Testing small open economy DSGE model with imperfect pass-through using Indirect Inference

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Thesis Submitted in Fulfilment of Requirements for the Degree of Doctor of Philosophy of Cardiff University

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December 2020

Acknowledgment

I would like to thank my supervisors, Patrick Minford and David Meenagh, for their valuable advice and their willingness to give up their time.

I deliver my many thanks to all lecturers who have taught me at Cardiff Business School.
Special thanks to mum for her support.
I dedicate this thesis to Cardiff Business School, my supervisors and my family.

Abstract

The response of consumer price to exchange rate fluctuations has been a major challenge for policy analysis. This paper develops a model of imperfect exchange rate pass-through within an open economy DSGE framework using quarterly UK data. The majority of papers use partial equilibrium models such as simple regressions rather than the general equilibrium model presented in this thesis. The former models have their own drawbacks, which significantly affect the inferences on a pass-through degree. Although some prior literature on pass-through analysis estimated the degree of pass-through in general equilibrium models, the overall performance of the models has been assessed by techniques such as fitting moment conditions. This work, on the other hand, uses Indirect Inference which has proved to be a more powerful test than standard testing tools such as moment comparisons or even the Likelihood Ratio test. Thus, in this thesis, I am testing the DSGE model where price rigidity is taken as a source of the sluggish response of prices to exchange rate movements. Consistent with previous studies, the thesis also concludes that the impact on consumer prices depends on the nature of macroeconomic shocks. The key to understanding this phenomenon lies in how the economy reacts to different shocks in the economy: whether the shock comes from foreign suppliers, domestic demand, or changes in monetary policy. The paper goes further and explores the reason behind different responses of CPI and exchange rate to different structural shocks. Therefore, the co-movement of exchange rate and CPI has been disentangled into separate dynamics. And the analysis shows that different behaviour under various shocks highly depends on estimated structural parameters.

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Chapter 1

Introduction

The exchange rate dynamics is one of the central questions in international macroeconomics. Fluctuations in the exchange rate can have sizeable effects on main macroeconomic variables such as output and price levels. Large exchange rate fluctuations have been observed both in the US and EU but the movement in domestic prices has been moderate. This muted response of variables has drawn the attention of academicians trying to understand the exchange rate transmission mechanism. Earlier empirical studies have estimated the exchange rate pass-through degree (ERPT) on a broad range of price levels- tradable and consumer prices. The vast literature of empirical studies has attempted to quantify the pass-through and found it to be imperfect in the short-run while long-run relationship to be one-to-one indicating perfect pass-through. However, despite substantial literature on the effect of exchange rate on price levels, it is still unclear how exchange rate movements will affect inflation, which has created a challenge for central banks.

The literature in international macroeconomics relates the high volatility of exchange rate to noisy behaviour of financial markets whereas the stability of prices is attributed to a wide range of rigidities including price stickiness, the choice of price-setting currency, inflation environment, distributional channel and variable markup. Other factors that might hinder the movement of prices and hence affecting the degree of exchange rate pass-through are weights on imported intermediate goods in domestic production function and persistence of exchange rate. Each of these factors has its own degree of importance in transmitting exchange rate volatility on price levels. Nevertheless, one of the major explanations for gradual adjustment of prices to exchange rate movements is attributed to sticky prices whereby firms refrain from changing prices continuously in the market because of "menu costs", which represent costs to consumers inflicted by price changes. In the open economy literature, this is known as local currency pricing (LCP). This thesis takes the situation of nominal rigidity in price setting as the unifying theory of pricing and consequent pass-through implications.

Prior work on open economy models predominantly based on the assumption of complete and immediate effect of exchange rate movements on import prices (Gali, Monacelli, et al. (2000), B. T. McCallum and Nelson (1999)). The empirical evidence, however, suggests systematic deviations from the law of one price, and that the exchange rate pass-through is incomplete both for export and import prices (see e.g. Adolfson (2001), Alexius and Vredin (1999), and Naug and Nymoen (1996)). Consider a foreign firm selling goods to the domestic market and setting its price in the domestic (buyer's) currency. If prices denoted in domestic currency are sticky, as a consequence of firms facing costs of changing prices, the domestic currency (import) price will not be fully altered even if exchange rate changes affect the marginal cost. This implies that import prices do not move immediately and not in a one-to-one relation with the exchange rate (i.e. incomplete exchange rate pass-through). Nominal rigidities thus imply that exchange rate movements have a minor immediate effect on consumer price inflation. In addition, nominal rigidities imply that expectations about future exchange rates as well as expectations about future inflation are important for the inflation–output relation.

Stable prices and highly volatile exchange rates are also found in the UK economy[1]. The evidence to date suggests that exchange rate pass-through (ERPT) to consumer price inflation (CPI) is of incomplete nature but the consensus on its exact magnitude is still vague. These different results are due to several factors including the choice of methodology and the model features. The estimated consumer price pass-through degree for the UK is estimated to be around -0.01 in the short-run and -0.07 in the long-run (K. Forbes, Hjortsoe, and Nenova (2018)). In other words, 1% change (appreciation) in exchange rate en-

[1] Bank of England paper by K. J. Forbes, Hjortsoe, and Nenova (2017)

tails only 0.01% change (fall) in CPI price level. This result is based on simple regression. On the other hand, SVAR estimates for the full sample between 1993 and 2015 is -0.13. This evidence suggests that pass-through degree is model and sample-dependent. Thus, the authors[2] remind us to be cautious while estimating the pass-through degree as standard simple regression used by most central banks may lead to misleading conclusions that would be detrimental to monetary policy.

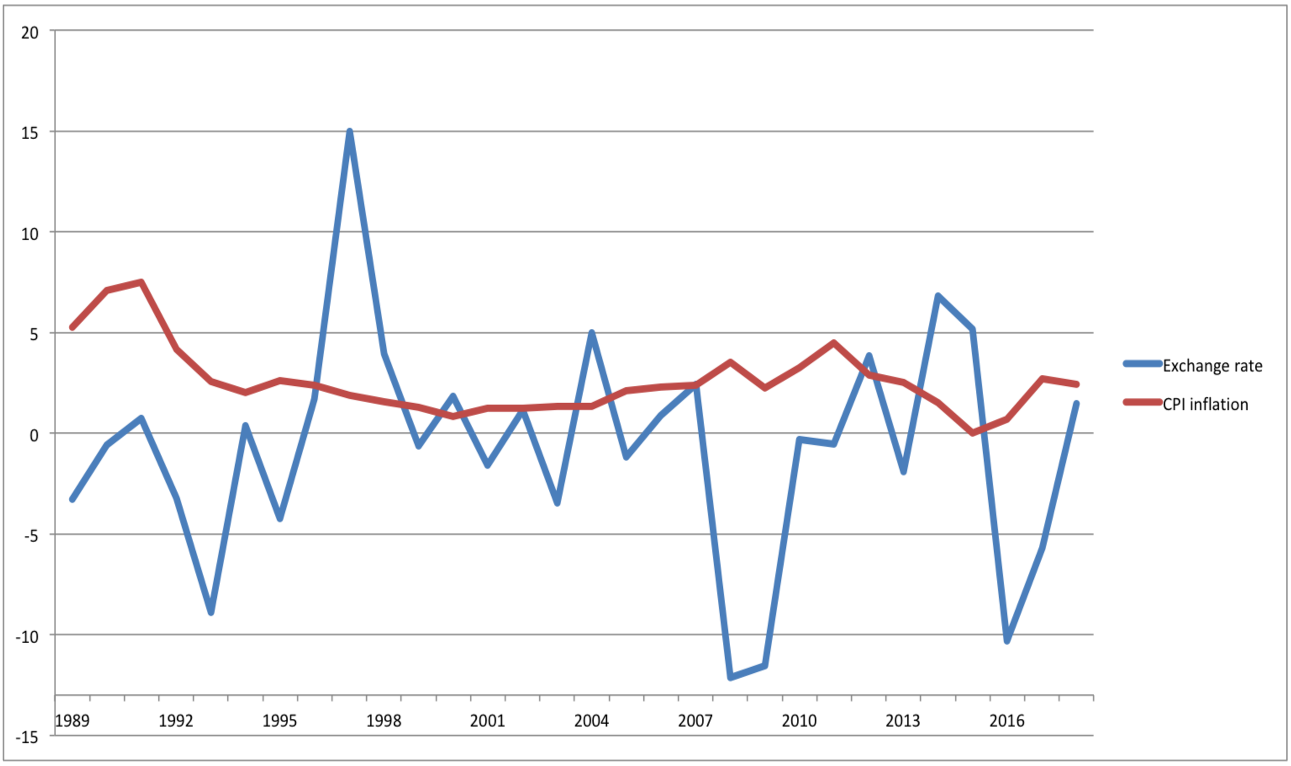

Figure 1.1: Annual percentage change in CPI and nominal exchange rate

Figure 1.1 depicts the evolution of annual change in CPI price level and nominal exchange rate (NER) for the UK between 1989 and 2017. Note that the pass-through degree is a ratio of changes in the price level over the nominal exchange rate. The nominal effective exchange rate is measured as a shift in the value of sterling relative to the currencies of the UK's major trading partners from the rest of the world. There are four significant moves in the currency that took place during this period. The big drop in sterling when the UK fell out from European Exchange Rate System (ERM) in 1992, after which the exchange rate appreciated substantially in 1998. The latter swing in NER can be

[2]K. Forbes, Hjortsoe, and Nenova (2018)

traced back to a shift in the monetary system when the central bank adopted a lower inflation target. Then, equally large depreciation has been spotted during the financial crisis. Specifically, the pound declined by more than 15% between 2007 and 2009. And recently, following the Brexit event, there is a substantial drop in the value of sterling, which is mostly due to the decline in investment and loss in consumer confidence. Although there have been four significant shifts in sterling in the past three decades, the movement in CPI has been stable- in all those episodes the change in CPI level is relatively mild. In particular, the adoption of an inflation targeting regime has been proved effective as an inflation rate has been quite steady since 1992. To sum up, these stylised facts result in two main conclusions that can be drawn from the graph. Firstly, the pass-through degree is imperfect as there is a large swing in NER while moderate movement in CPI. Secondly, it is apparent that the relationship between prices and exchange rate varies over time, which reveals a non-constant ERPT degree. The analysis performed here acknowledges this fact and attributes this property to the distribution of shocks. That is, ERPT degree depends on the type of macroeconomic shock that hits the economy.

The current DSGE model builds upon the model of Smets and Raf Wouters (2003) and Monacelli (2005) by introducing an intermediate goods production to improve the fit of the model. Moreover, adding intermediate level of production adds an additional transmission channel via imported intermediate goods. When imported goods enter the domestic production function, the marginal cost depends on the prices of imported goods. As emphasized by Smets and Raf Wouters (2002), this is an important channel in explaining exchange rate impacts on domestic prices. The paper conjectures that price rigidity is the main source of imperfect pass-through of the exchange rate in the short-run. Consequently, the model generates a complete pass-through in the long-run.

The main research question addressed in this thesis is to evaluate the performance of the open economy DSGE model based on nominal rigidity as the cause of incomplete pass-through for the UK since 1989s. Thus, the main contribution of this thesis is empirical. The model testing tool is powerful Indirect Inference (Le, Meenagh, Minford, and Wickens (2011), Le, Meenagh, and Minford (2016) and Le, Meenagh, Minford, Wickens, and Y. Xu (2016)) as opposed to other techniques, all of which have drawbacks I examine in the following chapter 5. In so doing we hope to provide accurate estimates of the various channels involved in ERPT, identified here in the general equilibrium framework. We provide a careful breakdown in what follows of the shocks and associated channels causing the ERPT for consumer prices.

The second question the paper appeals is to verify and explain the shock-dependent nature of pass-through, which we assume the main reason behind time-varying ERPT degree. The most recent literature on shock-dependency has been examined under the VAR framework while the current paper identifies these characteristics of pass-through degree using the general equilibrium framework. After verifying that pass-through is incomplete in the short-run, the paper goes further and explores the reason behind different responses of CPI and exchange rate to different structural shocks. Therefore, the co-movement of exchange rate and CPI has been disentangled into separate dynamics. And the study concludes that different behaviour of these variables is due to different behaviour of individuals residing in the economy: firms set different prices in response to a different state of the economy and so is the decision made by monetary authority. This also confirms the outcome of previous literature that the nature of the monetary policy is substantial on a pass-through degree as it influences not only the magnitude of ERPT degree but also its sign.

The answer to the first research question on testing the DSGE model that encompasses imperfect pass-through degree has been achieved by evaluating the model performance using Indirect Inference. The model's implied behaviour is tested for its closeness to the UK data by employing an auxiliary model (VARX model in this case) to describe both the sample data and the simulated data generated by the model. Specifically, a cointegrated vector autoregressive with exogenous variables (VARX) is used as an auxiliary model, and the test is based on the function of the VARX estimates. The Wald statistic then measures the statistical closeness of those estimates. The non-rejection of the null hypothesis implies that the imperfect pass-through property of the model is indeed a relevant feature of the model since it is accepted by historical UK data.

The size of ERPT degree by definition is a relative movement between CPI and exchange rate. Thus, the dynamics of the price level and the nominal exchange rate is considered separately. Unlike in partial equilibrium analysis where causality streams from exchange rate to price level, in general equilibrium the causality flows in both directions. Using this feature of the model I try to explain why the sign and magnitude of the pass-through degree depend on the distribution of structural shocks.

We also perform welfare analysis on different monetary policies including standard Taylor rule, core inflation targeting and price-level targeting. The thesis aims to identify the most efficient policy in terms of minimum welfare loss. In addition, I would like to see whether the pass-through degree alters as monetary policy changes.

The thesis is structured in the following way. Chapter 2 covers a survey on a pass-through degree. In Chapter 3, I present a small open economy DSGE model with an extension of intermediate goods production. The next chapter describes the data set. In the following chapter, the overview of estimation and testing methodology- Indirect Inference- has been outlined. An estimation result has been demonstrated. Chapter 6 illustrates the workings of the economy. As the model is general equilibrium, understanding transmission channels is essential prior to the analysis. To highlight the dynamics of key variables, I illustrate the impulse response functions generated from the estimated model in Chapter 7. This an essential step in discussing pass-through degree as the ERPT degree is calculated using these functions. The last section of this chapter outlines the reason behind the different signs and magnitude of pass-through degree. It also emphasizes the difference between the analysis presented here and the past literature. Chapter 8 summarises the shock processes. The behaviour of pass-through degree under different monetary policies is studied in Chapter 9. The welfare implications of each policy were reported. Chapter 10 concludes the thesis.

Chapter 2

Literature Review

There is a huge theoretical and empirical literature that has emerged on exchange rate pass-through. Unfortunately, the exact estimate of pass-through degree remains vague. The reason for such uncertainty can be attributed to the type of model and methodology that is being employed to assess the magnitude as well as the type of data that has been utilised. In addition, those constructed models with imperfect pass-through have been rarely evaluated[1]. Thus, in this chapter, I will survey four strands of literature on exchange rate pass-through. The first strand is concerned with theories behind the imperfect pass-through degree. In fact, I will list the conditions for a sluggish response of prices, which consequently implies an imperfect degree. The next three strands cover the type of models that have been used to assess the pass-through degree: simple regression, VAR and DSGE models respectively. Such classification of models identifies the weakness and strength of each methodology that is being employed.

A number of common findings emerge from the numerous studies on the sensitivity of price level on exchange rate. First, the pass-through degree is incomplete in the short-run and it varies across countries and industries. Second, it is higher for trade prices than for prices at final consumer level. As an example of the evidence, short-run ERPT for the US has been estimated between 0.01 (CPI) and 0.25 (import price); France estimates ranges from -0.05 (CPI) and 0.52 (import), whereas the UK settles between -0.05 (CPI) and 0.36 (import). These estimates are derived from the study by L. S. Goldberg and José Manuel Campa

[1] As far as I am aware, there is only one literature that tested the model. Adolfson, Laséen, et al. (2007)

(2006) where they implement both SVAR and regression analysis[2].

The studies on pass-through degrees mainly concern import prices. The pass-through degree to consumer prices, nevertheless, has been studied extensively in recent years only. Since the import prices are embedded in consumer prices, we would expect the ERPT degree to be lower for the latter, which is widely accepted by the literature.

Another issue in the literature is whether the pass-through degree is asymmetric. The existing studies assume the relationship between exchange rate and prices is symmetric and linear. Thus, appreciation and depreciation have an identical impact on prices, and that the size of the exchange rate impact has no effect on the pass-through degree. There are some factors that could result in non-linear and asymmetric pass-through: downward price rigidity, pricing-to-market and costs such as quotas. The literature does not reach a consensus on whether the asymmetry prevails in the UK economy. Herzberg, Kapetanios, and Price (2003) argue against it, finding no real evidence of non-linearity. A similar conclusion was reported by Lewis (2016) though they identify pronounced asymmetry in the bilateral exchange rate. On the other hand, Dainauskas (2018) finds that pass-through is higher for depreciation than appreciation in the UK. All these studies consider asymmetries in regard to either export or import prices. In terms of pass-through to CPI, Rincón-Castro, Rodrıguez-Niño, and Rincón-Castro (2016) supported evidence that pass-through is asymmetric for Colombia (VAR model). In my thesis, the variable of interest is final consumer price and I abstracted from asymmetry in pass-through degree in response to macroeconomic shocks. And the current DSGE model with this symmetric pass-through degree passes the most powerful macroeconomic test- Indirect Inference. Thus, asymmetry will be likely to be rejected as a mis-specification, given the power of the test.

