} $$

\textsuperscript{64}This implies that at least one further criterion is necessary in the RP. According to Kaplan and Glass (1992), measuring the direction of the trajectory can help determine if the system is deterministic. If the DET measure reaches approximately 1 for a very small recurrence density, such as RR $< 0.05$, the underlying system is deterministic.
If the measure DIV is high, this implies that the trajectories diverge quickly and the diagonal lines are therefore shorter. According to Eckmann et al. (1987) and Trulla et al. (1996), the length of these diagonal lines can be used as an indication of divergence behaviour in the system, which is measured by the Lyapunov exponent. The Lyapunov exponent is a measure of chaos in the system and determines the rate at which trajectories diverge (Webber and Zbilut, 1992). However, Marwan (2010) expresses caution in interpreting a positive DIV value as being considered evidence of chaos and states that it should not be used in isolation to determine if the underlying system is chaotic or not. The average diagonal line can also be calculated to determine the average duration of similar dynamics in two time series and is given as:

\[
L = \frac{\sum_{l=l_{\text{min}}}^{N} l P(l)}{\sum_{l=l_{\text{min}}}^{N} P(l)}
\] (5.8)

To establish the complexity of the recurrence plot, the entropy is calculated. This entropy refers to the Shannon entropy of the probability \( p(l) = P(l) / N \) which finds a diagonal line of exactly length \( l \) in the RP. This entropy is given as:

\[
ENTR = -\sum_{l=l_{\text{min}}}^{N} p(l) \ln p(l)
\] (5.9)

If the value of the entropy is small, this indicates that the system is not very complex and could represent, for example, uncorrelated noise.

The next two measures examine the length of the vertical lines formed in the RP. According to Marwan et al. (2007), RQA measures based on vertical lines are able to find chaos – chaos transitions and chaos – order transitions which is particularly important given the nature of this study. To establish the number of recurrence points that form vertical lines, a measure referred to as laminarity is calculated as follows:

\[
LAM = \frac{\sum_{v=v_{\text{min}}}^{N} v P(v)}{\sum_{v=1}^{N} v P(v)}
\] (5.10)

where \( v P(v) \) is the histogram of length \( v \) of the vertical lines in the RP. This provides the ratio between recurrence points that form vertical structures and the entire set of recurrence points and is therefore analogous to the DET measure except that it measures the percentage recurrence points that form vertical lines rather than
diagonal lines (Webber and Zbilut, 1992). The laminarity measure is used to identify laminar states in the system. If the RP contains more single recurrence points than vertical structures, the value of LAM will be low.

Again, focusing on the vertical structures of the RP, the *trapping time* can be calculated. This measures the mean time that the system will remain in a particular state and is given as:

\[
TT = \frac{\sum_{v=v_{\text{min}}}^{N} vP(v)}{\sum_{v=v_{\text{min}}}^{N} P(v)}
\]  

(5.11)

This refers to the average length of the vertical line segments in the RP. As with typology of the RP, the RQA measures can be applied to CRPs.

In addition, when quantifying recurrence plots, it is common to carry out ‘epoch’ analysis. Epoch analysis concerns breaking the sample into smaller segments, where these segments represent smaller and overlapping recurrence matrices (Webber and Zbilut, 1992). This allows for a focus on the local dynamics of the systems rather than the global dynamics\(^6\) and involves implementing a sliding window design where the sample is split up into several segments and the RQA measures are computed multiple times.

*Threshold Selection (\(\varepsilon\))*

A crucial parameter in recurrence analysis is the selection of the threshold \(\varepsilon\) which defines the neighbourhood for the states of the system. If the threshold \(\varepsilon\) is too small, there may be no recurrence points present to analyse the structure of the underlying system. If the threshold \(\varepsilon\) is too large, then almost every point within the system is considered a neighbour of every other point and may lead to an issue referred to as *tangential motion*. Tangential motion causes the diagonal structures to become altered and therefore not representative of the data (Marwan *et al.* 2007).

Within the literature, there are several approaches available to select \(\varepsilon\):

---

\(^6\) The global dynamics of the system can be explored by performing RQA on the entire system.
• $\varepsilon$ should be a few percent of the maximum phase space diameter (Mindlin and Gilmore, 1992)

• $\varepsilon$ should not exceed 10 percent of the mean or maximum phase space diameter (Koebbe and Mayer-Kross, 1992; Zbilut and Webber 1992)

• choose $\varepsilon$ so that the recurrence point density is approximately 1 percent (Zbilut et al., 2002)

For the purposes of this study, the measure of the threshold $\varepsilon$ is estimated using the same approach applied elsewhere in RP and RQA research using economic and financial data (see for example Crowley and Schultz 2010; Bastos and Caiado 2011; Chen 2011; and Goswami et al., 2012). In that case, the threshold is chosen based on Koebbe et al. (1992) and Zbilut and Webber (1992) where $\varepsilon$ is estimated to be no larger than 10 percent of the mean or maximum phase space diameter.

5.4 Data and Time Delay Embedding

The following section outlines the data used for this recurrence analysis and the choice of time delay embedding parameters, which includes the $m$ embedding dimension, the time delay $\tau$, and the selection of the threshold $\varepsilon$.

5.4.1 Data

Business Cycle

To analyse the business cycle, quarterly real GDP data, over the period 1976Q1 to 2014Q4, has been transformed into log year on year changes is used and is provided in Figure 5.3 below. Whilst the NBER examine a range of indicators when identifying the business cycle (Drehmann et al., 2012), output is the most common measure available to represent the business cycle (Crowley, 2007; Claessens et al., 2011; Borio, 2012). The data is obtained from the Federal Reserve Economic

---

66 According to Stock and Watson (1989), the range of macroeconomic indicators includes output, employment and sales.
Databank (FRED) for the US\textsuperscript{67} and covers the period 1976Q1 to 2015Q1. According to NBER Business Cycle dating, the US economy experienced five recessions over the sample period considered in this chapter. These recessions are outlined in Table 5.2 below. Examining both Table 5.2 and Figure 5.3, it is obvious that the duration and amplitudes of the contractions vary significantly. For example, the Great Recession resulted in an 18 month contraction and a decline in real GDP to the tune of 4.3 percent, while the 2001 recession resulted in an 8 month contraction and 0.3 percent decline in real GDP.

<table>
<thead>
<tr>
<th>Peak</th>
<th>Trough</th>
<th>Contraction (months)</th>
<th>Expansion (months)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1980.1</td>
<td>1980.3</td>
<td>6</td>
<td>58</td>
</tr>
<tr>
<td>1981.3</td>
<td>1982.4</td>
<td>16</td>
<td>12</td>
</tr>
<tr>
<td>1990.3</td>
<td>1991.1</td>
<td>8</td>
<td>92</td>
</tr>
<tr>
<td>2001.1</td>
<td>2001.4</td>
<td>8</td>
<td>120</td>
</tr>
<tr>
<td>2007.4</td>
<td>2009.2</td>
<td>18</td>
<td>73</td>
</tr>
</tbody>
</table>


Regarding the amplitude, frequency and duration of the business cycle, Drehmann \textit{et al.}, 2012 use the turning point analysis to identify the cyclical peaks and troughs. This uses the method originally proposed by Burns and Mitchell (1946), which was adapted by Bry and Boschan (1971) into a computerised algorithm and later used by Harding and Pagan (2002). Their results indicate that, for the business cycle, the frequency is between one and eight years and the duration is approximately 48 quarters in an expansion and five quarters in a contraction. Finally, the amplitude of the business cycle is estimated to be 38 percent in an expansion and -3 percent in a contraction.