[2]SVAR and OLS pass-through estimates are similar for certain countries such as UK and US. The estimates for France is 0.1 by OLS and -0.05 by SVAR.

2.1 Causes of imperfect pass-through

There is ample empirical evidence that the pass-through degree is incomplete. Their main focus has been on finding the source of incompleteness and on seeking an optimal monetary policy under such circumstances. A number of explanations behind imperfect ERPT degree has been incorporated into the macroeconomic models including share of imported goods in final consumption or domestic production, nominal rigidities (M. B. Devereux and Yetman (2002)), the currency choice in price-setting (Choudhri and Hakura (2015))), markup adjustments (Gopinath, Itskhoki, and Rigobon (2010)) and role of distributional services (Burlon, Notarpietro, and Pisani (2018)). Besides, there is sufficient literature at the firm level (José Manuel Campa and L. S. Goldberg (2008), which emphasises the pricing decision of firms under monopolistic competition. They confirm sluggish movement in prices in response to exchange movements and derive a range of implications for monetary policy. Another vein of the literature has documented that pass-through degree varies over time. Some authors argue that it is due to slow-moving structural changes such as shifts in monetary policy (Taylor (2000))), Bailliu and Fujii (2004)) or changes in the composition of goods towards imported products (Jose Manuel Campa and L. S. Goldberg (2005)). For instance, considerable variation in pass-through has been observed for Switzerland data(Fleer, Rudolf, Zurlinden, et al. (2016)) and for UK (K. Forbes, Hjortsoe, and Nenova (2018)). J. E. Gagnon and J. Ihrig (2004) links pass-through to monetary policy conditions; countries with lower inflationary environment tend to have a weaker pass-through degree due to credible central banks committed to keeping inflation low. They have estimated the pass-through level at the consumer level to be 0.18 for United Kingdom (1975-1992), which has declined to 0.08 (1992-2003).

A common argument on the imperfect degree of pass-through revolves around the currency of pricing. Obstfeld and Rogoff (1995) and Gopinath, Itskhoki, and Rigobon (2010) assume prices are rigid in producer currency (PCP). Exporters set prices in their own currencies and hence the response of import prices is immediate (full pass-through). The impact on final consumer price still depends on various factors including frictions in the domestic economy and import shares. A complete opposite of PCP is when prices are sticky in local currency (LCP). Then there is no transmission from exchange rate to import prices. The current thesis assumes LCP in all markets with a fraction of firms unable to reset prices for certain periods (Calvo (1983)). However, the forward-looking nature of the current model allows shock effects to be transmitted to consumer prices through future inflation. Thus, despite having sticky prices the pass-through degree is still non-zero.

According to Choudhri and Hakura (2015), the currency choice is sensitive to how a model is specified. The literature concludes that import price pass-through increases as the proportion of goods with PCP increases. On the other hand, it is evident that import price pass-through is low for the UK. Thus, without markup adjustment, it is supportive to assume that firms set prices in local markets. For instance, Choudhri and Hakura (ibid.) reveal that LCP generates a lower import price pass-through and a higher pass-through degree is attributed to PCP. However, they do not test the model itself, therefore it is still unclear which specification actually prevails in the economy.

Although the firm-level literature on UK imports indicates that the UK is both a local and producer currency setting country (Novy, Chen, and Chung (2019)) I assume LCP predominates across the economy and hence that nominal rigidity is the cause of incomplete pass-through, for two reasons. First, theoretically, I assume that foreign exporters face menu costs in adjusting prices in local currencies thereby allowing local currency pricing in all markets (Smets and Raf Wouters (2002), Corsetti, Dedola, and Leduc (2007)). Secondly, empirically I subject the resulting macro model to the most searching empirical testing on the macro facts- to check whether this DSGE approach well approximates the data behaviour- which as we will see, it does. Thus the aim of the thesis is to provide a fundamental model of imperfect pass-through that passes the macroeconomics test. And the test indeed confirms that the current DSGE model with local currency pricing is a true model in generating imperfect pass-through. Thus, the amendment of the model with both local and producer currency pricing is likely to be rejected since the model will be mis-specified with this hybrid feature of price-setting.

A seminal paper by Dornbusch (1987) has identified several factors behind the sluggish response of prices: the degree of market integration, functional form of the demand curve and strategic interaction between suppliers. The perfect market integration entails the Law of One Price (LOP) condition to be satisfied- identical products are equally priced when measured in common currency. Applying this law for consumer prices implies the Purchasing Power Parity (PPP) conditions. On the other hand, if a market is segmented, due to eg. trade barriers, then firms set different prices in local markets. In this thesis, I use Dixit and Stiglitz (1977) the version of demand function, which essentially implies optimal price is a constant markup over marginal cost. The consequence of such assumption is that, if prices are flexible then for a given marginal cost the prices are proportionally responding to movements in marginal cost, generating a perfect pass-through degree. Nevertheless, there is a huge literature on variable markup models where firms are able to change both markups in addition to prices. In such models the markup is inversely related to the elasticity of demand or demand is less convex than in the constant elasticity case. Thus, the incomplete pass-through is achieved since firms adjust markups in response to exchange rate movements rather than their prices. This phenomenon is widely known as "pricing-to-market".

An alternative view has been put forth by Taylor (2000), who argues that the decline in pass-through degree is associated with a low inflation environment. For instance, the adoption of inflation targeting rule by the UK considerably declined the fluctuation in the inflation rate. The author explains the link between price and exchange rate using a staggered price-setting firm in monopolistic competition. The intuition is that as firms set prices for several periods in advance, their price is more sensitive to changes in their cost. And higher inflation environment tends to have more persistent changes in cost. Thus, a credible lower inflation regime leads to a lower pass-through degree.

2.2 Simple regression

The earliest literature on pass-through was spurred from the muted response of US import prices (pass-through of 0.5) to the dollar appreciation in the 1980s [3]. The paper draws from the industrial level data and hence focuses on industrial characteristics such as market structure and the nature of competition. Although the model is partial equilibrium in structure, it points out the importance of rigidity in local prices and conjecture that markups partly absorb movements in the exchange rate.

Much of the literature estimating the ERPT has used simple regression- e.g. Jose Manuel Campa and L. S. Goldberg (2005) who regressed import prices on the exchange rate and other determinants for 23 OECD countries: they found an elasticity of 0.46 in the short-run and 0.65 in the long-run. This micro-based literature that used industry-level data (Knetter (1989), Marston (1990)) reported that firms tend to adjust markups rather than prices thereby generating imperfect pass-through. They also discover that pass-through degree is industry dependent implying that the structure of industries is a crucial aspect to consider. These results are confirmed by the study conducted by Anderton (2003) with pass-through ranging between 0.5-0.7 for manufacturing industries; on the other hand, Jose Manuel Campa and L. S. Goldberg (2005) conducted a study for various industries reporting the highest short-run pass-through to the energy industry (0.75) and lowest to manufacturing (0.43). Another empirical regularity is that the ERPT degree is gradual over the time horizon: pass-through is lower in the short-run than in the long-run. These findings are confirmed by all literature on pass-through degree analysis.

Most of the literature concentrated on traded goods prices such as import or export prices. In the past decades, a number of studies employed aggregate consumer prices. The consensus is that the pass-through degree is substantially lower than the case with trade prices. A study by Choudhri and Hakura (2006) estimated the pass-through to consumer price inflation for 71 countries over the period of 1979–2000. The estimated result for the UK is found to be -0.01 on impact and 0.02 for four quarters. They also confirmed a strong link between the pass-through degree and the average inflation rate, implying that the nature of monetary policy is endogenous to the pass-through degree.

The recent surveys on pass-through degrees document a significant

[3] P. K. Goldberg and Knetter (1996)

decline in pass-through degrees. Marazzi et al. (2005) provided evidence for US import prices: 0.5 in the 1980s dropped to 0.2 during the last decade. A possible explanation has been attributed to a shift in the composition of goods in both imports and exports, and changes in the pricing behaviour of the Asian firms around the time of the Asian financial crisis in 1997-98. Similar results have been claimed by J. E. Gagnon and J. Ihrig (2004), who find evidence that the exchange rate pass-through to consumer prices declined in 20 industrial countries since the 1980s and the factor for such shift has been attributed to a change in the behaviour of monetary policy. Although other micro-related literature achieves the same conclusion about an imperfect pass-through degree, unfortunately, as has been widely recognised, this approach suffers from endogeneity bias since both the exchange rate and prices are endogenous variables. This leads us to the next model, the VAR model.

2.3 VAR models

Vector autoregression analysis has been widely used as an alternative. This reduced form allows the ERPT to be estimated for all pricing chains simultaneously and accounts for the endogeneity of the exchange rate. In addition, it enables to trace the dynamic response of prices to exogenous shocks. More importantly, it captures both the size and speed of the pass-through degree. Choudhri and Hakura (2015) estimated pass-through to trade prices for 34 countries using both regression and VAR estimates, which confirms the muted response of import (0.35 for the UK) and export prices (0.21 for the UK). Although their effort on confirming these results on the structural model has been successful, the conclusion was based on calibrated rather than estimated model; and the evaluation criteria on model testing is based on matching the variability (of inflation and exchange rate) and pass-through statistics[4]. However, this is not a formal statistical test based on a single statistics that summarises the model. Although basic VARs are successful at capturing dynamic properties of the data, the identification problem still remains an issue. To assess the impact of structural shocks on the system, one has to impose identification restrictions based on economic theory to unravel the effect of structural shocks from VAR

[4] The paper simulated the structural model to get simulated data on inflation and nominal exchange rate. Then, applied simple regression on these simulated data

innovations. K. Forbes, Hjortsoe, and Nenova (2018) is one example. In their model firms react to different shocks in the economy according to whether the shock comes from foreign suppliers, domestic demand or changes in monetary policy. This can account for why the exchange rate pass-through varies over time.

The papers by K. Forbes, Hjortsoe, and Nenova (ibid.) and An and Wang (2012) are close to the present thesis in terms of revealing shock sensitivity characteristics of pass-through degree. They conjecture that different distribution of shocks behind exchange rate movements causes a different response in future marginal cost, demand conditions and expected exchange rate. Firms observing these movements in their future demand conditions tend to change their markups rather than price level thereby limiting the pass-through degree. In contrast, the present paper assumes constant markup and builds the analysis on the estimated DSGE model (not SVAR model). Nevertheless, we still expect the pass-through to be shock-dependent.

A similar study on the shock-dependent nature of pass-through has been accomplished by Hahn (2003) on Euro data. First, the author shows that the pass-through degree decreases along the pricing chain from import prices to producer and finally to a consumer price index. Second, the pass-through degree to HICP (Harmonized Index of Consumer Prices) indeed varies with the type of shock: highest for non-oil shock (4% on impact and 17% within a year time) and lowest for exchange rate and oil shocks (2.5% on impact and 8% within a year time). Finally, the speed of adjustment of pass-through degree to its long-run value of one also gradual and shock-dependent: fastest convergence for non-oil shock rather than other two shocks. Much lower pass-through degree to consumer price index has been obtained by Hüfner and Schröder (2002) using Vector Error Correction Model (VECM) model on Euro data (5 largest countries)- 0.04 (4 quarters) and 0.08 (long-run). VECM models account for the non-stationarity of variables and any cointegration relationships between them. This paper also confirms declining pass-through along the distribution chain of prices with the largest effect occurring in import prices.

2.4 General equilibrium models

Although several identification techniques have been proposed in the literature, the shock identification restrictions cannot be easily tested against the data[5] in VAR models. Accordingly, other works have built structural DSGE models to identify the transmission channels involved. Thus, the issue of imperfect exchange rate pass-through has gathered much attention in a class of optimising dynamic stochastic equilibrium models (DSGE) with imperfect competition. Since the introduction of Lucas critique in 1976, DSGE models have become a popular framework for policy analysis both in academia and in policy institutions. More importantly, an empirical evaluation of DSGE models is an active area of research as the testing of model itself is crucial for any policy purposes. The outcome of Lucas critique has resulted in models based on the optimising behaviour of microeconomic units, firms and households, so that model parameters are more likely to be policy invariant. Thus, the key characteristic of DSGE models is the use of a microeconomic foundation, which enables more rigorous analysis than any other conventional models can offer.

The feature of monopolistic competition and price rigidity has been introduced into open economy DSGE models by Obstfeld and Rogoff (1995). Later models focusing on explaining specific characteristics of the model included further extensions such as habit-forming preferences, capital accumulation with adjustment costs, financial structures, etc. The ones on imperfect pass-through analysis incorporated variable demand elasticity (that generates variable markups), intermediate inputs in production and other frictions that allow the sluggish response of prices.

In response to empirical works on incomplete pass-through, theoretical literature offered various explanations on price insensitivity. One trend in this literature (Betts and M. B. Devereux (2000) and Chari, Kehoe, and McGrattan (2002)) assume that prices are sticky in local currency, LCP, impeding the impact of exchange rate on consumer prices in the short-run. Another trend along the lines of Obstfeld and Rogoff (1995) embedded the rigidity of prices in producer's currency, PCP, so that consumer prices change one for one with changes in the nominal

[5] BOE paper by Liu and Theodoridis (2018)

exchange rate. The latest papers have been employing the weighted average of these price-setting regime[6].

The literature on the DSGE model with imperfect pass-through is extensive. There are several directions of focus on the DSGE models. The first stream deals with fitting the data using various methodologies. For instance, Adolfson, Laséen, et al. (2007) has estimated the DSGE model on Euro data using the Bayesian technique; their focus has been on fitting the data using vector autocovariance functions using unrestricted VAR on sample data and restricted VAR from the model. In addition, they have emphasized the importance of nominal and real frictions by comparing two models using the Bayes factor. Another example could be De Walque et al. (2017) who compared the out-of-sample performance of the two-country model; they have also included the check on matching stylized facts of business cycle fluctuations such as correlations and variance of a variable of interests[7]. Similarly, some papers tried to match the behaviour of real exchange rate (Dogan (2014)[8]).

The second stream reports on the shock dependence nature of pass-through. Ambler, Dib, and Rebei (2003) examined the dynamics of the price level (CPI) and exchange rate on US and Canadian data; using the impulse response functions on eight structural shocks they have demonstrated that variables respond differently under different shocks. Moreover, their sensitivity analysis showed that price rigidities decrease the pass-through degree but not necessary in generating limited pass-through since other structural features of the model such as the distributional sector can result in sluggish pass-through. Another stream investigates alternative monetary policy regimes under imperfect pass-through. If one study focuses on fixed versus flexible exchange rate policies (M. B. Devereux, Lane, and J. Xu (2006), others focuses on optimal monetary policy in terms of targeting different price levels including CPI, producer price or non-traded goods prices[9].

The rest of the literature on DSGE models similar to regression

[6] Choudhri and Hakura (2015)

[7] Other studies on matching stylised facts include Dogan (2014)

[8] Two country model of Euro and US, calibrated DSGE model including most of the frictions such as habit formation, home bias,etc.

[9] Corsetti, Dedola, and Leduc (2007), Monacelli (2005)

and VAR analysis has focused on testing different features of the model behind imperfect pass-through. However, these papers have not estimated (calibration mainly) either tested the model. Therefore, the conclusion on pass-through estimates is misleading. For instance, the paper by Jeanfils (2008) accommodates distribution services and variable markup in addition to staggering price characteristics. The paper concludes that these features of the model are important in accounting for an imperfect pass-through degree. Another paper by Corsetti, Dedola, and Leduc (2005) emphasizes the importance of nominal rigidities in prices as even small friction in prices can generate lower pass-through degree to consumer prices. Another characteristic that lowers the pass-through degree is the presence of distribution services, which leads to price discrimination by firms.

We follow this approach here. Our DSGE model builds on Smets and Raf Wouters (2003) and Monacelli (2005) by introducing intermediate goods production. This improves the model's fit and incorporates additional exchange rate transmission channel via imported intermediate goods thereby increasing the pass-through degree[10]. When imported goods enter the final domestic production function, marginal costs will depend on the prices of imported goods. As emphasized by Smets and Raf Wouters (2002) and Jose Manuel Campa and L. S. Goldberg (2005), this plays an important role in the pass-through disconnect. The paper conjectures that the price rigidity is a main source of imperfect pass-through of exchange rate in the short-run but complete pass-through in the long-run.