\textsuperscript{67} This data is expressed in Billions of chained 2009 dollars and is seasonally adjusted
As discussed in Section 5.2.2, the variable representing the financial cycle is property prices. Fig 5.4 above plots the All-Transactions House Price Index for the United States, which has been adjusted for inflation and is expressed in logs. The year on year growth rate is then estimated. As with the business cycle, the sample period considered is between 1976Q1 and 2014Q4.
According to the Federal Housing Finance Agency, the house price index\(^{68}\) is a weighted, repeat-sales index that measures average price changes in repeat sales or refinancing on the same property. Drawing on the work of Drehmann et al. (2012), the financial cycle is found to be longer and to have a larger amplitude than the business cycle. The duration of the financial cycle is found to last between 10 and 20 years while the contraction phase of the financial cycle is found to last more than three years on average\(^{69}\).

### 5.4.2 Time Delay Embedding

As outlined in section 5.3 of this chapter, two parameters are required for phase space reconstruction\(^{70}\) which is necessary for recurrence analysis. These two parameters; the embedding dimension \(m\) and the time delay \(\tau\), have been estimated using the false nearest neighbours and the mutual information methodologies, respectively. In addition, the selected threshold \(\varepsilon\) is calculated in accordance with Koebbe et al. (1992) and Zbilut and Webber (1992) whereby \(\varepsilon\) is estimated as less than 10 percent of the mean or maximum phase space diameter.

<table>
<thead>
<tr>
<th></th>
<th>Embedding Dimension ((m))</th>
<th>Time Delay ((\tau))</th>
<th>Threshold ((\varepsilon))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Business cycle</td>
<td>4</td>
<td>1</td>
<td>0.6</td>
</tr>
<tr>
<td>Financial cycle</td>
<td>4</td>
<td>1</td>
<td>0.6</td>
</tr>
</tbody>
</table>

\(^{68}\) The house price data used in this chapter is different from the house price data used in Chapter 3. According to the FHFA, this index provides economists with ‘an improved tool that is useful for estimating changes in the rates of mortgage defaults, prepayments, and housing affordability in specific areas.’ Given the nature of this study, this index will be more useful.  

\(^{69}\) The contraction phase of the business cycle is found to last approximately 1 year according to Drehmann et al. (2012).  

\(^{70}\) This analysis was carried out using Norbert Marwan’s CRP toolbox for Matlab and is available at [http://tocsy.pik-potsdam.de/CRPtoolbox/](http://tocsy.pik-potsdam.de/CRPtoolbox/)
The threshold \( \varepsilon \) is chosen as less than 10 percent of the mean phase space diameter to ensure that the recurrence plot is not too dense. Therefore, \( \varepsilon \) equal to 0.6 is selected for both the business cycle and the financial cycle (see Table 5.3 above). This choice of threshold is in line with Chen (2011) and Caraiani and Haven (2013) who also choose a threshold \( \varepsilon \) of 0.6. When using cross recurrence plots to analyse how the business and financial cycle interacts with each other, the same threshold \( \varepsilon \) of 0.6 is used.

To compute the appropriate embedding dimension \( m \), the method of false nearest neighbours is applied to both the business cycle and the financial cycle. Given the results provided in Table 5.3, an embedding parameter of 4 is selected for both the business cycle and the financial cycle. This value is consistent with the embedding parameter value used by Crowley and Schultz (2010) in their analysis of the business cycle for euro area members. The time delay parameter \( \tau \) is chosen to be 1 for both variables. This is in line with Zbilut (2005) and is normal for discrete time series data (as discussed in section 5.3.1).

### 5.5 Estimation Results

The following section outlines the estimation results for the business cycle, the financial cycle, and finally the interaction between the business and financial cycle. The results include an analysis of both the recurrence plots and recurrence quantification analysis of each cycle.

#### 5.5.1 Business Cycle

*Recurrence plot analysis*

As discussed in Section 5.3.2, RPs are used to visualise trajectories in a phase space. Using the typology and small scale structures provided by Marwan *et al.* (2005, 2007), we can characterise the structures present in the business cycle. First, as illustrated in Figure 5.5 and 5.6, it is clear that the system is non-stationary and there is evidence of an underlying trend in the system: the RP pales away from the line of identity (LOI) and fades to the upper left and lower right corners. Additionally, there
are white bands in the thresholded RP. White areas or bands are as a result of abrupt changes in the dynamics of the system and are usually indicative of some rare or extreme event, thus indicating transition is taking place in the system. Taking the period 1976 to 1985, it is clear from both the thresholded and unthresholded RPs that the business cycle fluctuates from short periods of stability (indicated by the vertical lines) to periods of instability (indicated by the white bands) and represents a volatile period for US economy. This finding is in line with Stock and Watson (2003) who find that the nature of the business cycle changed in 1985.

Examining the small scale structures of the RP reveals a clear cluster of points over the sample 1985 and 2007 period. Clustering of points indicates that the state doesn’t change, or changes very slowly for some time and can be representative of laminar states. The unthresholded RP clearly shows that over the sample period, the business cycle transitions from periods of relative stability to less stable, rare events. From 1985 to 1990 the RP displays a clustering of points indicating laminarity in the system and therefore a period of stability for the US economy. With the exception of the 1990 – 1992 period (during which time the US economy entered recession), the RP displays a clustering of RP points which remain in place until 2007 giving credence to theory of the Great Moderation period in the US. Both the thresholded and unthresholded RPs shows the severity of the Great Recession and indicates a transition takes place in 2007. This is reflected in the large white band in Figure 5.5 and the blue and violent area in Figure 5.6 below. The RP illustrates that this extreme event lasts from 2007 until 2010.

Recurrence quantification analysis

Going beyond the visual impression obtained from the RP, the small scale structures can reveal several measures of complexity present in the underlying system (Marwan et al. 2007). To examine these small scale structures in more detail, recurrence quantification analysis is undertaken. As stated previously in this chapter, moving window (epoch) RQA can display time dependent behaviour in the time series and can identify bifurcation points and transitions in the system, such as periodic-chaos transitions or chaos-chaos transitions. The RQA is given in Figures 5.7 – 5.9 below.
where a window of 24 periods long (6 years) is passed through the thresholded RP in order to undertake ‘epoch’ analysis.

Figure 5.5: The Threshold Recurrence Plot for the Business Cycle with an Embedding Parameter $m$ of 4, a Time Delay $\tau$ of 1, and a Threshold $\varepsilon$ of 0.6. The Euclidean Norm is Estimated.

Figure 5.6: The Unthresholded Recurrence Plot for the Business Cycle with an Embedding Parameter of 4 and a Time Delay $\tau$ of 1. The Jet Plot shows the Distance to the Next Recurrence Point
Figure 5.7 illustrates the variance, recurrence rate and determinism present in the RP of the business cycle. The variance during the first part of the sample is high relative to all other periods considered, indicating a reduction in volatility during the early to mid 1980s. The variance remains low until 2003, after which it begins to increase and remains elevated. This points to increased instability in the lead up to the Great Recession.

Figure 5.7: RQA Measures of the Variance, Recurrence Rate and Determinism for the Business Cycle. Window size is 24, m is 4, τ is 1 and ε is 0.6

The recurrence rate (RR) gives the percentage recurrences of the system to its ε-neighbourhood in the phase space. Figure 5.7 shows the percentage recurrence for the business cycle does not exceed 50 percent at any point and from 1998 becomes quite sparse. Figure 5.7 also illustrates the determinism found in the RP of the business cycle. Determinism (DET) is calculated as the ratio of recurrence points to diagonal lines and can indicate if the system is stochastic or deterministic. According to Trulla et al. (1996), Fabretti and Ausloo (2005), Marwan et al. (2007) and Marwan (2010), a sharp increase in determinism indicates a transition from a chaotic to a periodic state. Figure 5.7 clearly shows a sharp increase in determinism in 1980, perhaps showing the system transitioned from a chaotic state to a periodic state. The determinism measure remains high for the remainder of the sample (at, on average,
over 80 percent), with the exception of the 2005 period when it declines to approximately 60 percent.

Figure 5.8 illustrates the various RQA measures examining the vertical lines in the RP. These include a calculation of the maximum vertical line (Vmax), laminarity (LAM) and the trapping time (TT) of the system.

![Graphs of Maximum Vertical Line, Laminarity, and Trapping Time](image)

**Figure 5.8: RQA Measures of the Vertical Lines in the RP. This includes the Maximum Vertical Line, Laminarity and Trapping Time.**

These vertical structures can reveal features about the frequency of the business cycle since they can be used to identify laminar states. Laminar states occur when the system remains in a particular state for a period of time. Firstly, examining the Vmax shows a peak of 14, with this peak occurring directly after the Vmax collapses to zero. According to Marwan *et al.* (2002, 2007), the Vmax, LAM and TT all drop to zero during periodic-chaotic transitions and show distinct peaks during chaotic-chaotic transitions. Figure 5.8 shows this periodic-chaotic transition occurred after 1994 when the Vmax declines to zero, before quickly returning to a periodic regime. Additionally, LAM and TT are said to vanish during periodic windows. Examining the LAM and TT measures illustrates a transition occurs shortly after 1994 when they both vanish and may indicate a transition from a periodic to chaotic state. With the exception of the transition period after 1994, the early 1980s to the late 1990s seems to be characterised as periodic in nature with business cycle fluctuations.
appearing to decline during this time. This may be reflective of the Great Moderation periods. However, in 1999, the Vmax, LAM and TT all decline. This points to less stability in the system but no evidence of a transition in the dynamics of the underlying system is identified.

Finally, Figure 5.9 shows the RQA measures of complexity in the RP of the business cycle, with an estimation of the entropy (ENTR) and the longest diagonal line (Lmax) in the system. ENTR is used to estimate the complexity of the system. If the value of the ENTR is small (large), this indicates that the system has low (high) complexity. Examining Figure 5.9 shows that complexity increases during the mid-1990s. The peak of the Lmax is identified to be approximately 14 points with this peak occurring between 1995 and 1996, after which it declines to approximately 2 by 1999.

Source: Author’s calculations

Figure 5.9: Measures of the Complexity of the System including the Entropy and Longest Diagonal Line in the System.
5.5.2 Financial cycle

Recurrence plot analysis

Figure 5.10 plots the thresholded RP for the financial cycle. As with the business cycle, it is clear that the system is non-stationary but no trend is identified in the system. Additionally, there are white bands within the thresholded RP and as previously stated, these white areas or bands are as a result of abrupt changes in the dynamics of the system. They are therefore usually indicative of some rare or extreme event. The first white band is found over the period 1976 to 1980 and indicates some transition may have taken place in the financial cycle over this time period. The second white band occurs over a larger period of time: between 2006 to 2013. This of course is in line with the period leading up to the Great Recession. The financial cycle predicts in 2006 that some transition is occurring within the financial cycle. When comparing this with the business cycle period, it is clear the financial cycle leads the business cycle. The unthresholded RP given in Figure 5.11 illustrates the severity of this transition, where blue and violent bands characterise the system over this period, indicating the distance between recurrence points is large.

Analysing the small scale patterns of both the thresholded and unthresholded RPs shows vertical structures are present in the system. As discussed in previous sections, vertical structures are indicative of laminar states and can therefore show periodicity in the system. These vertical structures appear between 1992 and 1996. Horizontal lines also characteristic the system over a longer period: between 1981 and 2004. Finally, some diagonal structures also appear over the period 1981 to 1990 and 1994 to 2004. To analyse these small scale structures in more detail, recurrence quantification analysis of the RP of the financial cycle is undertaken and is provided in Figures 5.12 to 5.14 below.
Figure 5.10: The Threshold Recurrence Plot for the Financial Cycle with an Embedding Parameter \( m \) of 4, a Time Delay \( \tau \) of 1, and a Threshold \( \varepsilon \) of 0.6. The Euclidean Norm is estimated.

Figure 5.11: The Unthresholded Recurrence Plot for the Financial Cycle with an Embedding Parameter of 4 and a Time Delay \( \tau \) of 1. The Jet Plot shows the Distance to the next Recurrence Point.
**Recurrence quantification analysis**

To interpret the diagonal and vertical lines present in the recurrence plot of the financial cycle, recurrence quantification analysis is once again undertaken.

![Graphs showing variance, recurrence rate, and determinism](image)

**Figure 5.12: RQA Measures of the Variance, Recurrence Rate and Determinism for the Financial Cycle**

The RQA is shown in Figures 5.12 (above) to 5.14 (below) where a window of 24 periods long (6 years) is passed through the thresholded recurrence plot to undertake ‘epoch’ analysis. Unlike the business cycle, which has a high variance from the late 1970s until the mid 1980s, the variance of the financial cycle is low and stable until 2002, after which it begins to increase steadily to its peak in 2004. The percentage recurrence for the financial cycle is quite low over the entire sample period. While the RR does increase between the late 1980s and early to mid-2000s, it declines to zero prior to the onset of the Great Recession. This coincides with the increased variance in the RP of the financial cycle. Figure 5.12 also shows that the system exhibits, overall, a high level of determinism, with the exception of the 2006 period, when the value of DET collapse entirely. This decline in DET occurs in the run up to the Great Recession. Additionally, the DET value also experiences declines between 1979 and 1983, which coincides with two recessions that took place in the US: the six month recession from 1980Q1 to 1980Q3 and the 1981Q3 to 1982Q4 recession.
The RQA measures of determinism both decline prior to the onset of these recessions and may be representative of some early warning system.