B. McCallum and Nelson (2000) introduced imports as inputs instead of as consumer goods. In their model, the Phillips curve states that the impact of the exchange rate passes through only via the output gap (no direct effect). Thus, there is little support for central banks to move interest rates in the face of significant exchange-rate depreciation, unless the depreciation is associated with large increases in the output above potential. The conclusion from this literature is that including imported inputs in the UK economy is crucial as it significantly improves the fit of the model. If the model abstracts from imported inputs, then CPI inflation dynamics is not supported by UK data. This approach

[10] Georgiadis, Gräb, and Khalil (2019), Casas (2020)

predicts that CPI inflation and exchange rate changes should have a quite strong relationship, but this relationship is consistently weak in UK data. On the other hand, the modelling approach with imported inputs matches UK data well as it justifies CPI inflation targeting, floating exchange rate, high correlation between import price and exchange rate, and low pass-through to UK CPI. Thus, the model employed in this thesis is expected to fit the UK data well with targeting CPI inflation as monetary policy(Kara and Nelson (2003)).

Chapter 3

The open economy DSGE model

. The world economy consists of two countries denoted as Home and Foreign. As the Home economy is relatively smaller than its foreign counterpart, we assume that foreign inflation, output and interest rate are exogenously given. In the domestic economy, households maximise utility function for consumption and minimise disutility from labour where the consumption basket consists of domestically produced and imported goods. These products are supplied by domestic and importing firms, respectively. The labour market is assumed to operate under perfect competition due to declining unionisation since 1980s as the union membership plummeted from 13 million to under 7 million in 2015[1].

There are two types of producers in the economy: intermediate goods producers and final goods producers. Each category comprises domestic producers and importers. All producers are monopolistically competitive with staggered price setting, indexation variant of Calvo (1983), excluding home retailers. By allowing for nominal rigidities in the importing and exporting sectors, the final consumer price exhibits incomplete exchange rate pass-through in the short-run. Home retailers act as aggregators of home and imported intermediate goods, which they turn into a final good using Leontief production function. These retail products are then divided between home consumption, investment and government spending.

[1]Source: Department for Business, Energy and Industrial Strategy, Trade Union Membership, Statistical Bulletin, 2016

Throughout the thesis, I assume local currency pricing in all markets (except for home retailers operating in perfect competition) as opposed to producer currency pricing or the hybrid model. The current work estimates the pass-through degree and the causal reason for incomplete ERPT degree is rigid prices. The model conjectures that sticky prices occur due to menu costs present in the local markets. Although the firm-level literature on UK imports confirms that the UK is both a local and producer currency setting country (Novy, Chen, and Chung (2019)), I propose the unifying theory of Calvo pricing and LCP, and I test these specifications empirically by the powerful Indirect Inference test, as opposed to the variety of empirical methods used to date which I explain in my thesis suffer from a variety of drawbacks in chapter 5.

3.1 Households

3.1.1 Dynamics problem of households

The representative household derives utility from consumption, C_t, and disutility from labour, N_t. By maximising their lifetime utility households decide on their level of consumption, labour hours, domestic and foreign bond holdings. They also choose the level of capital services provided to the firms, their capital utilisation rate and investment level. Households own the capital stock and increase its volume by investing in additional physical capital (I_t) or increasing its utilisation rate, u_t, defined as $u_t = \tilde{K}_t / K_{t-1}$. Then, they supply labour and capital to domestic intermediate firms and receive total factor payment net of cost associated with variations in the degree of capital utilisation, $P_{ht} r_t^K K_t + P_{dt} w_t N_t - P_{ht} \psi(u_t) K_{t-1}$, where P_{ht} is domestic final good producer price, P_{dt} is domestic intermediate good producer price, K_t is capital stock and r_t^K is rental rate[2]. The expression $P_{ht} \psi(u_t) K_{t-1}$ is the cost of setting utilisation rate to u_t by households. Both return to capital and utilisation rate of capital are expressed in terms of retail price due to model simplicity[3]. Note, consumers receive a wage

[2]Following the model setup by Adolfson, Laséen, et al. (2007)

[3]So that real resource constraint, equation (3.37), will match the standard equation in the literature

deflated by producer price (intermediate goods price). The real wage is expressed in terms of the intermediate product since intermediate firms are the ones that hire the labour. Following Minford (1994) and Davidson et al. (2010), there is a distinction between two wages: real wage paid by intermediate firms ($\frac{W}{P_{dt}}$, based on producer price) and real wage deflated by consumer price ($\frac{W}{P_t}$, based on CPI). This is due to the open economy feature of the model. The final consumer price (CPI) is a weighted average of domestic and foreign retail prices. Suppose that the real exchange rate appreciates so that domestic price rises. This reduces producer wage relative to consumer wage thereby increasing the demand for labour and hence the output.

Households also receive profits or dividend payments, Div_t, from monopolistically competitive intermediate good producers as they own these firms. However, they are liable to lump-sum tax to the government, T_t. Households hold their wealth in the form of domestic bonds, B_t, and foreign bonds, F_t, where the latter is denominated in the foreign currency. Bonds are one-period securities with nominal return r_t and r_t^* respectively for domestic and foreign bonds.

The preferences of household are constant relative risk aversion type (CRRA) utility function, which is additively separable into consumption and labour:

$$E_0 \sum_{t=0}^{\infty} \beta^t \varepsilon_t^b [\frac{C_t^{1-\sigma}}{1-\sigma} - \varepsilon_t^{Ns} \frac{N_t^{1+\gamma}}{1+\gamma}]$$

subject to

$$C_t + \frac{P_{ht}}{P_t} I_t + \frac{B_t}{P_t} + \frac{S_t F_t}{P_t} + \frac{T_t}{P_t} = \frac{P_{dt}}{P_t} w_t N_t + \frac{Div_t}{P_t} + (1 + r_{t-1}) \frac{B_{t-1}}{P_t}$$
$$+ \frac{P_{ht}}{P_t} (r_t^K u_t K_{t-1} - \psi(u_t) K_{t-1}) + (1 + r_{t-1}^*) \frac{\Phi(f_{t-1}) S_t F_{t-1}}{P_t} \tag{3.1}$$

and capital accumulation function

$$\tilde{K_t} = (1 - \delta)\tilde{K_{t-1}} + [1 - \Gamma(\frac{\varepsilon_t^I I_t}{I_{t-1}})] I_t \tag{3.2}$$

where β is the discount factor, E_0 is the expectation operator conditional on the information available at period 0. σ is the degree of relative risk aversion and its reciprocal, $\frac{1}{\sigma}$, measures the inter-temporal elasticity of substitution of consumption between two periods; γ represents the inverse of elasticity of labour (Frisch elasticity) with respect to real wage.

Following Adolfson, Laséen, et al. (2007) and Schmitt-Grohé and Uribe (2004), the term $\Phi(f_{t-1})$ is a premium on foreign bond holdings which depends on real foreign asset position to output ratio, f_{t-1}, where $f_t = \frac{S_t F_t}{P_t Y_t}$. The function, Φ, is assumed to be strictly decreasing in f_t and satisfy $\Phi(0) = 1$. It captures the imperfect integration in the international financial market.

Equations (3.1) and (3.2) represent the budget constrain of households. Equation (3.1) suggests that households consume, invest, pay lump-sum taxes and buy both risk-free domestic and foreign bonds. And they cover these expenses by income from labour, return on capital stock, profits from firms and any additional savings, which is due at period t. Here, S_t is the nominal exchange rate defined as the domestic currency value of one unit of foreign currency (rise in S indicates nominal depreciation). The term I_t is a gross investment, δ is depreciation rate and capital adjustment cost function $\Gamma()$ is a positive function of changes in investment with the property of:

$$\Gamma_1(\frac{I_t}{I_{t-1}}) = \frac{\partial \Gamma}{\partial I} = -\Gamma'(\frac{I_t}{I_{t-1}})\frac{I_t}{I_{t-1}} + (1 - \Gamma(\frac{I_t}{I_{t-1}}))$$

$$\Gamma_2(\frac{I_t}{I_{t-1}}) = \frac{\partial \Gamma}{\partial I_{t-1}} = \Gamma'(\frac{I_t}{I_{t-1}})(\frac{I_t}{I_{t-1}})^2$$

where Γ_1 is derivative of Γ function with respect to I_t while Γ_2 is derivative with respect to I_{t-1}. The function, Γ, summarises the technology which transforms investment into installed capital. There is empirical evidence as to why adjustment cost has to be included in the model. This specific functional form is motivated by the empirical finding that investment exhibits a hump-shaped response to a monetary policy shock. From equation (3.2), adjustment cost is proportional to the deviation of current investment to its previous value. Thus, it is in the interest of households to smooth out investment as much as possible to avoid "leakage" in capital installment. In other words, a quick rise in investment from past levels is expensive. So that with this specification of Christiano, Eichenbaum, and Evans (2005) (CEE henceforth), the following holds in steady state: $\Gamma(1) = 0$ and $\Gamma'(1) = 0$, thereby allowing adjustment cost to depend on second-order derivative only, $\Gamma"(1) > 0$. The one functional form for Γ that satisfies the above properties is given by:

$$\Gamma(x) = g3\Big(exp[g1(x-\mu^I)] + \frac{g1}{g2}exp[-g2(x-\mu^I)] - (1+\frac{g1}{g2})\Big)$$

where $g1$,$g2$ and $g3$ are constants, $x = \frac{I_t}{I_{t-1}}$ and μ^I is steady-state growth rate of investment.

The preference shock, ε_t^B, labour supply shock, ε_t^{Ns} and investment specific shock, ε_t^I are assumed to follow first order autoregressive process with an i.i.d. normal error term:

$$\varepsilon_t^b = \rho_b \varepsilon_{t-1}^b + \eta_t^b \tag{3.3}$$

$$\varepsilon_t^{Ns} = \rho_{Ns} \varepsilon_{t-1}^{Ns} + \eta_t^{Ns} \tag{3.4}$$

$$\varepsilon_t^I = \rho_i \varepsilon_{t-1}^I + \eta_t^I \tag{3.5}$$

Then the optimisation problem of households in Lagrangian form is:

$$\begin{aligned} L = E_0 \sum_{t=0}^{\infty} \beta^t \varepsilon_t^b [\frac{C_t^{1-\sigma}}{1-\sigma} - \varepsilon_t^{Ns} \frac{N_t^{1+\gamma}}{1+\gamma}] + \lambda_t \Big[\frac{P_{dt}}{P_t} w_t N_t + \frac{Div_t}{P_t} + (1+r_{t-1})\frac{B_{t-1}}{P_t} \\ + \frac{P_{ht}}{P_t}(r_t^K u_t K_{t-1} - \psi(u_t)K_{t-1}) + (1+r_{t-1}^*)\frac{\Phi(f_{t-1})S_t F_{t-1}}{P_t} - C_t - \frac{P_{ht}}{P_t} I_t - \frac{B_t}{P_t} - \frac{S_t F_t}{P_t} - \frac{T_t}{P_t} \Big] \\ + \mu_t \Big[-\tilde{K_t} + (1-\delta)\tilde{K_{t-1}} + [1 - \Gamma(\frac{\varepsilon_t^I I_t}{I_{t-1}})] I_t \Big] \end{aligned} \tag{3.6}$$

where $\beta^t \varepsilon_t^b$ is Lagrange multiplier associated with household budget constraint. The first-order conditions corresponding to $C_t, N_t, B_t, F_t, K_t, K_t, u_t, I_t$

respectively is :

$$C_t: \qquad \varepsilon_t^b C_t^{-\sigma} - \lambda_t = 0 \tag{3.7}$$

$$N_t: \qquad \varepsilon_t^b \varepsilon_t^{Ns} N_t^{\gamma} - \lambda_t \frac{P_{dt}}{P_t} w_t = 0 \tag{3.8}$$

$$B_t: \qquad \frac{-\beta^t \lambda_t}{P_t} + E_t \frac{-\beta^{t+1}\lambda_{t+1}(1+r_t)}{P_{t+1}} = 0 \tag{3.9}$$

$$F_t: \qquad \frac{-\beta^t S_t \lambda_t}{P_t} + E_t \frac{-\beta^{t+1}\lambda_{t+1}(1+r_t^*)S_{t+1}}{P_{t+1}} = 0 \tag{3.10}$$

$$K_t: \qquad E_t \beta^{t+1}\left[\lambda_{t+1}\frac{P_{ht+1}}{P_{t+1}}(r_{t+1}^K u_{t+1} K_t - \psi(u_{t+1})K_t) + \mu_{t+1}(1-\delta)\right] - \beta^t \mu_t = 0 \tag{3.11}$$

$$u_t: \qquad \lambda_t \frac{P_{ht}}{P_t}\Big(r_t^k K_{t-1} - \psi'(u_t) K_{t-1} = 0\Big) \tag{3.12}$$

$$I_t: \qquad \beta_t\left[\lambda_t \frac{P_{ht}}{P_t} + \mu_t\Big(1 - \Gamma(\frac{\varepsilon_t^I I_t}{I_{t-1}}) - \Gamma'(\frac{\varepsilon_t^I I_t}{I_{t-1}})\frac{\varepsilon_t^I I_t}{I_{t-1}}\Big)\right]$$
$$+ E_t \beta_{t+1}\mu_{t+1}\big(-\Gamma"(\frac{\varepsilon_{t+1}^I I_{t+1}}{I_t})\big)\big(-\frac{\varepsilon_{t+1}^I I_{t+1}}{I_t}\big)^2 = 0 \tag{3.13}$$

Substitution of the first-order condition for consumption (3.7) into equation (3.8) determines the labour supply equation, which equates the marginal rate of substitution between consumption and leisure to the real wage. This is an intra-temporal condition:

$$\varepsilon_t^{Ns} N_t^{\gamma} = \frac{P_{dt}}{P_t} w_t C_t^{-\sigma} \tag{3.14}$$

The log-linearised equations can be found in Appendix A. The Euler equation, which describes the inter-temporal substitution in consumption is obtained by combining optimal conditions (3.7) and (3.9):

$$\beta E_t \frac{C_{t+1}^{-\sigma}}{C_t^{-\sigma}} \frac{P_t}{P_{t+1}} \frac{\varepsilon_{t+1}^b}{\varepsilon_t^b}(1+r_t) = 1 \tag{3.15}$$

The Euler equation essentially says that one must be indifferent between consuming one more unit today and saving that unit and consuming it tomorrow. The optimal portfolio allocation between domestic and foreign bonds conditions (3.9 and 3.10, respectively) yields uncovered interest rate parity condition (UIP):

$$(1+r_t) = (1+r_t^*)\frac{E_t \Phi(f_{t-1}) S_{t+1}}{S_t} \tag{3.16}$$

The equation states that the returns on domestic and foreign bonds are identical when measured in the same currency. The current model is solved in Dynare. The UIP condition in the current form ensures stationary net foreign assets in the long-run due to a risk premium term, which takes the form of lagged net foreign asset position. The log-linear form then becomes[4]:

$$lnS_t = lnE_tS_{t+1} - r_t + r_t^* - \phi f_{t-1} \tag{3.17}$$

where I assume that premium on foreign bond holdings is $\Phi(f_{t-1}) = exp(-f_{t-1})$ following the paper by Adolfson, Laséen, et al. (2007). The idea of risk premium originally stems from the paper of (Schmitt-Grohé and Uribe (2004)). The current model has incomplete financial markets implying households access only risk-free foreign bonds whose rate of return is exogenously determined. As a result, the steady-state of the model depends on initial conditions, an initial value of net foreign assets. Consequently, when we simulate the model, the long-run steady-state of the model depends on all accumulation of net foreign debt position starting from t_0. Usually, papers set subjective discount factors equal to real interest rate. If the return on foreign bonds exceeds the discount rate then there is perpetual growth (no steady-state). That is, the impact of transient shocks is everlasting, and the system will contain a random walk element. This is a serious matter as standard techniques in estimation are all about locally convergent stationary path (balanced growth path).

To resolve this problem, economists appealed to a number of modifications that induce stationarity of the equilibrium dynamics. One such technique is debt elastic interest rate. The foreign interest rate now has additional term ϕf_{t-1}. In steady-state, the Euler equation (3.15) implies that $\beta(1 + r^* - \phi f) = 1$ where f is steady-state net debt. Then steady-state net foreign asset position is a function of world interest rate and discount factor.

The first order conditions for capital, investment and utility rate

[4] $lnE_tS_{t+1} = E_tlnS_{t+1} + \frac{Var(\epsilon_t)}{2}$ where $lnS_{t+1} = lnS_t + \epsilon_t$ with $\epsilon_t \sim N(0, \sigma^2)$. Thus, lnE_tS_{t+1} approximates E_tlnS_{t+1} if S_t has a constant error.

can be rearranged as:

$$Q_t = \beta E_t \frac{\lambda_{t+1}}{\lambda_t}\left[Q_{t+1}(1-\delta) + \frac{P_{ht+1}}{P_{t+1}}(r^K_{t+1}u_{t+1}K_t - \psi(u_{t+1})K_t)\right] \quad (3.18)$$

$$\frac{P_{ht}}{P_t} = Q_t\Big(1 - \Gamma(\frac{\varepsilon^I_t I_t}{I_{t-1}}) - \Gamma'(\frac{\varepsilon^I_t I_t}{I_{t-1}})\frac{\varepsilon^I_t I_t}{I_{t-1}}\Big) + \beta E_t Q_{t+1}\frac{\lambda_{t+1}}{\lambda_t}\Gamma"(\frac{\varepsilon^I_{t+1}I_{t+1}}{I_t})(\frac{\varepsilon^I_{t+1}I_{t+1}}{I_t})^2 \quad (3.19)$$

$$\psi'(u_t) = r^K_t \quad (3.20)$$

Equation (3.18) states that the value of the installed capital, Tobin Q, depends on its future value net of depreciation rate and expected future return as rental rate taking into account the cost associated with variation in the degree of capital utilisation. The shadow value of installed capital is defined as the ratio of the marginal value of installed capital, μ_t, and the marginal value of consumption, λ_t. Equation (3.19) determines the motion for the investment function. The current level of investment depends on past as well as future inflation and subject to investment-specific shock.