![Graphs showing RQA measures of the vertical structures in the recurrence plot of the financial cycle.](image)

**Figure 5.13: RQA Measures of the Vertical Structures in the Recurrence Plot of the Financial Cycle**

As with the business cycle, the RQA measures associated with the vertical structures of the RP of the financial cycle are provided in Figure 5.13 above. Again, three measures are examined: the longest vertical line (Vmax), laminarity (LAM), and trapping time (TT). Examining Vmax first, one can see the maximum vertical line in the system contains 12 points, which occurs in 1990. In 2004, the Vmax measure collapses completely. As discussed previously in this chapter, a collapse in the Vmax can indicate a transition has taken place in the system: if the Vmax collapses to zero, it indicates a transition from a periodic-chaotic regime. The Vmax does not reappear within the system. Additionally, both the LAM and TT measures vanish during this period, again providing evidence of a transition in the system. Laminarity appears, for the most part, to be high. As with the measure of DET, LAM is over 80 percent between 1982 and 2002. From 2003 onwards, the LAM declines significantly, until it disappears in 2004. Notably, the LAM disappears when a transition is taking place in the system. This clearly reflects the instability in the financial cycle in the lead up to, and after, the Great Recession.
Finally, Figure 5.14 below illustrates the RQA measures of the entropy (ENTR) and longest diagonal line (Lmax) within the RP of the financial cycle. According to Fabretti and Ausloos (2005), the ENTR measures gives an indication of how much information one needs to recover the system. The ENTR is small when the length of the longest segment parallel to the diagonal is short and doesn’t vary much. It is therefore closely associated with information of determinism. A high ENTR is typical of periodic behaviour and a low ENTR indicates chaotic behaviour. Figure 5.14 below clearly shows the ENTR is high during the mid 1980s to 2004, after which it begins to decline. Regarding the Lmax measure illustrates in Figure 5.14, and as previously outlined, periodic signals produce long lines, while short lines are indicative of chaos (Trulla et al., 1996). The Lmax clearly displays peaks between 1988 and 1999 indicating some periodicity in the financial cycle over this period. Prior to the Great Recession, the Lmax begins to decline steadily between 1991 and 2007, before it begins to increase again in 2010.

![Entropy and Longest Diagonal Line](image.png)

**Figure 5.14: RQA Measures of the Complexity of the Financial Cycle**

160
5.5.3 Interaction between the Business and Financial Cycle

In order to examine the synchronicity and convergence of the business cycle and the financial cycle, cross recurrence analysis can be implemented and follows a similar approach to Crowley (2007, 2008) and Crowley and Schultz (2010). As with the recurrence analysis for the individual cycles, this section illustrates the CRP and the CRQA between the business and financial cycle.

Cross Recurrence Plot Analysis

Figure 5.15 below illustrates the thresholded CRP between the business cycle and the financial cycle. As outline by Marwan et al. (2007), both systems are represented in the same phase space because the CRP looks for those periods of time when the state of the first system recurs to the state of the other system. Examining the CRP reveal some key features of the interaction between the business and financial cycle. The unthresholded CRP is given in Figure 5.16. The growth rates in the business and financial cycles display obvious different growth rates particularly between 1976 and 1985. The vertical lines present in the CRP confirm this.

Moving onto the period after 1985 evidence of convergence up to 1991 is found. Evidence of convergence is again seen in the CRP between 1992 and 2000. Some evidence of synchronicity is obtained over this period, as illustrated by the diagonal lines visible within the red area of the graph. However, it appears these diagonal lines are bowed, rather than straight, meaning they won’t be recognised in the RQA of the CRP. Within the CRP many horizontal and vertical structures appear and correspond closely with recessions in the US (1980; 1981; 1991; 2001; 2008). After the Great Recession, the CRP is showing signs of synchronisation between the business and financial cycle, as illustrated by the red area and diagonal lines forming in the plot between 2010 and 2014.
Figure 5.15: The Threshold Cross Recurrence Plot of the Business and Financial Cycle with an Embedding Parameter $m$ of 4, a Time Delay $\tau$ of 1, and a Threshold $\varepsilon$ of 0.6. The Euclidean Norm is estimated.

Figure 5.16: The Unthresholded Cross Recurrence Plot of the Business and Financial Cycle with an Embedding Parameter of 4 and a Time Delay $\tau$ of 1. The Jet Plot shows the Distance to the Next Recurrence Plot.
Cross Recurrence Quantification Analysis

Following the same procedure applied for the business cycle and financial cycle, the CRQA is calculated based on the CRP of the two underlying systems. Figure 5.17 below plots the variance, recurrence rate (RR), and determinism (DET) measures of the CRQA. The variance of the business cycle and the financial cycle is first illustrated, and the interpretation of both has been undertaken in the previous sections. The RR reveals the probability of the occurrence of similar states in both systems. As with the RQA, a high RR indicates a high density of recurrence points in the diagonal.

The RR remains low over the entire sample period considered, with a peak of 50 percent occurring for a short period of time in the mid to late 1990s. Over the period 1976 to 1981, the probability of similar states occurring in both systems was zero percent. This indicates that the business cycle and the financial cycle behaved very differently during this period of time and is in line with the findings of the CRP. After 1981 however, the RR increases steadily until it peaks in 1987 at 38 percent. Over this six year period, the trajectories of both systems visited the same phase.
space. For the remainder of the sample, the RR remains low. As with DET measures of the RP, the DET measures of the CRP contains important information. The DET measure can provide information about the time evolution of the systems’ states. The DET measure will be high when two deterministic processes have a similar time evolution, and it will be low when they don’t. Examining Figure 5.17 shows that the DET is high with the exception of four key points in time: 1977 to 1980; 1990 to 1991; 2000 to 2002 and 2007 to 2009. As previously explained, a collapse in the DET measure can indicate a periodic-chaotic transition in the system. These transitions coincide with the findings of the CRP.

Next, to analyse the vertical structures present in the CRP, the Vmax, LAM and TT was measured. The results of this analysis showed no vertical structures were present. This is not surprising: when analysing the vertical structures in the CRP, it was noted that whilst vertical structures were present, they were bow shaped. The RQA measures will only examine diagonal lines, not bowed ones. As such, the Vmax, LAM and TT do not pick up any vertical structures in the CRP, even though bowed lines are present. Therefore, it is difficult to test for the presence of laminar states between these systems.

![Figure 5.18: Cross Recurrence Quantification Analysis Measures](image)
Finally, Figure 5.18 above provides the CRQA measures of the entropy (ENTR) and the longest diagonal line (Lmax). As discussed in the previous section, the ENTR measures gives an indication of how much information one needs to recover the system and is closely related to determinism. A high ENTR is typical of periodic behaviour and a low ENTR indicates chaotic behaviour. It is clearly that the ENTR is low over the following periods: 1978 to 1981 and 2007 to 2008, indicating possible chaotic behaviour over those periods. Examining the Lmax reveals that the longest diagonal line contains 15 points and occurs in 1984 and between 1991 and 1997. Additionally, the Lmax collapses three times: between 1977 and 1981 and becomes low between 2000 and 2011 which is in line with the unthresholded CRP given in Figures 5.15 and 5.16.

5.6 Conclusions

The aim of this chapter is to observe the key features present in both the business cycle and the financial cycle to aid understanding of the complex macroeconomic system. Additionally, the interaction between the business and financial cycle is undertaken to determine their convergence and synchronicity. Whilst there has been much agreement in the literature regarding the business cycle, there has been little research in comparison on the financial cycle. Given the financial nature of the Great Recession, it seems prudent to understand how the financial cycle can be defined and how it interacts with the business cycle. This aim is achieved through the use of recurrence analysis, which is nonparametric technique frequently used in the sciences. To our knowledge, this is the first study to use recurrence analysis (recurrence plots and recurrence quantification analysis) to examine the characteristics of the business cycle, financial cycle, and their interactions.

The RP and RQA measures of the business cycle indicate that it appears to be deterministic in nature. The vertical structures identified in the RQA show that the Great Moderation period can be identified from the early to mid 1980s to 1999 after which the system becomes less stable. There is also evidence of a periodic-chaotic-periodic transition in the system in 1994/1995. No evidence of transition is found to correspond with the Great Recession.
Turning to the financial cycle, the RP and RQA measures are particularly interesting. Overall, the system is found to exhibit a high level of determinism, with the exception of the period 1979 - 1980 and 2006, when it declines significantly. This decline occurs prior to the onset of both recessions and may correspond to some early warning system for the financial economy. As with the business cycle, the financial cycle exhibits clear periodic-chaotic-periodic transitions, with these transitions occurring prior to two recessions: the recessions of 1980/1981 and the Great Recession.

Finally using CRP and CRQA measures, the synchronisation between the business and financial cycle can be examined. Convergence between the business and financial cycle is low over the period between 1976 and 1985. This is confirmed through a visual inspection of the CRP and from the CRQA measure of the RR. However, between 1992 and 2000, and 2010 and 2014, evidence of convergence is again obtained. Evidence of synchronicity is also obtained and illustrated by the diagonal lines in the CRP. However, no evidence of laminar states between the system is found. This may be attributed to the failure of the CRQA to account for bowed lines that are clearly visible in the CRP.

Overall, the results of this study underlies the complexity of the macroeconomic system and the importance of the financial sector to the real economy. The results indicate that a possible lead-lag relationship exists between the two cycles, with the financial cycle leading the business cycle. The importance of reconsidering the complexity that exists in financial and macroeconomic variables should be addressed and carefully included in the modelling of the macroeconomy. Additionally, as discussed by Karagianni and Kyritsou (2011), this should be considered carefully by policymakers regarding their decisions on policy.
6.1 Thesis Overview and Contributions

This thesis contains six chapters in total. Chapters 2 to 5 provide the empirical kernel of the thesis with the conclusions in each of the chapters informing the research objectives for the next. The primary aim of this thesis was to critically examine the interactions between the real and financial economy, particularly in the context of financialisation, and its implications for the transmission of monetary policy. Understanding this interaction has never been more important given the nature of the Great Recession, where financial market innovations had severe implications for the real economy. This complex interaction is particularly important when one considers the role of monetary policy under financialisation and the transmission of monetary policy to the real economy. This is particularly relevant given the IS puzzle established in Chapter 1 of this thesis. The traditional IS curve states that an inverse relationship exists between the real interest rate and output. However, using data from the US since 1976, we find that the IS curve is actually upward sloping. That is, a positive relationship exists between the real interest rate and output. This puzzle was highlighted by Goodhart and Hofmann (2008) who find that additional financial variables are required if we are to understand how monetary policy can influence the real economy.

To achieve this primary aim, the thesis is comprised of four empirical interlinked chapters that critically examine the interaction between the real and financial economy, using several alternative modelling techniques. Chapter 2 of this thesis examines the policy model used by the most influential central banks around the world for policy analysis and forecasting: the DSGE model of Smets and Wouters (2003, 2007). The aim was to assess the empirical properties of the prototypical macroeconomic model used by central banks and policy makers in the run up to the Great Recession. As such, this model is estimated for the period 1947Q1 to 2007Q4 (when the US economy enters recession). There are two central conclusions of this chapter which contribute to the literature: one methodological conclusion and one
substantive conclusion. Methodologically, this chapter illustrates that linearised models, such as DSGE models, do not adequately model the key dynamics inherent in macroeconomic time series, such as asymmetries and regime change. Substantively, this chapter shows that a DSGE model without essential financial variables cannot be representative of the key features inherent in the complex macroeconomy. The transversality condition implies that bubble formation is not possible within this framework; this is clearly at odds with the bubbles that characterized the US economy and the debt accumulation by US households which drove wealth-driven consumption. In addition to the transversality condition, the DSGE model also assumes that money is neutral and that the short term interest rate is sufficient to represent the financial economy.

The objective of Chapter 3 was to examine the nonlinear properties of both macroeconomic and financial variables. To this end, the BDS test is used to establish if some nonlinear dependence remains in the residuals of a linear model. The results of this chapter shows that, with the exception of investment, all variables examined display clear nonlinear dependence. As such, the use of linear models to represent data that is inherently nonlinear will not be capable of capturing the true dynamics of the data being modelled. This chapter contributes to the literature by providing evidence of nonlinear dependence in both macroeconomic and financial variables. This contribution underlies the need for nonlinear, rather than linear, models in explaining the fundamental dynamics inherent within macroeconomic data.

The objective of Chapter 4 was to examine the transmission mechanism of monetary policy under financialisation. This proceeded in two ways: (i) by introducing the financial economy through the incorporation of house prices and credit, and (ii) by modelling the nonlinear transmission of monetary policy that can arise as a result of the interaction between the real and financial economy. This research is particularly important in light of the IS puzzle established in Chapter 1, which showed an upward sloping IS curve exists, rather than a downward sloping IS curve. The nonlinear Markov switching model of Hamilton (1989) is used since it can capture asymmetries and regime change, both of which are established to be important in the context of the US economy. Two key conclusions are established within this chapter which are relevant for policy makers and underlie the importance of the financial economy to fluctuations in the real economy. The first finding provides evidence
that, during expansionary periods, the real economy is driven primarily by movements in the credit market. The real interest rate plays no statistically significant role in influencing output. In recessions, however, all variables become important: the real interest rate and the financial variables impact upon the real economy. This chapter contributes to the literature by providing evidence of an IS puzzle in the US economy, and providing evidence of variables which are key to understanding this puzzle. This is particularly important for policy makers in periods of both expansion and recession.

Chapter 4 established that the asymmetric impact of monetary policy is due to the nonlinear interaction between the real and financial economy. However, the nature of the nonlinearity driving this asymmetric impact still required examination. Thus, the objective of Chapter 5 was to study the nature of the business cycle, the financial cycle, and their interaction using nonparametric methods, with a view to informing the development of alternative macroeconomic theory and policy. Nonparametric techniques have many advantages over their parametric counterparts since they make no assumptions about the underlying data. This objective is examined using Recurrence Analysis, which uses Recurrence Plots and Recurrence Quantification Analysis to identify the fundamental features of the individual cycles and their interactions. Whilst there has been much agreement in the literature regarding the business cycle, there has been little research in comparison on the financial cycle.

This chapter contributes to the literature in two ways. Firstly, to our knowledge, this is the first study to use Recurrence Analysis to examine the characteristics of the business cycle, financial cycle, and their interactions. The Recurrence Plots (RPs) and Recurrence Quantification Analysis (RQA) measures indicate that the business cycle appears to be deterministic in nature. The vertical structures identified in the RQA show that the Great Moderation period can be identified from the early to mid 1980s to 1999 after which the system becomes less stable. There is also evidence of a periodic-chaotic-periodic transition in the system in 1994/1995. The RP and RQA measures of the financial cycle are particularly interesting. Overall, the system is found to exhibit a high level of determinism, with the exception of the period 1979 - 1980 and 2006, when it declines significantly. This decline occurs prior to the onset of both recessions and may correspond to some early warning system for the financial economy. As with the business cycle, the financial cycle exhibits clear
periodic-chaotic-periodic transitions, with these transitions occurring prior to two recessions: the recessions of 1980/1981 and the Great Recession. Finally the interaction between the two cycles is examined using Cross Recurrence Plots (CRPs) and Cross Recurrence Quantification Analysis (CRQA) measures. These measures show that convergence between the business and financial cycle is low over the period between 1976 and 1985. This is confirmed through a visual inspection of the CRP and from the CRQA measure of the recurrence rate. However, between 1992 and 2000, and 2010 and 2014, evidence of convergence is obtained. Evidence of synchronicity is also obtained and illustrated by the diagonal lines in the CRP.