Equation (3.20) equates the rental rate with the first derivative of a capital utilisation cost function. Under CEE specification, cost function, $\psi(u_t)$ is an increasing and convex function of utilisation rate. The following must hold in steady-state: $u = 1$, $\psi(1) = 0$ and $\psi^" > 0$. Thus, the higher is the rental rate the higher is the utilisation rate implying it is more profitable to use capital intensively. This mechanism also prevents a sharp movement in marginal cost by reducing fluctuations in the rental rate of capital in response to structural shocks, thereby generating persistence in marginal cost.

3.1.2 Static problem of households

The model assumes that domestic resident of UK consumes both home and foreign final goods. The domestic final good market is perfectly competitive whereas the imported final good market is monopolistically competitive. According to the Armington model (Armington 1969), a country consumes both home and foreign goods, which are differentiated purely due to their origins. Thus, households in the home country divide total consumption between domestically produced goods, C_{ht} and imported goods, C_{ft}. By Armington aggregator, the aggregate consumption is a bundle of domestic and foreign goods that can be represented as a constant elasticity of substitution (CES) index given by:

$$C_t = \left[\omega^{\frac{1}{\rho}} (C_{ht})^{\frac{\rho-1}{\rho}} + (1-\omega)^{\frac{1}{\rho}} (C_{ft})^{\frac{\rho-1}{\rho}} \varepsilon_t^{cf} \right]^{\frac{\rho}{\rho-1}} \tag{3.21}$$

where ρ is the elasticity of substitution across consumer goods and ω is home bias in preferences. The value of $\omega > 1/2$ implies a bias towards domestic goods relative to imported consumption goods from the rest of the world. Domestically produced goods and imported goods are perfect substitutes if ρ approaches infinity and complements if ρ is close to zero. And ε_t^{cf} is a random preference shock for foreign consumption goods, which is i.i.d with zero mean. The variable C_{ht} in equation (3.21) is a retail good, which is produced via the combination of intermediate goods imported from abroad and intermediate goods produced domestically, where the latter represents the non-traded products. Therefore, there is a clear distinction between the notion of home bias and the non-traded sector. Due to the monopolistic competition nature of the imported sector, the products are differentiated according to:

$$C_{ft} = \left[\int_0^1 (C_{ft}(j))^{\frac{\kappa-1}{\kappa}} dj \right]^{\frac{\kappa}{\kappa-1}} \tag{3.22}$$

where $\kappa \in [0, \infty]$ represents the elasticity of substitution across differentiated imported consumption goods. The level of consumption C_t is chosen to satisfy the expenditure constraint on consumption:

$$C_{ht}P_{ht} + C_{ft}P_{ft} = P_t C_t \tag{3.23}$$

where P_{ht} denotes the price of home final goods and P_{ft} is the price of imported consumption goods.

Domestic households maximises their total consumption (equation 3.21) subject to constraints (3.22) and (3.23):

$$\begin{aligned}\mathfrak{L} = &\left[\omega^{\frac{1}{\rho}} (C_{ht})^{\frac{\rho-1}{\rho}} + (1-\omega)^{\frac{1}{\rho}} \Big(\left[\int_0^1 (C_{ft}(j))^{\frac{\kappa-1}{\kappa}} dj \right]^{\frac{\kappa}{\kappa-1}} \Big)^{\frac{\rho-1}{\rho}} \varepsilon_t^{cf} \right]^{\frac{\rho}{\rho-1}} \\ &+ \lambda_t \big[P_t C_t - C_{ht}P_{ht} - P_{ft} \left[\int_0^1 (C_{ft}(j))^{\frac{\kappa-1}{\kappa}} dj \right]^{\frac{\kappa}{\kappa-1}} \big]\end{aligned}$$

and the first order conditions are:

$$C_{ht}: \qquad C_t^{\frac{1}{\rho}} \omega^{\frac{1}{\rho}} C_{ht}^{\frac{-1}{\rho}} - \lambda_t P_{ht} = 0 \tag{3.24}$$

$$C_{ft}(j): \qquad C_t^{\frac{1}{\rho}} (1-\omega)^{\frac{1}{\rho}} \varepsilon_t^{cf} C_{ft}^{\frac{\kappa-1}{\kappa}(\frac{\rho-1}{\rho}\frac{\kappa}{\kappa-1}-1)} C_{ft}^{-\frac{1}{\kappa}}(j) - \lambda_t P_{ft} C_{ft}^{\frac{\kappa-1}{\kappa}\frac{1}{\kappa-1}} C_{ft}^{\frac{-1}{\kappa}}(j) = 0 \tag{3.25}$$

The latter equation then simplifies to:

$$\begin{aligned} C_t^{\frac{1}{\rho}} (1-\omega)^{\frac{1}{\rho}} \varepsilon_t^{cf} C_{ft}^{\frac{\rho-1}{\rho\kappa}} C_{ft}^{-\frac{1}{\kappa}}(j) &= \lambda_t P_{ft} C_{ft}^{\frac{1}{\kappa}} C_{ft}^{-\frac{1}{\kappa}}(j) \\ C_t^{\frac{1}{\rho}} (1-\omega)^{\frac{1}{\rho}} \varepsilon_t^{cf} &= \lambda_t P_{ft} C_{ft}^{\frac{1}{\rho}} \end{aligned} \tag{3.26}$$

Combining equations (3.24) and (3.26) yields:

$$\left(\frac{\omega}{1-\omega}\right)^{\frac{1}{\rho}} \left(\frac{C_{ft}}{C_{ht}}\right)^{\frac{1}{\rho}} \frac{1}{\varepsilon_t^{cf}} = \frac{P_{ht}}{P_{ft}}$$

Multiplying both sides by $\frac{C_{ht}}{C_{ft}}$, using (3.21) and finally rearranging equation generates the optimal condition for foreign and home consumption, respectively:

$$C_{ht} = \omega(\frac{P_{ht}}{P_t})^{-\rho} C_t \tag{3.27}$$

$$C_{ft} = (1-\omega)(\frac{P_{ft}}{P_t})^{-\rho} C_t \varepsilon_t^{cf} \tag{3.28}$$

The domestic demand for home goods is proportional to total consumption, C_t and negatively depends on its own relative price where the weight is the elasticity of substitution between home and foreign goods. According to equation (3.28), the higher is the elasticity the higher is the impact of relative prices on import consumption. Thus, the higher is the elasticity of substitution, the higher is the expenditure switching effect of the nominal exchange rate (higher pass-through as well). This is a desirable quality of the model especially when the prices are sticky: movements in nominal exchange rate adjusts relative prices and hence the smoother adjustment is achieved in quantities. The same argument can be applied for pass-through to final consumer prices. If the effect of expenditure switching is large, then the higher is the pass-through to CPI (because larger shifts in quantities drive larger movement in prices[5]). However, the model assumes local currency pricing in all markets. So, foreign exporters set the import prices in pounds and these

[5]Chapter 7, domestic demand channel of shock effects

prices are rigid as well. Thus, the effect of nominal exchange on the domestic economy is limited.

Substituting optimal conditions to (3.23) yields aggregate consumer price index in home country:

$$P_t = [\omega P_{ht}^{1-\rho} + (1-\omega) P_{ft}^{1-\rho}]^{\frac{1}{1-\rho}}$$

The log-linearised version of this equation is:

$$P_t = \omega P_{ht} + (1-\omega) P_{ft} \tag{3.29}$$

Equation (3.29) is one of the key equations determining the pass-through degree. It states that the final consumer price is a weighted average of home and imported consumer price goods, where the weight is a home bias parameter. Firstly, the estimated home bias parameter is highly likely to influence the pass-through degree to a certain extent. Assuming higher pass-through degree to import prices[6], the pass-through estimate is proportional to the openness parameter. Secondly, since the price of the domestic final product, P_{ht}, is a weighted average of intermediate goods' prices[7], the pass-through degree depends on how nominal exchange rate passes through the marginal cost. Thus, any disturbances that shift the marginal cost of intermediate producers increase the pass-through degree.

3.2 Firms

3.2.1 Domestic retailers

It is common in the general equilibrium model that tradable goods reach final consumers through distribution (Burstein, Neves, and Rebelo (2003), Dedola and Leduc (2004)). In these models, the distribution sector produces final consumer goods by combining non-traded home goods (including distribution and other local services) with intermediate foreign goods. In the present model, we do not explicitly have a non-tradable sector. However, the domestic component of the

[6] Conclusion made by all literature

[7] Next section reveals that it is a weighted average of home and imported intermediate goods' prices

final retail product that is not subject to any foreign trade is considered as a non-tradable good. Put it differently, home retailers combine a fixed proportion of domestic non-traded goods with foreign inputs to produce retail goods. The final good, Y_{ht}, is composite of intermediate domestic goods, Y_{dt}, and imported intermediate goods, Y_{mt}. Here Y_{dt} reflects non-traded goods-the goods exclusively traded in the domestic market. These perfectly competitive bundlers combine these inputs using Leontief technology, to produce final consumption goods, which they sell domestically to households and the government. Leontief technology provides zero elasticity of substitution between two different inputs. According to Burgess et al. (2013), the Leontief approach is probably a reasonable approximation to reality in the short run.

$$Y_{ht} = min[\frac{Y_{dt}}{\upsilon}, \frac{Y_{mt}}{1-\upsilon}] \tag{3.30}$$

where υ represents the share of home inputs in final production. Since final producers act in perfect competition, they take prices as given. The minimisation of cost problem yields optimal demand for each inputs, which are linear function of final good, Y_{ht}:

$$Y_{dt} = \upsilon Y_{ht} \tag{3.31}$$

$$Y_{mt} = (1-\upsilon) Y_{ht} \tag{3.32}$$

where the budget constraint for final good producers is:

$$P_{ht}Y_{ht} = P_{dt}Y_{dt} + P_{mt}Y_{mt} \tag{3.33}$$

According to a zero-profit condition of final good firms, substitution of optimal input demand functions (3.31 and 3.32) to (3.33) yields:

$$P_{ht} = \upsilon P_{dt} + (1-\upsilon) P_{mt} \tag{3.34}$$

Equation (3.34) underlines an additional exchange rate pass-through channel via imported input prices and marginal cost. However, the imported input price, P_{mt} is a small proportion of the final retail price[8], and hence its movement is partially reflected in the latter. As discussed in previous literature by Smets and Raf Wouters (2002), Corsetti and Dedola (2005) and Jeanfils (2008), the introduction of imported inputs affect the degree of transmission of exchange rate movements along the

[8] Literature calibration is between 0.5-20% while our estimation is 33%

pricing chain. Given that pass-through to import prices are high, the introduction of imported inputs should increase the pass-through degree. Nevertheless, the effects of disturbances that pass through marginal cost channel have a relatively larger impact on CPI.

Prior to combining aggregate inputs, retailers act as assemblers since they bundle each differentiated intermediate goods into aggregate inputs using constant elasticity of substitution (CES) function:

$$Y_{dt} = \left[\int_0^1 (Y_{dt}(j))^{\frac{\chi_d - 1}{\chi_d}} dj \right]^{\frac{\chi_d}{\chi_d - 1}} \tag{3.35}$$

where $\chi_d \in [0, \infty]$ is elasticity of substitution across differentiated domestic intermediate goods. Similarly, the aggregate imported inputs has the following CES form:

$$Y_{mt} = \left[\int_0^1 (Y_{mt}(j))^{\frac{\chi_m - 1}{\chi_m}} dj \right]^{\frac{\chi_m}{\chi_m - 1}} \tag{3.36}$$

with $\chi_m \in [0, \infty]$ reflecting the elasticity of substitution across differentiated imported intermediate goods. Thus, the optimal demand for each home intermediate good is[9]:

$$Y_{dt}(j) = (\frac{P_{dt}(j)}{P_{dt}})^{-\chi_d} Y_{dt}$$

Similarly, the demand for imported intermediate good is:

$$Y_{mt}(j) = (\frac{P_{mt}(j)}{P_{mt}})^{-\chi_m} Y_{mt}$$

Finally, the total demand for final goods are delivered to households as consumption and investment goods; and to government:

$$Y_{ht} = C_{ht} + I_t + G_t + \psi(u_t) K_{t-1} \tag{3.37}$$

where it is assumed that capital utilisation costs are in terms of domestic final goods.

[9] Derivation is in Appendix E

3.2.2 Domestic intermediate good producers

Following the paper by Le, Meenagh, and Minford (2012), I employ a hybrid model for domestic intermediate goods producers as it gets closest in matching the data. According to this model, the majority of home producers operate under perfect competition while the rest is subject to nominal contracts. In other words, the hybrid model merges the New Keynesian (NK) and New Classical models (NC) by assuming that price setters find themselves supplying intermediate output partly in a competitive market with flexible prices, and partly in a market with imperfect competition. Thus, the price-setting equation for domestic intermediate good producers is a weighted average of NC and NK Phillips Curves.

There is a continuum of domestic producers indexed by $j \in [0, 1]$, each producing distinct home intermediate goods using capital and labour as inputs and exposed to stochastic technology growth. The produced good is then delivered to domestic and foreign retailers where the latter represents the exporting sector. The intermediate home goods are produced with a Cobb-Douglas technology:

$$Y_t(j) = A_t \tilde{K_t^{\alpha}}(j) N_t^{1-\alpha} - \Phi_y \tag{3.38}$$

where A_t is a unit root productivity shock, $A_t = \alpha + A_{t-1} + \rho(A_{t-1} - A_{t-2}) + \eta_t^a$; $\tilde{K}_t = u_t K_{t-1}$ is the effectively utilised capital stock, N_t is homogeneous labour hired by firm, and Φ_y is a fixed cost enabling zero profits in steady state. Since the intermediate good producers are subject to exogenous price-setting shock, they cannot freely adjust prices to maximise profits, but will always act to minimise the cost. The minimisation problem for these firms then is:

$$\min_{N_t, \tilde{K_t(j)}} \quad w_t N_t + r_t^K \tilde{K_t(j)} - \lambda_t (Y_t - A_t \tilde{K_t^{\alpha}}(j) N_t^{1-\alpha} - \Phi_y)$$

Then first order conditions with respect to N_t and $\tilde{K}_t$ are:

$$w_t - \lambda_t (1-\alpha) A_t \tilde{K_t^{\alpha}}(j) N_t^{-\alpha} = 0 \tag{3.39}$$

$$r_t^K - \lambda_t \alpha A_t \tilde{K_t^{\alpha-1}}(j) N_t^{1-\alpha} = 0 \tag{3.40}$$

The Lagrangian parameter, λ_t, represents the real marginal cost, which is derived by combining equations (3.39) and (3.40):

$$mc_t = \frac{w_t^{1-\alpha} {r^K}_t^\alpha}{A_t(1-\alpha)^{1-\alpha}\alpha^\alpha} \tag{3.41}$$

Exporting sector

Intermediate home good, Y_t is supplied to domestic and foreign retail markets in a manner of monopolistic competition:

$$Y_t = Y_{dt} + X_t \tag{3.42}$$

Similar to equation (3.35), optimal export demand for each differentiated good is:

$$X_t(j) = (\frac{P_{xt}(j)}{P_{xt}})^{-\chi_x} X_t \tag{3.43}$$

where $\chi_x \in [0, \infty]$ is elasticity of substitution across differentiated exporting goods. Furthermore, as the UK economy is small relative to the foreign economy, the export sector accounts for a negligible size of the whole world economy. Therefore, the aggregate demand for export can be written as[10]:

$$X_t = (\frac{P_{xt}}{P_t^*})^{-\rho_f} \varepsilon_t^x Y_t^* \tag{3.44}$$

where the shock to export demand is assumed to be transient shock, $\varepsilon_t^x = \rho_x \varepsilon_{t-1}^x + \eta_t^x$. The foreign variables, P^* and Y^*, are world price and world output respectively, which are exogenous in the model. They are defined as the first-order autoregressive process with an i.i.d. normal error terms (log-linear form):

$$lny_t^* = \rho_{yf} lny_{t-1}^* + ln\varepsilon_t^{yf} \tag{3.45}$$

$$lnp_t^* = \rho_{pfo} lnp_{t-1}^* + ln\varepsilon_t^{pfo} \tag{3.46}$$

Price-setting behaviour of firms The fraction, τ, of domestic firms are subject to price stickiness through Calvo (1983) model, whereas the remaining firms operate under a competitive market following a similar setup by Le, Meenagh, and Minford (ibid.). Thus, in every period, a fraction τ of intermediate firm faces a probability $1 - \xi_d$ that it can reset its price. On the other hand, those firms that are not allowed to re-optimise their price are allowed for partial indexation to

[10]Derivation is similar to Appendix E

last period's inflation rate (Adolfson, Laseen, et al. (2004)):

$$P_{dt}(j) = \left(\frac{P_{d,t-1}}{P_{d,t-2}}\right)^{\varphi_d} P_{d,t-1}(j) \tag{3.47}$$

where φ_d is indexation parameter. This mechanism facilitates a lagged term in the Phillips curve. The paper assumes that exporting sector operates under a monopolistic competition using a local currency pricing and hence they deliver domestic intermediate goods to foreign retailers at foreign prices. Therefore, a firm with price-setting power will maximize its expected profit stream, using the household's marginal utility, Λ_t, as the discount factor. The re-optimised new price is $P^{\sharp}_{dt}$ and $P^{\sharp}_{xt}$ for domestic intermediate firms and exporters, respectively. If firms with probability $\xi_d(\xi_x)$ are not allowed to change their prices during t periods, the price in period t will be $\prod_{k=1}^{t} \pi_{d,k-1}^{\varphi_d} P^{\sharp}_{dt} = \frac{P_{d,t-1}}{P_{d,0}} P^{\sharp}_{dt}$ ($\prod_{k=1}^{t} \pi_{x,k-1}^{\varphi_x} P^{\sharp}_{xt} = \frac{P_{x,t-1}}{P_{x,0}} P^{\sharp}_{xt}$), where π_d and π_x are domestic and exporting intermediate goods inflation. The firm who does not reset its prices for t periods ahead faces the following optimisation problem:

$$Max \sum_{t=0}^{\infty}(\beta\xi_d)^t\Lambda_t[(P^{\sharp}_{dt}\prod_{k=1}^{t}\pi_{d,k-1}^{\varphi_d} - mc_t^N)Y_{jt}^d] + \sum_{t=0}^{\infty}(\beta\xi_x)^t\Lambda_t[(S_t P^{\sharp}_{xt}\prod_{k=1}^{t}\pi_{x,k-1}^{\varphi_x} - mc_t^N)X_{jt}]$$

subject to

$$Y_{dt}(j) = (\frac{P^{\sharp}_{dt}\prod_{k=1}^{t}\pi_{d,k-1}^{\varphi_d}}{P_{dt}})^{-\chi_d} Y_{dt} \tag{3.48}$$

$$X_t(j) = (\frac{P^{\sharp}_{xt}\prod_{k=1}^{t}\pi_{x,k-1}^{\varphi_x}}{P_{xt}})^{-\chi_x} X_t \tag{3.49}$$

Λ_t is the marginal utility of the households' nominal income, which is exogenous to intermediate firm; export price, P_{xt}, is priced in foreign currency (LCP), $P^{\sharp}_{dt}$ is a new price of domestic intermediate goods, which cannot be reset for t periods, the re-optimised price for exporting goods is $P^{\sharp}_{xt}$, mc_t^N is nominal marginal cost defined in equation (3.41), φ_d and φ_x are price indexation parameters for home and exporting goods, respectively. Similarly, exporting firms will be able to adjust its price with a probability $1-\xi_x$ in the following period. The nominal exchange rate is S_t (increase means depreciation). The details about Phillips Curve derivation can be found in Appendix F. Exporting firms care about relative price between their own and aggregate export price in a foreign market, as well as domestic price, P_{dt}. The fraction, ξ_x, of exporting firms who are unable to change their price also index their price to previous inflation:

$$P_{xt}(j) = \left(\frac{P_{x,t-1}}{P_{x,t-2}}\right)^{\varphi_x} P_{x,t-1}(j) \tag{3.50}$$

The New Keynesian Phillips Curve that describes the price-setting behaviour of monopolistic intermediate good producers takes the following log-linear form:

$$\begin{aligned}\pi_{dt}^{NK} =& \frac{\beta}{1+\beta\varphi_d}E_t\pi_{dt+1} + \frac{\varphi_d}{1+\beta\varphi_d}\pi_{dt-1} \\ &+ \frac{(1-\xi_d)(1-\beta\xi_d)}{\xi_d(1+\beta\varphi_d)}(\alpha r_t^K + (1-\alpha)lnw_t - lnA_t) + ln\varepsilon_t^{Pd}\end{aligned}$$

where ε_t^{Pd} is markup shock to domestic intermediate goods. Since the remaining $1-\tau$ firms set prices competitively, the dynamics of the producer price inflation in the domestic intermediate goods sector is:

$$\begin{aligned}\pi_{dt} =& \tau\Bigg[\frac{\beta}{1+\beta\varphi_d}E_t\pi_{dt+1} + \frac{\varphi_d}{1+\beta\varphi_d}\pi_{dt-1} + \frac{(1-\xi_d)(1-\beta\xi_d)}{\xi_d(1+\beta\varphi_d)} \\ &(\alpha r_t^K + (1-\alpha)lnw_t - lnA_t) + ln\varepsilon_t^{Pd}\Bigg] + (1-\tau)[\alpha r_t^K + (1-\alpha)lnw_t - lnA_t]\end{aligned} \tag{3.51}$$

The paper assumes that the main reason for a sluggish response of prices relative to exchange rate movements is due to price rigidity. Since all intermediate sectors operate in a monopolistically competitive market, this phenomenon is captured by Calvo parameter, ξ. A higher Calvo parameter reduces the frequency of price revisions, and hence lowers the pass-through of exchange rate to CPI in the short-run. However, as time elapses after a given structural shock, the proportion of firms that have been allowed to adjust prices increases, and the pass-through degree converges to one. Similarly, NKPC for exporters is:

$$\begin{aligned}\pi_{xt} =& \frac{\beta}{1+\beta\varphi_x}E_t\pi_{xt+1} + \frac{\varphi_x}{1+\beta\varphi_x}\pi_{xt-1} + \frac{(1-\xi_x)(1-\beta\xi_x)}{\xi_d(1+\beta\varphi_x)} \\ &(\alpha r_t^K + (1-\alpha)lnw_t - lnA_t - lnS_t - lnP_{xt} + lnP_{dt}) + ln\varepsilon_t^{Px}\end{aligned} \tag{3.52}$$

3.2.3 Import sector

In this section, I describe the importing sector and report its relevant equations. There are an infinite number of foreign firms directly selling their goods to households, C_{ft}, and to domestic final producers, Y_{mt}. These firms operate under monopolistic competition and set prices in the local market (LCP). The total foreign goods consist of a CES aggregator and dedicated for consumption and production purposes:

$$M_t = \left[\theta^{\frac{1}{\eta}}(C_{ft})^{\frac{\eta-1}{\eta}} + (1-\theta)^{\frac{1}{\eta}}(Y_{mt})^{\frac{\eta-1}{\eta}}\right]^{\frac{\eta}{\eta-1}} \tag{3.53}$$

Parameter, θ, accounts for the share of imported goods dedicated to direct consumption and η is the elasticity of substitution between two types of imported goods. The total import volume M_t satisfies the expenditure constraint:

$$Y_{mt}P_{mt} + C_{ft}P_{ft} = P_t^M M_t \tag{3.54}$$

where P_{mt} denotes the price of imported intermediate goods, P_{ft} is the price of imported consumption goods and P_t^M is the price of total imports. The importer's problem is to maximise their total imports (equation 3.53) subject to the constraint (3.54). Then Lagrangian problem is:

$$\begin{aligned}\mathfrak{L} = &\left[\theta^{\frac{1}{\eta}}(C_{ft})^{\frac{\eta-1}{\eta}} + (1-\theta)^{\frac{1}{\eta}}(Y_{mt})^{\frac{\eta-1}{\eta}}\right]^{\frac{\eta}{\eta-1}} \\ &+ \lambda_t\big[P_t^M M_t - Y_{mt}P_{mt} - P_{ft}C_{ft}\big]\end{aligned}$$

and the first order conditions are:

$$C_{ft}: \qquad C^{\frac{1}{\eta}}\theta^{\frac{1}{\eta}}C_{ft}^{\frac{-1}{\eta}} - \lambda_t P_{ft} = 0 \tag{3.55}$$

$$Y_{mt}: \qquad C^{\frac{1}{\eta}}(1-\theta)^{\frac{1}{\eta}}Y_{mt}^{\frac{-1}{\eta}} - \lambda_t P_{mt} = 0 \tag{3.56}$$

Combining equations (3.55) and (3.56), then multiplying both sides by $\frac{C_{ft}}{Y_{mt}}$, using (3.53) and finally rearranging equation generates the optimal condition for each type of imported goods:

$$C_{ft} = \theta(\frac{P_{ft}}{P_t^M})^{-\theta}M_t \tag{3.57}$$

$$Y_{mt} = (1-\theta)(\frac{P_{mt}}{P_t^M})^{-\theta} M_t \tag{3.58}$$

Then, the price associated with aggregate import (log-linear version[11]) is derived by substituting equations (3.57) and (3.58) to (3.54) :

$$lnP_t^M = \theta lnP_{ft} + (1-\theta) lnP_{mt} \tag{3.59}$$

where P_t^M, aggregate import price, is a weighted average of imported consumption good price and imported input price.

All imported good producers are monopolistic competitors that sell their differentiated goods to domestic households and final good producers, and their price-setting behaviour mimics those of their domestic competitors. Therefore, the fraction of imported final good producers (imported input producers) that are able to reset their price is $1-\xi_f$ $(1-\xi_m)$ whereas the remaining firms index the price to previous inflation:

$$P_{ft}(j) = \left(\frac{P_{f,t-1}}{P_{f,t-2}}\right)^{\varphi_f} P_{f,t-1}(j) \tag{3.60}$$

$$P_{mt}(j) = \left(\frac{P_{m,t-1}}{P_{m,t-2}}\right)^{\varphi_m} P_{m,t-1}(j) \tag{3.61}$$

where φ_f (φ_m) is indexation parameter. Each type of these firms maximise their lifetime profit in a similar manner as domestic intermediate good producers:

$$Max \sum_{t=0}^{\infty} (\beta\xi_f)^t \Lambda_t[(P_{ft}^{\sharp} \prod_{k=1}^{t} \pi_{f,k-1}^{\varphi_f} - S_t mc_t^*) C_{ft}(j)] + \sum_{t=0}^{\infty} (\beta\xi_m)^t \Lambda_t[(P_{mt}^{\sharp} \prod_{k=1}^{t} \pi_{m,k-1}^{\varphi_m} - S_t mc_t^{m*}) Y_{mt}(j)]$$

subject to optimal demands for imported goods:

$$C_{ft}(j) = (\frac{P_{ft}^{\sharp} \prod_{k=1}^{t} \pi_{f,k-1}^{\varphi_f}}{P_{ft}})^{-\chi_f} C_{ft}$$

$$Y_{mt}(j) = (\frac{P_{mt}^{\sharp} \prod_{k=1}^{t} \pi_{m,k-1}^{\varphi_m}}{P_{mt}})^{-\chi_m} Y_{mt}$$

here we used the fact that foreign exporters set prices in local markets (LCP), π_{ft} and π_{mt} are imported consumer goods inflation and imported intermediate goods inflation, respectively. Following Adolfson, Laséen, et al. (2007), since I modeled foreign economy as exogenous process,

[11] Derivation is similar to equation 3.29

I assumed that marginal costs are $mc_t^* = lnP_t^* + lnS_t - lnP_{ft}$ and $mc_t^{m*} = lnP_t^* + lnS_t - lnP_{mt}$ for imported consumption and imported input firms, respectively. This allows foreign firms to operate under perfect competition[12]. The corresponding NKPC for both importers are (log-linear form):

$$\pi_{ft} = \frac{\beta}{1+\beta\varphi_f}E_t\pi_{ft+1} + \frac{\varphi_f}{1+\beta\varphi_f}\pi_{ft-1} + \frac{(1-\xi_f)(1-\beta\xi_f)}{\xi_f(1+\beta\varphi_f)}(lnP_t^* + lnS_t - lnP_{ft}) + ln\varepsilon_t^{Pf} \tag{3.62}$$

$$\pi_{mt} = \frac{\beta}{1+\beta\varphi_m}E_t\pi_{mt+1} + \frac{\varphi_m}{1+\beta\varphi_m}\pi_{mt-1} + \frac{(1-\xi_m)(1-\beta\xi_m)}{\xi_m(1+\beta\varphi_m)}(lnP_t^* + lnS_t - lnP_{mt}) + ln\varepsilon_t^{Pm} \tag{3.63}$$

where φ_m and φ_f parameters reflect indexation parameters; ξ_m and ξ_f represent the probability of not-resetting the price.

Equations (3.51), (3.52), (3.62) and (3.63) clearly show that as the price rigidity becomes severe, the parameter ξ is increasing, the lower is the pass-through degree of exchange rate to both import price and CPI. The same argument can be applied for indexation parameters, φ, as the value of coefficient increases the effect of exchange rate on prices lowers as the slope of the Phillips Curve is declining. Nevertheless, using iterations or lag parameter, we can deduce that inflation is a weighted sum of current and future marginal costs:

$$\pi_t = \alpha_1\pi_{t-1} + \alpha_2\sum_{k=0}^{T}(\beta)^k E_t mc_{t+k} \tag{3.64}$$

Therefore, the impact of the exchange rate transmits through expectational variables. The forward-looking nature of the model therefore offsets some effect of price rigidity on a pass-through degree.

[12] I assume this is a reasonable assumption since the size of the world economy is large

3.3 Monetary Policy

The behaviour of the central bank is approximated with Taylor rule, which specifies how central bank adjusts the short term nominal interest rate in response to inflation and output gap:

$$\frac{r_t}{r_{ss}} = \left(\frac{r_{t-1}}{r_{ss}}\right)^{\mu} \left[(\frac{\pi_t}{\pi_{ss}})^{r_p} (\frac{y_t}{y_{ss}})^{r_y} \right]^{1-\mu} \left(\frac{\frac{y_t}{y_{t-1}}}{\frac{y_t^*}{y_{t-1}^*}}\right)^{r_{\triangle y}} \left(\frac{\frac{\pi_t}{\pi_{t-1}}}{\frac{\pi_t^*}{\pi_{t-1}^*}}\right)^{r_{\triangle p}} \varepsilon_t^r \tag{3.65}$$

where π_t is consumer price inflation, ε_t^r follows AR(1) process with i.i.d shock.

3.4 Government

The government in this economy collects lump sum tax revenues from households, issues government bonds,B_t, and spends resources on government consumption of the final domestic good, G_t, so that the budget is balanced each period. Therefore, the government budget constraint is given by:

$$G_t + (1 + r_{t-1})B_{t-1} = B_t + T_t \tag{3.66}$$

3.5 Market Clearing and Net Foreign asset evolution

The consolidated budget constraint of households (equation 3.1) generates the accumulation of net foreign assets. The combination of household budget constraint with government resource constraint (equation 3.66) and using the fact that total cost of final good producers is $P_{ht}Y_{ht} = P_{dt}Y_{dt} + P_{mt}Y_{mt}$, gives us the evolution of net foreign assets:

$$\frac{S_tF_t}{P_t} - \frac{S_tF_{t-1}}{P_t}(1 + r_{t-1}^*) = \frac{S_tP_{xt}}{P_t}X_t - \frac{P_t^M}{P_t}M_t \tag{3.67}$$

Defining the real foreign debt as debt to GDP ratio

$$f_t = \frac{S_tF_t}{P_tY_t}$$

where f_t is real debt to output ratio. The log-linear approximation around steady-state is:

$$f_t = \frac{1}{1+g}[f_{t-1}(1+r)+fr^*_{t-1}]+\frac{X}{Y}(lnS_t+lnP_{xt}+lnX_t-lnP_t)-\frac{M}{Y}(lnP^M_t+lnM_t-lnP_t) \tag{3.68}$$

According to Le, Meenagh, Minford, and Wickens (2015), a transversality condition is required to achieve a balanced growth equilibrium in which individuals cannot borrow or lend abroad forever. This condition imposes a restriction on the balance of payment that change in net foreign assets must be zero, $\triangle f_t = 0$. In the long-run (time period T) when the real exchange rate converges to its steady-state, any remaining debt has to be balanced by trade surplus.