The second contribution of this chapter underscores the overall complexity of the macroeconomic system and the importance of the financial economy to the real economy. The results indicate that a possible lead-lag relationship exists between the two cycles, with the financial cycle leading the business cycle. The importance of reconsidering the complexity that exists in financial and macroeconomic variables should be addressed and carefully included when modelling the macroeconomy. This is important for policymakers in the development of alternative macroeconomy theory and policy.

Overall, this thesis contributes to the literature on the complex interactions between the real and financial economy. These interactions are particularly important in light of the financial nature of the Great Recession and the subsequent exclusion of these features from modern macroeconomic models. Within the literature, there is no coherent understanding of how these interactions take place, or the complexities that arise from their nonlinearities. If we are to develop and establish an alternative macroeconomic theory and policy, then the nature of these nonlinear interactions must be understood in order to build coherent models of the macroeconomy. This cannot be achieved by simply adding on additional blocks, such as a housing block, or banking block, to the DSGE models (as is currently being done in central banks). Instead, we must move away from the general equilibrium modelling framework and instead move towards a thorough investigation of the data itself. Only then can we begin to understand the complexities of the macroeconomy and formulate appropriate theory and policy.
6.2 Limitations

Each of the individual chapters is not without their drawbacks. Regarding Chapter 2 of this thesis, there are two main limitations. The first of these limitations refers to the DSGE model used (Smets and Wouters, 2007). Since the onset of the Great Recession, much work has been undertaken by central banks to include a housing sector and banking sector within the standard modeling framework. However, given that the aim of this research was to establish the output facing policymakers at the time, it would be inappropriate to evaluate the model by incorporating these additional sectors, since these models did not typically include them. The second limitation refers to the evaluation of the DSGE model, and in particular, judging the DSGE model by its forecasting ability. This has been a bone of contention within the literature supporting DSGE models and could, therefore, be argued that their forecast ability is not a sufficient metric by which to access any model.

The conclusions of Chapter 3 notes that, using the BDS test, some nonlinear dependence is present in the residuals of macroeconomic and financial variables after some linear model has been applied. However, the BDS test does not give us an indication of the structure or nature of the nonlinearity, and therefore represents one drawback of this test. As such, additional testing would be required to establish the structure of the nonlinear and its underlying data generating process. To deal with the nonlinear dependence established in Chapter 3, Chapter 4 used the nonlinear Markov switching model to capture regime change in the US economy. While Markov switching models have many advantages, one drawback is their forecasting ability, which has been shown in some literature to be poor.

Finally, a limitation of Chapter 5 is the use of housing as the primary variable representing the financial cycle. While much research has been carried out that indicates housing is representative of the financial cycle, additional robustness could be achieved by including some additional variables, such as credit, stock prices, or bonds. However, for the purposes of this thesis, and the importance of house price fluctuations for the Great Recession, it was deemed appropriate to use this variable. However, as noted in the following section, this has been established as an objective for further research.
6.3 Future Research

This thesis has provided several important avenues for future research. One particular avenue, which is gaining significant interest in the literature, is the use of flow-of-funds, or accounting type models. Bezemer (2009) in his paper “Why some economists could see the crisis coming” undertook a study of the models used by economists who did foresee the crisis. Central to their thinking was this flow of funds model where there was specific accounting of financial flows (in the form of credit, interest, profits and wages), stocks (debt and wealth), and a sharp distinction between the real economy and financial sector. This flow-of-funds type model has many advantages over the framework of general equilibrium models, since they make no modeling assumptions. As such, one is working with the data, rather than working within a specific modeling paradigm.

A second avenue for further research is established from Chapter 4 of this thesis which examines the transmission of monetary policy under financialisation, and in particular, further analysis of the IS puzzle. This includes establishing why the IS puzzle exists and how to amend this puzzle to be more reflective of the data. As mentioned in Chapter 1 of this thesis, a simple theoretical model is provided in Appendix A1 which outlines one possible way of solving this puzzle.

Thirdly, we would like to devote additional research on further characterising the variables representing the financial cycle, thereby building on the current work being undertaken by Drehmann et al., 2012, Claessens et al., 2013, and Borio et al., 2014. Within the current analysis, housing represents the financial cycle. However, going forward, additional research can be carried out using additional variables; particularly items from the financial account of the SNA such as credit spreads (the spread between US Treasury Bonds and Baa Corporate Bonds).
THESIS APPENDIX
As outlined in Bhaduri et al. (2015), one way to consider the IS puzzle arising in the US is as follows:

\[ Y = C(i - dH_p) + I(Y, i) \]  

(1.1)

Taking equation (1.1) above, consumption is a function of the real interest rate where \( i \) is the nominal interest rate and \( dH_p \) is rate of change of house price. Instead of considering general inflation rate, we consider house price inflation, which we posit may be a more relevant variable. The influence of the interest rate and the rate of change in house prices on consumption is assumed to be \( C_i < 0, C_{dH_p} > 0 \). The influence of the nominal interest rate on consumption is assumed to be negative, since the cost of borrowing has a negative impact on consumption demand. However, we assume that this increase in asset prices influences the household’s collateral, and therefore their ability to obtain mortgage financing. This increase in house prices, however, only provides some potential gain to the households. Attempts by householders to realize this gain will only lead to fall in the house prices and therefore a loss in the value of collateral for the banks. In order to circumvent this problem, banks might offer to release household’s equity as house price increases. Thus, the resulting cash flow from property income, without selling the property, is what is being captured in the condition \( C_{dH_p} > 0 \).

On the investment function, we assume the conventional signs such as \( I_Y > 0, I_i < 0 \). Total differentiation of (1.1) yields,

\[ \frac{dY}{di} = \frac{(I_i - S_i) + S_{dH_p}(\ddot{H}_p)}{(S_Y - I_Y)} \]  

(1.2)

The signs of partial derivatives with respect to savings are \( S_i > 0, S_{dH_p} > 0 \). Assuming the usual Keynesian stability condition holds, which makes the denominator of (1.2) positive. The model (1.1) posited here is more general than the conventional analysis, where the influence of house price on consumption and saving is not captured. In our model (1.1), when there is no change in the house price, i.e. \( dH_p = 0 \), then we get the traditional downward sloping IS curve.
However, in the scenario where property income is influencing consumption, the slope of the IS curve is ambiguous. Consider when house prices are increasing, i.e. both $dH_p > 0$, $\ddot{H}_p > 0$. In this case, the condition for output to increase with respect to interest rate is:

$$\frac{dY}{di} > 0 \Rightarrow I_i - S_i + S_{dH_p} \ddot{H}_p > 0$$

$$\Rightarrow |I_i| < S_{dH_p} \ddot{H}_p - S_i$$

Hence, the IS curve is positively sloped in the $(i, Y)$ plane when the negative response of investment is more than outweighed by the positive response of saving to the rise in the interest rate, owing to influence of house price increases on savings.

Thus, in this case, output expands for a higher interest rate through consumption demand arising from house (asset) price increases, which more than outweighs the falling investment owing to the higher cost of borrowing. Thus, under financialisation, tighter monetary policy, via a higher interest rate, may not be effective in restraining the consumption led expansion in so far as the positive influence of asset prices outweighs the higher cost of borrowing. In such a case, a lower or falling real interest rate $(i - dH_p)$ is associated with a higher output regime, essentially through a consumption boom.
APPENDIX A2.1

The Linearised DSGE model

The following linearised DSGE model has been taken from Smets & Wouters 2007 and represents the log-linearised version of a DSGE model which has been estimated using data from the US. All variables are log-linearised around their steady-state balanced growth path.