The real resource constraints ensure that supply equals demand. The aggregate resource constraint at the level of intermediate good producers is:

$$\begin{aligned} Y_t &= \int Y_t(j).dj = \int (X_t(j) + Y_{dt}(j)).dj = s_{xt}X_t + \upsilon s_{dt}Y_{ht} = s_{xt}X_t + \frac{\upsilon}{1-\upsilon}s_{dt}Y_{mt} \\ &= s_{xt}X_t + \frac{\upsilon}{1-\upsilon}s_{dt}(M_t - C_{ft}) = s_{xt}X_t + \frac{\upsilon}{1-\upsilon}s_{dt}(M_t - C_t + C_{ht}) \\ &= s_{xt}X_t + \frac{\upsilon}{1-\upsilon}s_{dt}(M_t - C_t + Y_{ht} - I_t - G_t - \psi(u_t)K_{t-1}) \\ &= s_{xt}X_t + \frac{\upsilon}{1-\upsilon}s_{dt}(M_t - I_t - G_t - \psi(u_t)K_{t-1}) + \frac{\upsilon}{1-\upsilon}s_{dt}Y_{ht} \\ &= s_{xt}X_t + \frac{\upsilon}{1-\upsilon}s_{dt}(M_t - I_t - G_t - \psi(u_t)K_{t-1}) + \frac{1}{1-\upsilon}s_{dt}(Y_t - s_{xt}X_t) \end{aligned} \tag{3.69}$$

Rearranging (3.69) yields the resource constraint:

$$Y_t = s_{dt}(I_t + G_t) + s_{xt}X_t - s_{dt}M_t + \psi(u_t)K_{t-1} \tag{3.70}$$

where s_{dt} is price dispersion and the followings have been used to derive equation (3.69):

- First line used optimal demand for intermediaries, equations (3.31) and (3.32)
- Second line used the fact that aggregate consumption is composite of home and foreign goods, equation (3.23)
- Third line employed equation (3.37)

Chapter 4

Data description

The data included in the study covers the period between the first quarter of 1989 and the last quarter of 2016. This time horizon captures major events such as sterling leaving Exchange Rate Mechanism in 1992, and the aftermath of this foreign exchange crisis is Bank of England adopting inflation targeting rule. Later in 1997 the institution updated its framework by lowering its target rate. There is also a turbulent period of financial crisis around 2008, and the decision of UK leaving EU borders commencing in 2016. These episodes in UK history had a huge impact on both the dynamics of exchange rate and inflation and hence the pass-through degree.

The data are seasonally adjusted and in real terms unless specified alternatively (nominal interest rate and nominal exchange rate). The data is unfiltered. Macroeconomics data are generally non-stationary, which makes long-term aspects of the economy hold some uncertainties. Economists responded by filtering out trends (deterministic and stochastic elements) from the data thereby making it stationary. The most known filter is Hodrick- Prescott (HP) for example. The HP filter separates the time series into a trend and cyclical component. The trend is extracted by smoothing method using two-sided moving average, where smoothness parameter is arbitrarily fixed. According to Canova(2014), HP filter generates spurious autocorrelations and variability in a single data and spurious comovement between series. So it changes the properties of the data completely.

The majority of techniques for filtering the data are not based on theories used in models but rather based on statistical properties of data. The history illustrates several events (recent financial crisis and Great Recession) where the economic activity may resume its growth rate but cannot recover its previous long-run trend. Such experiences indicate the non-neutrality of random disturbances hitting the economy. This also implies their effect as cyclical swings might be mistaken for trends. As a result, they will be removed by filters. Moreover, stationary data might lose important interactions between variables; hence it is better not to remove the stochastic trend from the model. Moreover, the main aim of the current thesis is to evaluate the performance of the model. Therefore, it is more conclusive to test the model on original data.

To estimate or test the model using known methodologies we allow for a cointegrated relationship of variables with non-stationary variables to make residuals stationary. Then, we employ Vector Error Correction Mechanism (VECM). The details are specified in the following chapters.

The source of data was obtained from the following resources: the UK office of National Statistics (ONS), Bank of England and Federal Reserve Bank of St. Louis (FRED)[1].

[1] Appendix D

Chapter 5

Estimation and Model testing

Friedman(1953) proposed the use of simple and smaller models than traditional macroeconometric models, which implies that DSGE models are likely to be misspecified. Thus, Lucas and Prescott found that testing DSGE model using classical procedures lead to the rejection of too many good models. As a consequence, the model is started to be calibrated rather than estimated, and their testing applied the comparison of moments rather than formal statistical test. The calibration of models is based on the idea that the DSGE models are inherently false and hence the model cannot be regarded as a null hypothesis to be statistically tested (Canova, 1994). Since then testing the empirical performance of the DSGE model became one of the unresolved issues in macroeconomics.

None of the current macroeconomic models can be regarded as true model since the reality is unknown. The idea is whether this approximately true model is a good representation of the sample data (Meenagh, Minford, and Wickens (2012), Minford, Wickens, and Y. Xu (2016)). Therefore, the Indirect Inference (IIW) test measures "how true is the false model?", and computes the probability of rejecting the false model. The power of a test is greater if the falseness of parameters rises along with the frequency of being rejected. Suppose that the true model is more complex than a pseudo-true designed model. Then how can we detect if our model is a good approximation? The actual model that is being tested is VAR model, which itself is an approximation to pseudo-true DSGE model. Thus, if the model passes the test then this implies that we could use a simpler DSGE model as a proxy for more complex models, as both models will yield exactly the same test results.

A common approach on testing the macroeconomic model is to calculate and compare (informally) moments derived from the model's simulated data to those extracted from sample data. In other words, the approach is based on replicating some stylised facts (Kydland and Prescott (1982)). The Indirect Inference (IIW), on the other hand, formally assesses the distance between statistics. The test compares the behaviour of variables as summarised by an auxiliary model (instead of moments).

Thus, we employ Indirect Inference as a method for testing and estimating the DSGE model by comparing simulated data behaviour with the behaviour of actual data. The previous literature by Le, Meenagh, Minford, and Wickens (2015) and a survey by Minford, Wickens, and Y. Xu (2016) on Indirect Inference affirm that this test has more power than LR test against both mis-specified models and models with wrong parameters. The information on data behaviour is retained in an auxiliary model such as VAR model of low order in few variables. Unlike other simulation-based methods, Indirect Inference employs an auxiliary model to capture the important features of the data we are focused on. The VAR model has been selected as an auxiliary model because DSGE models can be reduced to a restricted VAR model. Hence, the comparison will be made between descriptive statistics of unrestricted and restricted VAR models such as Impulse Response Functions or VAR coefficients where the unrestricted VAR represents the behaviour of actual data.

In estimation, the structural parameters are chosen to match the estimates of VAR model based on simulation data with those based on actual data. Therefore, the procedure for finding optimal parameters involves minimising the distance between estimates of VAR coefficients. On the other hand, under evaluation, the structural parameters are taken as given. They could be estimated using IIW or the Bayesian technique. The null hypothesis of the test is that model under consideration is a true representation of the sample data. The auxiliary model is then estimated for each data generated by simulating the structural model many times yielding the distribution of statistics. Then the actual data-based estimate occurs with a certain probability within this distribution. The test rejects the model if the probability metric lies below the test threshold.

The earlier literature on IIW confirms that Indirect Inference is superior to Bayesian and MLE methods as an estimation tool, and dominates LR and Bayes factor techniques as a testing tool. The estimation by IIW generates a little bias in small samples as opposed to MLE as the higher power of the test rejects false parameter values. This is because MLE chooses structural parameters that will fit dynamics in the observed data thereby missing the long-run characteristics of the model. In other words, there is a presence of strong data-mining elements in classical testing procedures. As a result, it will generate parameters not compatible with economic theory. The use of Bayesian techniques reaches the consensus by using a weighted average of prior knowledge and likelihood functions. However, Bayesian estimate assumes the validity of model specification and prior information, which itself has to be tested. Bayesian does not test the model as a whole but check the improvements conditional on prior distributions and the model structure.

In terms of testing models, LR evaluates the overall fit of the model whereas IIW can be tailored to specific properties of an auxiliary model. That is, we are testing particular features of DSGE model we are interested in by employing "Directed" Wald test. The point is if we test a whole model (full reduced VAR) under IIW test then it will certainly be rejected as models do not meant to capture all relationships in the data. The intuition is that models are constructed in such a way that captures certain features of the data; hence, they cannot grasp all features and therefore are being rejected by conventional hypothesis tests on the basis that they cannot explain inessential features. For this reason, IIW test focuses on replicating the feature of interest we are observing in the sample data by choosing few variables as a basis for an auxiliary model.

The additional power of IIW test under a numerically incorrect model comes from the distribution of VAR coefficients that is based on simulated data that the structural model implies. In contrast, LR test uses the distribution implied by observed data as opposed to the restricted model. In the case with mis-specified model, under LR test, the model is re-estimated by MLE with unrestricted errors[1]. Since LR test is heavily biased towards fitting the data, LR produces new autoregressive coefficients thereby offsetting the effect of the falseness of structural parameters. In other words, it is hard to distinguish between true and mis-specified models as the re-estimated error process absorbs all mis-specified dynamics. As a result, mis-specified model will generate similar reduced form dynamics as the true model. Hence, LR test has no power at all against mis-specified models. Contrarily, under IIW, the error processes are pre-specified, in fact, the autoregressive parameters are falsified along with structural parameters as there is no need to minimise forecast errors[2], thereby producing a completely different reduced form than true VAR. Alternatively, this simply means that under LR the test statistics is built upon a one-period ahead forecast error matrix of VAR, implying that the likelihood method incorporates in-sample predictions from the auxiliary model as opposed to causal relationships we are interested in.

On the hypothesis that the DSGE model is true, LR and IIW test is asymptotically equivalent. This implies that if we use the distribution of VAR estimates based on sample data as opposed to simulated data, which encompasses the model restrictions, the LR and IIW test will produce similar test results. However, when the model parameters are falsified, IIW test based on the distribution of unrestricted model has significantly less power than IIW test based on the restricted model. This is because the variance matrix of auxiliary model coefficients becomes more precise and hence increases the power[3]. An alternative ex-

[1]Since previous literature has shown that in DSGE models errors are serially correlated, this property was added into the model by assuming that they follow VAR(1) process. Thus there is a re-estimation of autoregressive parameters. The paper by Meenagh, Minford, and Wickens (2012) illustrates that if we falsify autoregressive parameters as opposed to re-estimation, the power of LR test would have increased substantially

[2]When the parameters are falsified, IIW uses true residual processes for conventional purposes as the number of simulations is large. That is, the model is false in all respects except for innovations. According to Le, Meenagh, Minford, and Wickens (2015), if only innovations are being falsified, then this produces negligible power and hence the data on residuals has been kept intact

[3]Using the distribution implied by sample data is equivalent to using variance matrix of VAR based on sample data. More specifically, in these circumstances LR and IIW tests become equivalent. Furthermore, if the number of VAR coefficients is large, then there is insufficient information in the data to measure variance matrix as there is an over-fitting in small samples

planation is, the distribution under IIW test statistics is simulated from the model being tested in contrast to LR test that uses distribution from sample data generated by an unknown true model. In particular, if we increase the order of VAR, there is insufficient information in observed data to explain movements in too many coefficients[4].

The only concern with IIW test would be which variables have to represent the auxiliary model and how many of them. The paper by Le, Meenagh, Minford, Wickens, and Y. Xu (2016) verified that the power of Indirect Inference is proportional to the number of variables in VAR and order of lags, but the choice of variables is not that statistically significant as the same number of variables provide the same information about the data features. However, the more VAR coefficients are included in the test the more features of the data have to be replicated by model. In the current paper, since we are interested in the behaviour of nominal exchange rate and price level, the auxiliary model is based on these variables in addition to output. Thus, the number of VAR coefficients is 12 including the variance matrix of reduced-form errors.

The solution for the DSGE model with exogenous variables generated by VAR(1) is VAR model with restrictions on its coefficients. Hence, actual data is represented by unrestricted VAR whilst the model by restricted VAR where the restriction is already incorporated in simulated data extracted from a model by bootstrapping structural shocks. The errors are backed out from the model for a given set of structural coefficients and data. The test statistics is Wald[5]. The paper estimates the DSGE model in levels with single non-stationary shock, productivity shock, and thereby uses restricted VARX (VAR with exogenous variables) as an auxiliary model. In other words, there is a unique mapping with restricted VAR due to the model being identified[6].

The steps of estimating the model by Indirect Inference are as fol-

[4]Information in data sample cannot provide estimates of the distribution of VAR coefficients

[5]While estimating with IIW we employ the numerical distribution of estimated VAR parameters and in testing, we make the use of numerical distribution of test statistics rather than its asymptotic distribution.

[6]Le, Meenagh, Minford, and Wickens (2015), confirmed that structural parameters can uniquely be recovered from the data meaning as there is a unique reduced form

lows [7]:

- Extract the residuals of the model using observed data and calibrated parameter set, and generate s sets of simulated data by bootstrapping innovations.

- Choose an auxiliary model (VECM/VARX in our case) and estimate it on both simulated and the observed data.

- Set up the null hypothesis and compute the Wald statistic by

$$W = (\beta^{\alpha} - \overline{\beta^{s}(\theta_0)})'\Omega^{-1}(\beta^{\alpha} - \overline{\beta^{s}(\theta_0)}) \tag{5.1}$$

where β^{α} is VAR parameter based on actual data, and β^{s} is N (for $s = 1, 2...N$) set of VAR parameters based on simulated data, from which we calculate the average $\bar{\beta}$. Thus, the null hypothesis for this test is $\beta^{\alpha} = \bar{\beta}$. The non-rejection of the null hypothesis implies that the dynamic behaviour of the structural model is not significantly different from that of the observed data. Otherwise, rejection indicates the mis-specification of the model. Ω is covariance matrix defined as $\Omega = cov(\beta^{s} - \bar{\beta})$. In essence we are measuring the distance the actual VAR parameters are from the average of the simulated VAR parameters.

The literature on IIW including Le et al. (2016) showed that the power of the test is proportional to the number of variables in VAR and the lag order of lags. I use "Directed Wald" statistic rather than full Wald criterion following Le et al (2011,2015a) where the latter includes all the endogenous variables of the model. The more of each element the higher the number of data features the model has to match, hence the higher the power. However, including all variables leads to the uniform rejection of the model as it is impossible to replicate the reality in the model. The Directed Wald involves selecting few key variables that evaluate the theory being tested. In the test application, the aim is to set the power high enough to discriminate strongly between true and false models but not so high that few tractable models could pass. In our model here we find from our Monte Carlo power calculations below that a VAR(1) with the three central macro variables inflation, the exchange rate and output gives this satisfactory level of power. The evaluation

[7]Meenagh, Minford, and Wickens (2012) and Le, Meenagh, Minford, and Wickens (2015) for non-stationary data

criteria are then not only replicating features of a single time series (output or inflation separately) but the joint behaviour of all three variables.

For the model to fit the data at the 95% confidence level, the Wald statistic for the actual data has to be less than $95th$ percentile of the Wald statistics under simulated data. The Wald statistics from the simulated data come from χ^2 distribution with degrees of freedom equal to $k-1$, where k is the number of parameters in β. So, compare the test statistic with the critical value (or use p-value) and derive the conclusion. Alternatively, we use the Mahalanobis Distance based on the same joint distribution, normalised as a t-statistic[8]:

$$T = 1.645\left[\frac{\sqrt{2W}-\sqrt{2k-1}}{\sqrt{2W^{95}}-\sqrt{2k-1}}\right] \tag{5.2}$$

where W a is Wald statistic on the actual data and W^{95} is the Wald statistic for the $95th$ percentile of the simulated data. This procedure implies that when we estimate the model, we actually prove that model fits the data and hence already being tested.

The choice of auxiliary model

The solution to a DSGE model is restricted VARMA (reduced form). Moreover, the DSGE model has a distinct reduced form, meaning there is no other "true" DSGE model that could generate exactly the same reduced model. The identification is insured by the rational expectation variables that imply over-identifying restrictions on VARMA. So there is a unique causal relationship maintained. Having non-stationary data as data resources, the auxiliary model should have stationary errors indicating VECM as an auxiliary model, which allows for the cointegration of variables.

An auxiliary model with stationary errors is required when endogenous variables are non-stationary by virtue of their dependency on non-stationary exogenous variables. Therefore a Vector Error Correction Model is appropriate here. Below it is shown, following Meenagh,

[8] As the true distribution of model residuals is unknown, $\beta^{\alpha}-\beta^{s}$ does not follow a normal distribution in the finite sample, but it is asymptotically normally distributed when the sample size is large. In turn, the Wald statistic can compare against an asymptotic chi-squared distribution. Thus, $\sqrt{2W}$ asymptotically follows t-distribution as it can be converted into a t-statistic by adjusting the mean and the size. The resulting t-statistic should be less than 1.645 at the 95% point of the distribution

Minford, and Wickens (2012) and Le, Meenagh, Minford, and Wickens (2015), how the chosen auxiliary model is an approximation of the reduced form of the DSGE model under the null hypothesis, and that it can be represented as a cointegrated VARX.

Suppose the structural model in log linearised form is:

$$A(L)y_t = B(L)E_t y_{t+1} + C(L)x_t + D(L)e_t \tag{5.3}$$

where y_t is a $p \times 1$ vector of endogenous variables and x_t is $q \times 1$ vector of exogenous variables. Assuming x_t as a vector of non-stationary exogenous variables (productivity) and follows a unit root process:

$$\Delta x_t = a(L)\Delta x_{t-1} + d + c(L)\epsilon_t \tag{5.4}$$

The disturbances e_t and ϵ_t are both vectors of i.i.d. error processes with zero means. L denotes the lag operator and $A(L), (B(L), a(L), c(L)$ are polynomial functions having roots lying outside the unit circle. Since y_t is linear function of x_t, it is also non-stationary. The general solution of y_t is:

$$y_t = G(L)y_{t-1} + H(L)x_t + l + M(L)e_t + N(L)\epsilon_t \tag{5.5}$$

where l is a vector of constants and polynomial functions in the lag operator. Since y_t and x_t are both non-stationary, the solution has p cointegrating relationships:

$$\begin{aligned} y_t &= [I - G(L)]^{-1}[H(L)x_t + l] \\ &= \Pi x_t + g \end{aligned} \tag{5.6}$$

where Π is a $p \times p$ matrix with a rank $0 \leq r < p$, with r representing the number of linearly independent cointegrating vectors. In the long run, the solution is given by:

$$\overline{y_t} = \Pi \overline{x_t} + g \tag{5.7}$$

$$\overline{x_t} = [1 - a(1)]^{-1}[dt + c(1)\xi_t] \tag{5.8}$$

$$\xi_t =_{i=0}^{t-1} \epsilon_{t-s} \tag{5.9}$$

where $\overline{y_t}$ and $\overline{x_t}$ are the long run solution to y_t and x_t respectively. The generic solution of $\overline{x_t}$ can be decomposed into a deterministic trend $\overline{x_t}^d = [1-a(1)]^{-1} dt$ and a stochastic trend $\overline{x_t}^s = [1-a(1)]^{-1} c(1)\xi_t$.

Subtracting y_{t-1} from both sides yields the solution of y_t as in the cointegrated VECM:

$$\begin{aligned} \Delta y_t &= -[I-G(L)](y_{t-1}-\Pi x_{t-1}) + P(L)\Delta y_{t-1} + Q(L)\Delta x_t + l + \omega_t \\ \omega_t &= M(L)e_t + N(L)\epsilon_t \end{aligned} \tag{5.10}$$

where ω_t is a mixed moving average process. The VECM can be approximated by Vector Autoregression with exogenous variables (VARX):

$$\Delta y_t = -K(y_{t-1}-\Pi x_{t-1}) + R(L)\Delta y_{t-1} + S(L)\Delta x_t + g + \zeta_t \tag{5.11}$$

where ζ_t is an i.i.d. with zero mean. Since $g = \overline{y}_{t-1} - \Pi\overline{x}_{t-1}$, the VECM can also be written as:

$$\Delta y_t = -K\left[(y_{t-1}-\overline{y}_{t-1}) - \Pi(x_{t-1}-\overline{x}_{t-1})\right] + R(L)\Delta y_{t-1} + S(L)\Delta x_t + h + \zeta_t \tag{5.12}$$

By Le et al (2015), either of equation (5.11) or (5.12) can be auxiliary model. In particular, (5.12) distinguishes between the effect of the trend component of x_t and the temporary deviation of x_t from trend; it can be rewritten to be a VARX(1) in level:

$$y_t = [I-K]\,y_{t-1} + \Pi K\overline{x}_{t-1} + \eta t + v_t \tag{5.13}$$

where $\overline{x}_{t-1}$ contains the stochastic trends in the exogenous variables, ηt is included to pick up the deterministic trends in y_t, and v_t is a vector of the error terms.

I calculate Wald statistic where we account for the VAR coefficients of the lagged endogenous variables $(I-K)$ and the variances of the VAR errors $Var(v_t)$ that we take as descriptors of the data. Previous papers on IIW reported that (Meenagh et al (2018)) using either moments or IRFs as auxiliary model is identical to using the VAR coefficients. In this thesis, I use VAR coefficients as auxiliary model.

The time trend in equation (5.13) incorporates deterministic trend in $\overline{x}_t$, which has impact on endogenous variables; term x_{t-1} contains unit root variable to control the effect of shocks on long-run path of variables. Similar to productivity, the lagged net foreign debt, f_{t-1}, is a driving variable of the system. That is, it preserves all past and present current account imbalances affecting the long-run solution path of the endogenous variables. Thus, it is included in x_{t-1} to guarantee cointegration.

Recall that in estimation the structural parameters are chosen to obtain the closest possible match to the auxiliary model. Therefore, the procedure for finding optimal parameters involves minimising the distance between the model-simulated and the data-given estimates of VAR coefficients. On the other hand, under evaluation the structural parameters are taken as given. They could be estimated using IIW or the Bayesian technique. The null hypothesis of the test is that model under consideration is a true representation of the reality. The auxiliary model is then estimated for each data generated by simulating structural model many times yielding distribution of statistics. Then the actual data-based estimate occurs with a certain probability within this distribution. The test rejects the model if the probability metric lies below the test threshold.

Before commencing IIW estimation, calibration of parameters can be predefined as starting values. I used magnitudes in consensus with commonly used values in the literature based on UK data[9]. The estimation then proceeds by randomly searching across the parameter space within a bound of 50%. The process selects the set of coefficients that minimises the Wald distance extracted from sample data and model simulation data.

Table 5.1 shows the estimated structural parameters of the model where the model passes IIW test with p-value of 0.06 for a subset of $[S_t, Y_t, \pi_t]$[10]. Apart from the quarterly discount factor (β) and quarterly depreciation rate (δ), all parameters have been estimated using IIW. The discount factor is calibrated to 0.99, implying an almost 1% quarterly (or 4% annual) rate of interest in a steady-state. The value is somewhat close to other literature (Minford, Theodoridis, and Meenagh (2009)). The quarterly capital depreciation rate is set to 0.025 following Smets and Rafael Wouters (2007) to produce a 10% annual depreciation rate.

[9]Since the estimation of parameters are important in pass-through analysis, the calibration parameters are not reported

[10]The Transformed Wald is 1.48 less than 1.645, the critical value. So the model is not rejected

Table 5.1: Estimated parameters

Parameters	Description	Value
Fixed parameters		
β	Discount factor	0.99
δ	Depreciation rate	0.0.25
Estimated parameters		
α	Share of capital in production	0.3
σ	Risk aversion	3.34
γ	Inverse of Frisch labour supply elasticity	7.63
$\Gamma"(1)$	Investment adjustment cost	1.12
ρ_h	EOS between home and foreign goods for home consumers	1.34
ρ_f	EOS between home and foreign goods for foreign producers	3.77
ω	Home bias	0.74
ψ	Elasticity of capital util	3.07
ϕ_y	Share of fixed cost	1.2
Taylor rule		
r_p	Response to inflation	5.04
r_y	Response to output	0.21
$r_{\triangle}p$	Response to inflation changes	0.05
$r_{\triangle}y$	Response to output changes	0.001
μ	Interest rate smoothing	0.76
Calvo parameters		
φ_d	Home price indexation	0.1
φ_f	Imported cons rice indexation	0.4
φ_m	Imported input price indexation	0.1
φ_x	Export price indexation	0.1
ζ_d	Home price rigidity	0.45
ζ_f	Imported cons rice rigidity	0.76
ζ_m	Imported input price rigidity	0.79
ζ_x	Export price rigidity	0.4
υ	Share of imported inputs in final production	0.33
θ	Share of imported cons goods in total imports	0.61
τ	Proportion of sticky prices	0.57

There are other fixed model parameters, which were calibrated to match the UK data characteristics. For instance, the quarterly steady-state output growth is 0.5%. The following variables were calibrated to match the steady-state (average) features of each times series: government to output ratio is 0.19, consumption to output ratio is 0.6, $\frac{I}{Y}$ equals to 0.22, $\frac{K}{Y}$ is 2.66, $\frac{X}{Y}$ is 0.22 and $\frac{M}{Y}$ is 0.21.

On the household side, the relative risk aversion in the utility function for consumption (σ) is 3.34, higher than previous literature implying that movement in consumption is less sensitive to changes in interest rate. Similarly, the coefficient of the inverse of Frisch labour supply elasticity (γ) of 7.63 indicates that working hours weakly respond as the wage rate alters. These two parameters imply inelastic intertemporal consumption and labour supply decisions. Although domestic households are biased towards domestic products as they put less weight on foreign goods, the substitution rate between these goods is perfect (perfect substitutes) as the elasticity for imports is 1.34. On the other hand, the elasticity for exports (ρ_f) is even higher (3.77) implying that foreign consumers hold a large basket of goods making their consumption choice more sensitive to relative price changes. For instance, a 1% increase in relative domestic to foreign price causes a 1.12% increase in the quantity of imports but 3.77% decrease in exported goods. These estimates are consistent with Marshall-Lerner condition that sum of elasticities with respect to imports and exports should be greater than one. The condition is required to reduce the current account deficit by adjusting the exchange rate. However, obtained estimates are still larger than empirical values reported by Hooper, Johnson, and J. R. Marquez (2000). The preference bias towards domestic goods is estimated to be 0.74 similar to other literature (Meenagh, Minford, Nowell, et al. (2010)).

On the firms' side, the share of fixed cost in production is 20%, while the share of capital is 30%. The share of fixed cost is quite low in comparison to previous literature with an average of 0.5. On the other hand, the share of capital in production is consistent with the UK estimates produced by Gollin (2002). The parameter governing the elasticity of equilibrium investment adjustment cost (S"(1)) is as low as 1.12, while the parameter of the degree of capital utilisation is 3.07.

That is, a 1% drop in rental rate is equivalent to 3.07% fall in capital efficiency rate. The share of imported inputs in final production is 33%, which signals the importance of foreign intermediate goods in the UK manufacturing industry. The rate is quite similar to the share of imported consumption goods in a total basket of consumer goods, 0.26 (home bias is 0.74). These estimated parameters, nevertheless, is higher than the literature based on EU data (De Walque et al. (2017) reports the Bayesian estimation of 23% for non-oil imports plus 0.6% for oil imports). The proportion of imported consumption goods in total imported volume is estimated to be 0.61 implying that the UK mostly imports final goods.

The parameters on inflation dynamics incorporate price stickiness and price indexation parameters. The latter parameters estimates range between 0.1 to 0.4 implying that price inflation is not persistent. Nevertheless, the price rigidity parameters are widely spread. For instance, the highest average price duration has been observed for importing goods prices (8 quarters), and 2 quarters for domestically produced goods. The proportion of New Keynesian elements in price dynamics is 0.4 with a price rigidity of 0.56 for domestically produced goods, implying the presence of flexibility in the UK economy.

On the policy side of the central bank, the indexation on interest rate is 0.76, while the weight on inflation is 5.04 and 0.21 for output. Interestingly, the change in output has no significant impact on policy rate (0.001) as opposed to inflation change (0.05), which strengthens the bank policy on inflation targeting.

Power test. Previously I have estimated as well as tested whether the current model is rejected or not by Indirect Inference test. The next step of the evaluation process is to conduct a power test. The power of a hypothesis test is the probability of rejecting a false null hypothesis. The power of the test depends on a list of factors including significant level and how false the null hypothesis is. We would like to see how the rejection rate increases as the model becomes increasingly mis-specified.

Another standard test that exists in the literature is LR test. Le, Meenagh, Minford, Wickens, and Y. Xu (2016) compared the power of IIW and LR test on most popular models of macroeconomics such as three-equation New Keynesian model of Clarida, Gali, and Gertler (1999) and Smets and Raf Wouters (2003). The data supplied are both stationary and non-stationary. The authors claimed that the power of IIW significantly outweighs that of LR test in a finite sample. As aforementioned, the reason for the lower power of LR test lies in re-estimation of the error process to bring the model back on track. Each simulation data is generated by redrawing the VAR innovations as opposed to IIW test that uses the model's own restrictions to generate simulated data.

The sample data is 112 periods, thus the distribution of Wald statistic is unknown. Hence, the model evaluation by Indirect Inference employs the Monte Carlo procedure where we generate 10,000 samples from the true model (estimated parameters), and find the distribution of the Wald for these true samples. Similarly, we draw a set of 10,000 samples from the false model where the estimated parameters have been falsified by some $x\%$ and calculate the Wald distribution for this false model. We then calculate how many of the actual samples from the True model would reject the False Model on this calculated distribution with 95% confidence. More specifically, the steps of the model evaluation experiment are as follows:

- For given actual data, estimated structural parameters and autocorrelation coefficients, obtain structural residuals and innovations to generate 10,000 samples. Then calculate the distribution of Wald statistics under this true model

- Falsify the estimated structural and autocorrelation coefficients of the true model by $x\%$, and draw 10,000 simulated data

- Estimate auxiliary model VECM/VARX and obtain mean of VAR parameters $\beta^{\bar{false}}$ and covariance matrix Ω^{false}. Then calculate the 95th percentile of Wald statistics, W_{95}^{false} by ordering 10,000 Wald statistics computed for each sample.

- Calculate how many of True Wald would reject the False Wald at 95% confidence level. The rejection rate indicates the power of the test:

$$W^{test} = (\beta^{true} - \overline{\beta^{false}})'\Omega_{false}^{-1}(\beta^{true} - \overline{\beta^{false}}) \tag{5.14}$$

Table 5.2: Model evaluation based on Monte Carlo test

Percent misspecified	3 varb VAR(1)-12	3 varb VAR(2)-18
True	5.00	5.00
1%	8.00	6.00
3%	35.00	25.00
5%	96.00	91.00
7%	100.00	100.00

As mentioned previously, including all endogenous variables of the model (25 variables) leads to the rejection of the model as no model represents the reality for 100% certainty. In addition, economists are focused on certain aspects of the model that could explain some features of interest, eg. the causal relationship between nominal exchange rate and CPI price level. Therefore, the results of the Power test are also based on a limited number of endogenous variables and a number of lags.

The results in column 1 of Table 5.2 show that the estimated model passes the test as the simulation result illustrates that the true model is being rejected exactly at 95% confidence level. Moreover, the rejection rates increase with the degree of falseness so that when we falsify structural parameters as small as 7%, the model is being rejected 100% by the test. Note, the auxiliary model that the test is based on is VARX(1) model including the variances of VAR residuals[11]. A higher rejection rate implies greater power of Indirect Inference test.

The outcome of the test depicted in column 2 justifies our choice on the length of VAR. The rejection rates are quite similar to column 1- 7% inaccuracy in the model parameters are already being rejected by the test- thus the choice of VAR(1) can be considered as a valid choice.

Unlike other estimation procedures such as Bayesian, Indirect Inference does not require to report standard deviations or confidence intervals for estimated parameters. This is because of the nature of the estimation method. The estimation proceeds by randomly searching across the parameter space. The process selects the set of coefficients that minimises the Wald distance extracted from sample data and model simulation data. Any deviation from the "true" parameters has a risk of

[11]The length of VAR parameter is 12

being rejected by the test. For instance, Table 5.2 reports that as long as estimated parameters are "wrong" by 1% the test rejects 8% of the time (C.I. is 92%). Similarly, if the coefficients are alternated by 7% the test completely rejects the model.

In summary, we can conclude the main research question of the thesis in this section. The constructed model of imperfect pass-through passes the evaluation test. Moreover, unlike the majority of general equilibrium models of pass-through, the current model has been estimated. Therefore, in the following sections, we can now estimate the pass-through degree using Impulse Response Functions (IRFs) based on these estimated model parameters.

Chapter 6

The response of nominal exchange rate and CPI to orthogonal shocks

This section discusses the workings of the economy under different orthogonal shocks. I will accentuate the dynamics of the following key variables: nominal exchange rate and consumer price.