The aggregate resource constraint is given by:

1. \[ \bar{y}_t = c_y \hat{c}_t + i_y \hat{i}_t + z_y \hat{z}_t + \hat{\varepsilon}_t^y \]

Output is composed of consumption, investment, capital-utilisation costs that are a function of the capital utilisation rate, and an exogenous spending disturbance term.

The consumption equation follows from the consumption Euler equation and is given by:

2. \[ \hat{c}_t = \frac{h_y}{1 + h_y} \hat{c}_{t-1} + \frac{1}{1 + h_y} E_t \hat{c}_{t+1} + \frac{w_y (\sigma - 1)}{\sigma (1 + \gamma)} (\hat{i}_t - E_t \hat{I}_{t+1}) - \frac{1 - \beta}{(1 + \gamma)} (\hat{r}_t - E_t \hat{r}_{t+1}) - \frac{1 - h_y}{(1 + \gamma)} \hat{\varepsilon}_t^b \]

Current consumption depends on a weighted average of past and expected future consumption, on expected growth in hours worked, the ex-ante real interest rate and a risk premium disturbance term.

The investment equation follows the investment Euler equation and is given by:

3. \[ \hat{i}_t = \frac{1}{1 + \beta (1 + \gamma)} \hat{c}_{t-1} + \frac{\hat{c}_y (\sigma - 1)}{1 + \beta y (1 + \gamma - \varepsilon_0)} \hat{c}_{t+1} + \frac{1}{\gamma y (1 + \beta (1 + \gamma - \varepsilon_0))} \hat{q}_t + \hat{\varepsilon}_t^i \]

The corresponding arbitrage equation for the value of capital is given by:

4. \[ \hat{q}_t = \beta (1 - \delta) \gamma^{-\alpha_c} E_t \hat{q}_{t+1} - \hat{r}_t + E_t \hat{r}_{t+1} + (1 - \beta (1 - \delta) \gamma^{-\alpha_c}) E_t \hat{q}_{t+1} - \hat{\varepsilon}_t^b \]

The current value of capital stock depends positively on its expected future value and the expected real rental rate on capital, and negatively on the ex-ante real interest rate and the risk premium disturbance from equation (2).
The aggregate production function is given by:

5. \( y_t = \Phi(\alpha \hat{k}_t + (1 - \alpha) \hat{l}_t + \varepsilon_t) \)

Output is produced using capital and labour services. The parameter \( \alpha \) captures the share of capital in production, while the parameter is one plus the share of fixed costs in production, reflecting the presence of fixed costs in production.

The current capital services used in production equation is given by:

6. \( \hat{k}_t^1 = \hat{k}_{t-1} + \tilde{z}_t \)

Newly installed capital becomes effective with a one-quarter lag, current capital service used in production are a function of capital installed in the previous period and the degree of capital utilisation.

The degree of capital utilisation equation is given by:

7. \( \tilde{z}_t = \frac{1 - \psi}{\psi} \hat{r}_t^h \)

where \( \psi \) is a positive function of the elasticity of the capital utilisation adjustment cost function and normalised between zero and one. Cost minimisation by households that provide capital services implies that the degree of capital utilisation is a positive function of the rental rate of capital.

The accumulation of installed capital equation is given by:

8. \( \hat{k}_t = \frac{(1 - \delta)}{\psi} \hat{k}_{t-1} + \left( 1 - \frac{1 - \delta}{\psi} \right) \hat{l}_t + \left( 1 - \frac{1 - \delta}{\psi} \right) \psi \hat{r}_t^h \left( 1 + \beta \gamma^{(1 - \alpha)} \right) \varepsilon_t \)

The accumulation of installed capital is not only a function of the flow of investment, but also of the relative efficiency of these investment expenditures as captured by the investment-specific technology disturbance term.

The price mark-up equation is given by:

9. \( \mu_t^p = \alpha (\hat{k}_t^1 - \hat{l}_t) - \tilde{\omega}_t + \varepsilon_t^p \)

Regarding the monopolist competitive goods market, cost minimisation by firms implies that the price mark-up, defined as the difference between the average price and the nominal marginal cost, is equal to the difference between the marginal product of labour and the real
wage. The second equality in equation (9), implies that the marginal product of labour is a positive function of the capital-labour ratio and total factor productivity.

The inflation equation is given by:

\[ 10. \quad \hat{\pi}_t = \frac{\beta \gamma (1 - \rho)}{1 + \beta \gamma} \sigma_\pi E_1 \hat{\pi}_{t+1} + \frac{1 - \beta}{1 + \beta \gamma} \sigma_\pi \hat{\pi}_{t-1} - \frac{(1 - \beta \gamma) \sigma_\pi}{(1 + \beta \gamma)} \sigma_\pi \hat{\pi}_{t-1} - \frac{(1 - \beta \gamma) \sigma_\pi}{(1 + \beta \gamma)} \sigma_\pi \hat{\pi}_{t-1} + \epsilon_t^p \]

Due to price stickiness as in Calvo (1983) and partial indexation to lagged inflation of those prices, prices only adjust sluggishly to their desired mark-up. Profit maximisation by firms gives rise to the above New-Keynesian Phillips curve, where inflation depends positively on past and expected future inflation, negatively on the current price mark-up and positively on a price mark-up disturbance.

The rental rate of capital equation is given by:

\[ 11. \quad R_t^k = l_t + \hat{w}_t - \hat{z}_t^k \]

Cost minimisation by firms implies that the rental rate of capital is negatively related to the capital-labour ratio and positively to the real wage.

The wage mark-up equation is given by:

\[ 12. \quad \mu_t^w = \hat{\pi}_t - \sigma_t \frac{l_t}{l_t} = \frac{\sigma_t}{\sigma_t} \left( \hat{\pi}_t - \frac{\sigma_t}{\sigma_t} \right) \]

In the monopolistically competitive labour market, the wage mark-up will be equal to the difference between the real wage and the marginal rate of substitution between working and consuming.

The real wage equation is given by:

\[ 13. \quad \hat{w}_t = \frac{\beta \gamma}{1 + \beta \gamma} \sigma_\pi \left( E_1 \hat{\pi}_{t+1} + E_1 \hat{\pi}_{t+1} \right) + \frac{1}{1 + \beta \gamma} \sigma_\pi \left( \hat{w}_{t-1} - \hat{w}_{t-1} \right) - \frac{1 + \beta \gamma}{1 + \beta \gamma} \sigma_\pi \hat{w}_{t-1} - \frac{(1 - \beta \gamma) \sigma_\pi}{(1 + \beta \gamma)} \sigma_\pi \hat{w}_{t-1} + \epsilon_t^w \]

Due to nominal wage stickiness and partial indexation of wages to inflation, real wages adjust gradually to the desired wage mark-up. The real wage is a function of expected and past real wages, expected, current and past inflation, the wage mark-up and a wage mark-up disturbance.

Finally, the monetary policy reaction function is given by:

\[ 14. \quad \hat{p}_t = \rho \hat{p}_{t+1} + (1 - \rho) \left( r_s \hat{p}_1 + r_s (\hat{p}_t - \hat{p}_t) \right) + \gamma_2 \left( \hat{y}_t - \hat{y}_t - (\hat{y}_1 - \hat{y}_1) + \epsilon_t^p \right) \]
Monetary authorities follow a generalised Taylor rule, by gradually adjusting the policy-controlled interest rate in response to inflation and the output gap. The parameter $\rho$ captures the degree of interest rate smoothing. There is also a short-run feedback from the change in the output gap.
Appendix 2.2 Prior and Posterior distributions

The following figures represent the prior and posterior distribution of the parameters and shock processes used in the model estimation. The grey line is the prior density and the black line is the posterior density.

Figure A2.2.1: Estimated Distribution of Parameters

Figure A2.2.2: Estimated Distribution of Parameters
Figure A2.2.3: Estimated Distribution of Parameters

Figure A2.2.4: Estimated Distribution of Parameters
Figure A2.2.5: Metropolis-Hastings Convergence Diagnostics
APPENDIX A2.3

Figure A2.3.1: Transformed Variables
APPENDIX A2.4

Figure A2.4.1: Impulse Response Functions (Total Factor Productivity shock)

Figure A2.4.2: Impulse Response Functions (Risk Premium shock)
Figure A2.4.3: Impulse Response Functions (Exogenous Spending shock)

Figure A2.4.4: Impulse Response Functions (Monetary Policy shock)
Figure A2.4.5: Impulse Response Functions (Price Mark-Up shock)

Figure A2.4.6: Impulse Response Functions (Investment Specific Shock)
Figure A2.4.7: Impulse Response Function (Wage Mark-Up Shock)
APPENDIX A4

Deriving the IS Curve

The IS curve equation is obtained by log linearizing the consumption Euler equation. The consumption Euler equation is obtained from the household’s optimal saving decision after imposing the condition that $Y_t = C_t + G_t$. This is the market clearing equilibrium condition that consumption is composed of output minus government expenditure.

Log-Linearizing the Euler Equation

The Euler equation can be written as,

$$U'(c_t) = \beta E_t [U'(c_{t+1})]i_t$$

The consumption Euler equation says that one will be indifferent between consuming an additional asset today $U'(c_t)$ and saving that asset for consumption in the future $\beta E_t [U'(c_{t+1})]i_t$.

This consumption Euler equation is used to derive the IS curve. Since it is a non-linear function, we first need to linearize it using a first-order Taylor series approximation. This method involves taking the derivative of the expressions and evaluating the derivative at full employment levels. The difference between the variable at time $t$ is then multiplied by the full employment level.

First, assume that the utility function $U(c_t)$ is given as:

$$U(c_t) = \frac{c_t^{1-\gamma}}{1-\gamma}$$

The marginal utility is then defined as:

$$c_t^{-\gamma}$$

By taking the first-order Taylor series approximation around $c_f$ we get:

---

71 Sims (2011) defines the process of log-linearization as taking the natural logs of the system of nonlinear difference equations. Then linearizing the logged different equations about a steady state and simplify until a system of linear equations is achieved, where variables of interest are percentage deviations about a point (steady state).
\[
c_t^{-\gamma} \approx c_f^{-\gamma} - \gamma c_f^{-\gamma-1} (c_t - c_f) \tag{A4.4}
\]

The consumption Euler equation (A4.1) can be rewritten as
\[
c_t^{-\gamma} = \beta E_t[c_{t+1}^{-\gamma}] i_t \tag{A4.5}
\]

If we then let \( i_t \) be the full employment interest rate, the Euler equation becomes
\[
c_f^{-\gamma} = \beta [c_f^{-\gamma}] i_f = \beta i_f = 1 \tag{A4.6}
\]

Linearizing the Euler equation using the first-order Taylor series approximation, we get
\[
c_t^{-\gamma} = \beta E_t[c_{t+1}^{-\gamma}] i_t \\
-\gamma c_t^{-\gamma-1} (c_t - c_f) = \beta i_f E_t[-\gamma c_t^{-\gamma-1}(c_t - c_f)] + \beta c_f^{-\gamma}(i_t - i_f) \\
-\gamma c_t^{-\gamma} (c_t - c_f)/c_f = \beta i_f E_t[-\gamma c_t^{-\gamma}(c_t - c_f)/c_f] + \beta c_f^{-\gamma}(i_t - i_f)/i_f \tag{A4.7}
\]

Next, we define variables as the percentage deviation from full employment.

\[
\frac{(c_t - c_f)}{c_f} \text{ is rewritten as } \hat{c}_t
\]

This represents consumption as its percentage deviation from full employment. Common terms are cancelled out and using equation (A4.6), we can rewrite the consumption Euler equation as:
\[
-\gamma \hat{c}_t = -\gamma E_t(\hat{c}_{t+1}) - i_t \tag{A4.8}
\]

Next, divide equation (A4.8) by \( \gamma \) and remove accents for simplicity. We can we rewrite the consumption Euler equation as
\[
c_t = E_t(c_{t+1}) - \alpha i_t \tag{A4.9}
\]

where \( \frac{1}{\gamma} = \alpha \) = the coefficient that indicates the sensitivity of current consumption to changes in the real interest rate or the intertemporal elasticity of substitution.

Finally, we use the Fisher relationship which states that the real interest rate, \( r_t \) is equal to the nominal interest rate \( i_t \) minus the expected inflation rate \( E_t(\pi_{t+1}) \)
\[
r_t = i_t - E_t(\pi_{t+1})
\]
\[ c_t = E_t(c_{t+1}) - \alpha(i_t - E_t(\pi_{t+1})) \]  

Since in equilibrium we stated that \( Y_t = C_t + G_t \), we can re-write the log linearized consumption Euler equation as follows

\[ (y_t - \bar{y}_t) - g_t = -\alpha(i_t - E_t(\pi_{t+1})) + E_t(y_{t+1} - \bar{y}_{t+1}) - g_{t+1} + \alpha r_t + \varepsilon_t \]

A4.11

where \((y_t - \bar{y}_t) = \text{output gap} = \bar{y}_t\)

Rearranging we get the modern IS curve

\[ \bar{y}_t = E_t(\bar{y}_{t+1}) - \alpha(i_t - E_t(\pi_{t+1})) + \nu_t \]

A4.12

where \( \nu_t = E_t(\Delta y_{t+1} - \Delta g_{t+1}) + \frac{1}{\sigma} r_t + \varepsilon_t \)

Equation (A4.12) states that current output depends on expected future output, as well as the interest rate. Because individuals prefer smooth consumption, expectations of higher consumption in the future next period (associated with higher expected output) leads them to want to consume more today which raises current output demand. The negative effect of the real interest rate on current output in turn reflects the intertemporal substitution of consumption. The interest elasticity in the IS curve, represented as \( \alpha \) corresponds to this.

Finally, the disturbance term \( \nu_t \) is a function of expected changes in government purchases relative to expected changes in potential output. Since this term \( \nu_t \) shifts the IS curve, it is interpreted as a demand shock (Clarida, Gali and Gertler, 1999).
REFERENCES


196


FERNÁNDEZ-VILLAVERDE, J. 2010. The econometrics of DSGE models. SERIEs, 1, 3-49.


HENRY, O.L., SHIELDS, K. 2003. Is There a Unit Root in Inflation? , Department of Economics, University of Melbourne


KOLLMAN, R. 1997. The exchange rate in a dynamic-optimizing current account model with nominal exchange rate. 