The definition of pass-through relies on whether one defines it as partial or total effect on the price level. The former is the common type of pass-through estimate in the literature as it measures the direct effect of nominal exchange rate on price relation ignoring the effect on other variables. The latter, on the other hand, measures the total effect as it encompasses the entire effect an exchange rate produces, operating through every interaction of the price determination:

$$\frac{\partial p_t}{\partial e_t} \neq \frac{dp_t}{de_t} = \frac{\partial p_t}{\partial e_t} + \frac{\partial p_t}{\partial x_t}\frac{\partial x_t}{\partial e_t} \tag{6.1}$$

where x_t is any model variable. In a simple regression, the equality sign holds in equation (6.1) unlike the case in general equilibrium- the transmission flows from price to exchange rate and vice versa. For instance, if we consider the Phillips curve solely excluding all other model equations, then the slope of Phillips curve reflects the partial pass-through estimate. However, if we take the entire model then the effect of shock transmits in both directions with the major effect dependent on the type of shock hitting the economy. For example, productivity shock mainly

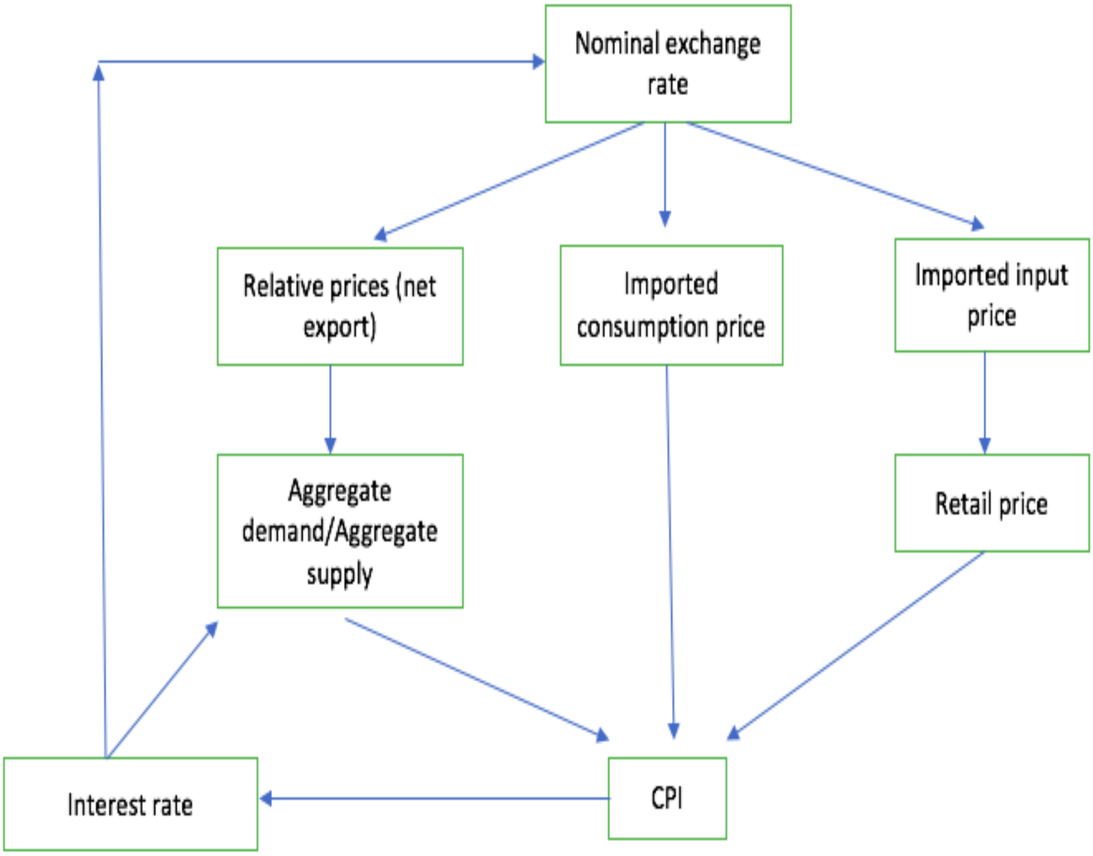

Figure 6.1: The workings of the economy

works in the direction of price to exchange rate whereas foreign interest rate shock triggers a movement in the nominal exchange rate (NER) before shifting the price level (CPI). The details of shock effects will be discussed in the next section.

The transmission channel of shocks is depicted in Figure 6.1. What ultimately matters is the type of shock hitting the economy, which either triggers a movement in the nominal exchange rate or consumer price first. If the nominal exchange rate moves first, then transmission to CPI works through aggregate demand and import prices. The aggregate demand channel encompasses an adjustment in relative prices in response to fluctuations in NER. In particular, relative prices between domestic and imported goods determine the level of net export that shifts the aggregate demand. Due to New Keynesian feature of the model, aggregate supply follows the aggregate demand. Consequently, the movement in both supply and demand determines the CPI level. The model in this paper includes imported inputs in addition to imported consumption goods. The latter has a direct effect on CPI whereas the imported inputs affect the cost for domestic retailers (equation 3.34), which eventually disturbs CPI (equation 3.29).

If the shock, on contrary, hits the consumer price first then transmission of shocks works through monetary policy and Uncovered Interest Parity (UIP) channel. The policy-makers adjust the interest rate in response to movement in inflation, which directly affects aggregate demand (consumption and investment) and affects the nominal exchange rate via UIP condition. In general, these channels represent the main flow of shock effects. However, there is a secondary effect of shocks that works in other directions- if the main channel is NER to CPI, then there is an additional effect from CPI to NER with the former effect dominating the latter.

These transition channels also emphasize the importance of estimated coefficients. In particular, pass-through is highly sensitive to Taylor rule parameters, home bias, the share of imported inputs in final production, the elasticity of substitution between home and foreign goods and price rigidity parameters. For instance, the higher is the openness coefficient (low home bias) the higher is pass-through; the higher is the elasticity of substitution between foreign and home goods the higher is pass-through since the domestic economy is more responsive to relative price adjustments[1]; and finally, the higher is rigidity in prices the lower is pass-through. In the last scenario under constant markup and gradual price adjustment, the transition breaks through expectation about inflation or marginal cost[2]. Thus, the forward-looking nature of the model plays a major role in pass-through estimation. On contrary, if the markup is variable (not in this model) then pass-through declines as firms tend to change their markup rather than adjusting their price level as to not lose their market share. This is specifically true for a monopolistic competition where firms hold some market power. The variable markup requires either a specific functional form of the demand curve (eg. Kimball demand curve) or strategic pricing, which is

[1]The argument is not valid for pure local currency pricing (LCP) where there is no expenditure switching effect or pass-through is around zero

[2]Discussed in Chapter 3

not analysed in this thesis.

Another important feature of the model is the type of monetary policy embedded in the model-inflation targeting (IT). Under IT, policy-makers do not place any importance on the level of price thereby entailing non-stationary behaviour on both NER and CPI. According to PPP (Purchasing Power Condition), $P = SP^*$, where P is domestic CPI, S is nominal exchange rate and P^* is foreign price level. The PPP rule is satisfied in the long-run implying cointegrating relation between NER and home price. Since world variables are taken exogenously, the following must hold for NER:

$$\lim_{i \to \infty} E_t S_{t+i} = \lim_{i \to \infty} E_t P_{t+i} \tag{6.2}$$

In the long-run, the real exchange rate must return to its equilibrium value to satisfy the current account equilibrium given output at its potential level. For brevity, let us call these two conditions as Purchasing Power Parity Condition (PPP). Thus, in the short-run, NER is determined by UIP rule whereas in the long-run it has to satisfy PPP rule. On the impact, if the nominal exchange rate rises but CPI falls then in the following periods the exchange rate has to decrease according to PPP condition.

The novelty of this paper. Before elaborating our analysis on ERPT degree, I would like to make a clear distinction between the study performed here and the past literature. Firstly, the ERPT analysis here is based on the estimated and tested model in contrast to calibrated models. Moreover, papers based on Bayesian estimation did not perform comprehensive analysis on a pass-through degree. Their focus mainly lies on identifying optimal monetary policy or on the determination of causes of pass-through. For instance, how important is price rigidity or variable markup in generating an imperfect ERPT degree? Secondly, the papers on partial equilibrium, as opposed to general equilibrium models do not encompass economic structure. Most importantly, under these models, the causality streams only from exchange rate to price levels whereas in DSGE models the flow runs in both directions. This is a key point in our analysis. Third, the literature on shock dependency of pass-through degree has emphasised that they are shock dependent. However, they did not go into detail to explain the reason behind such behaviour. In this paper, we clarify this point using the estimated DSGE model. Lastly, I have constructed a basic model of the UK economy with imperfect pass-through based on a unified theory of firm optimization: monopolistic competition with Calvo type price setting. I proposed this model of the UK economy as a causal model of the extent of pass-through degree; I then estimated it and subjected it to this powerful Indirect Inference test procedure. This confirmed that this basic model of the UK indeed fits the data, and can be further implemented for policy analysis. Le, Meenagh, Minford, Wickens, and Y. Xu (2016) show that the power against a mis-specified model is close to 100% (mis-specified models are rejected with high probability). Therefore, it is highly unlikely that any of these rival models, which thereby count as mis-specified, would pass the test. Many of the queries that follow concern such as alternative hypotheses; it should be noted that this methodology is designed to deal with all of them.

Chapter 7

Impulse Response Analysis

In order to conduct monetary policy efficiently, it is essential to understand the workings of the economy so that the central bank could adequately respond to different macroeconomic shocks. This section delivers results on Impulse Response Functions (IRFs henceforth) for a different set of structural shocks on the estimated DSGE model. The analysis presented here of paramount importance for the whole thesis as IRFs are used to evaluate the pass-through degree. There are fifteen shocks including shocks to domestic supply (productivity, labour supply, four types of markup shocks), domestic demand (consumer preference, demand for import and export, government spending, investment) as well as foreign shocks (world price, output and nominal interest rate). However, I will demonstrate IRFs for the following four shocks: productivity, monetary policy, foreign interest rate and investment-specific shocks. The paper aims at explaining the different behaviour of CPI and nominal exchange rate (NER henceforth) in response to various shocks.

Before describing the behaviour of the economy under different shocks, I would like to emphasize the following points. Firstly, the literature on partial equilibrium analysis regresses price level on exchange rate. In other words, the causality runs from NER to CPI only. However, under general equilibrium, the direction is two-sided. Therefore, depending on the type of shock, the magnitude of ERPT degree is different under different shocks. In other words, decision made by firms, households and monetary authority is different under a different state of the economy[1]. Nonetheless, in the analysis below I highlight the main

[1] This claim was reported by K. Forbes, Hjortsoe, and Nenova (2018)

stream of causality running between NER and CPI. This also helps to identify the sign of ERPT degree.

7.1 Productivity shock

Figure 7.1 depicts a non-stationary positive productivity shock to home intermediate goods that permanently increases output, consumption and investment. Nevertheless, aggregate demand does not respond fully to unanticipated technology shock due to rigid prices generating excess supply that triggers a decline in consumer prices. Expansionary monetary policy in response to falling CPI and rising output depreciates nominal exchange rate. However, this depreciation effect is partly offset by huge export demand due to the estimated coefficient of higher elasticity of substitution between home and domestic goods (for foreigners). That is, a decreasing domestic marginal cost followed by a fall in export prices boosts the export volume demanded by foreigners. Thus, to balance the current account nominal exchange rate has to decline thereby restraining initial increase.

In the labour market real wage improves as technology progresses but the employment level drops as supply dominates the demand effect. The import level increases significantly due to rising national income. Consequently, there is a current account deficit. The pattern in import prices closely follows the nominal exchange rate. The price increases on impact and declines immediately afterward. This also can be attributed to higher rigidity in import prices that prevents its rise in response to depreciation.

Over the simulation period, a rise in real wage increases labour supply by offsetting some initial drop in employment though new equilibrium level is lower than the level prior to a shock. In contrast to output, consumption and investment level subsides later due to a significant fall in a net foreign asset that has to be balanced in the long run.

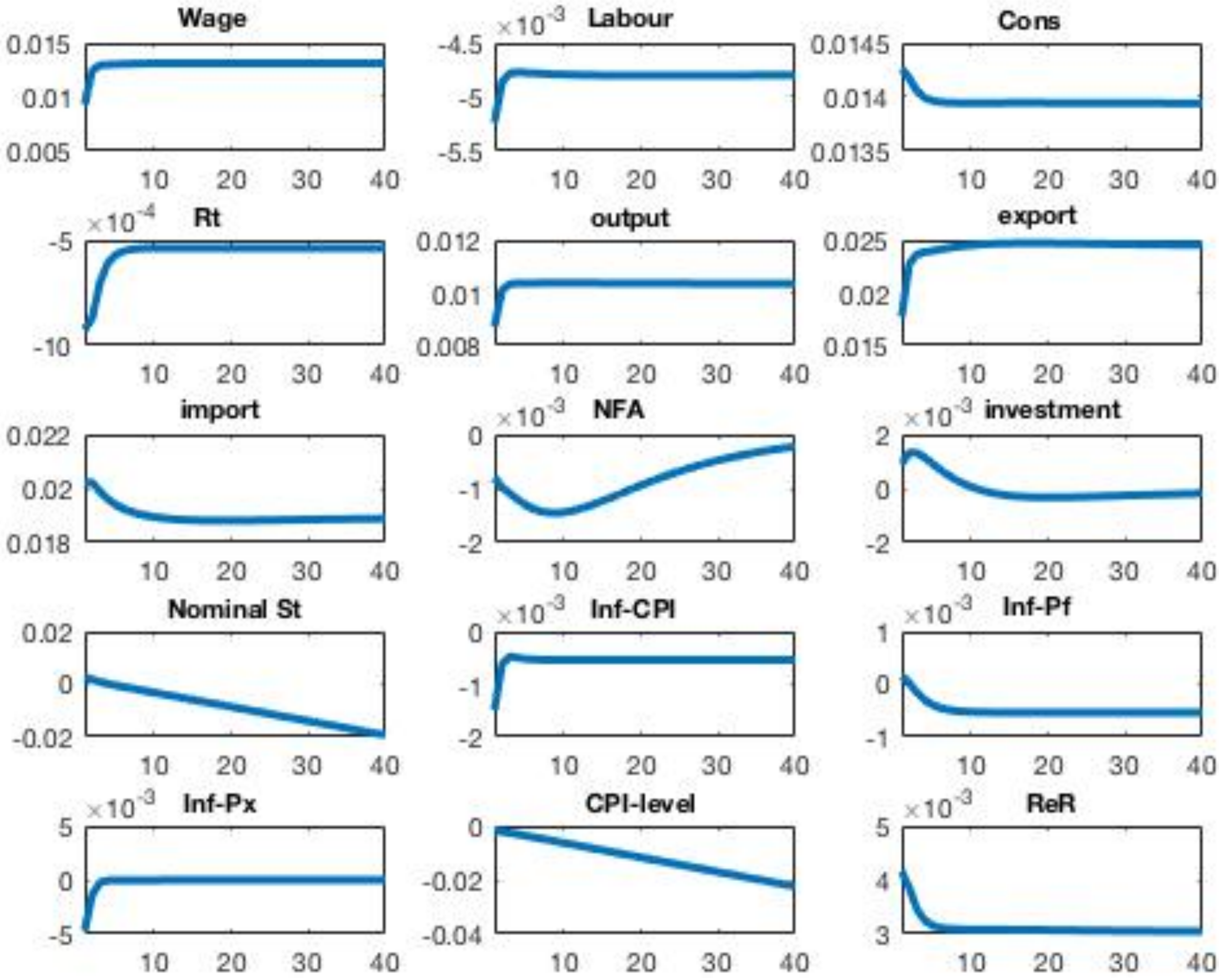

Figure 7.1: Response to 1% productivity shock

Now, let us summarise the dynamics of NER and CPI price. The primary effect of productivity shock on CPI comes through supply conditions (marginal cost). Then, monetary policy authorities decrease the nominal interest rate in response to falling CPI. On the other hand, UIP condition implies that NER depreciates as the interest rate keeps falling, which induces foreign investors to move their assets out of the country. Thus, the main causality runs from price level to NER. Note that in general equilibrium, the causality flows in both directions but here we are interested in the main transition of shock effects.

Let us consider the sign of ERPT degree now. On impact, a positive productivity shock decreases CPI price and depreciates the nominal exchange rate (rising S). Thus, ERPT degree is negative on impact. In the long run, however, PPP conditions must be satisfied implying a constant real exchange rate, which causes the nominal exchange rate to appreciate [2] due to falling prices. As a result, ERPT degree is positive.

A sign switch in ERPT degree is due to behaviour of NER that rises initially and appreciates aftermath whereas CPI price level is constantly declining. An initial depreciation of the nominal exchange rate is due to falling nominal interest rate[3] while the latter appreciation is caused by falling CPI to keep equality in the long-run PPP equation. Note that when the main causality runs from CPI to NER, the sign of ERPT is negative.

Another interesting feature is that pass-through to CPI is larger than to import prices[4], which is in contrast to previous literature that has illustrated that movement in import prices are usually greater. This could be due to the fact that technology shock is a real shock that has a direct impact on marginal cost and partly due to higher rigidity in import prices.

[2] falling S

[3] UIP condition. Falling interest rate induces capital outflow, which entails depreciation

[4] Not displayed in the graph but IRF for CPI level is -0.0015 but for import price is 0.0001

7.2 Monetary policy shock

As the monetary policy is stationary shock, all variables return to their steady-state. An upswing in the nominal interest rate reduces aggregate demand following a decrease in consumption and investment. Firms also cut their production level as capital drops, which evokes less labour demand. However, as the fall in demand exceeds the fall in supply, the economy experiences deflation. In the labour market, positive labour supply is dominated by labour demand from the declining supply, which results in falling real wages. Since a decline in real wage far exceeds an increase in the rental rate, a joint behaviour reduces total marginal cost, which in turn reduces domestic prices. In the foreign exchange market, a rise in interest rate entails exchange rate appreciation, which makes foreign goods relatively cheaper than domestic. Hence, CPI falls due to deflated import prices, cheaper marginal cost and a fall in domestic demand. Net foreign asset accumulation decreases on impact as the current account deteriorates due to a huge decline in the nominal exchange rate.

Let us summarise the behaviour of CPI level and nominal exchange rate under monetary policy shock. A contractionary monetary policy has a simultaneous effect on NER and CPI. First, the policy entails nominal appreciation as rising interest rate attracts foreign investment. Then, as discussed in the previous section, the transmission channel works through import prices and net export (exchange rate channel). On the other hand, rising interest rate decreases domestic demand through investment and consumption (aggregate demand channel). Therefore, CPI level falls. This is the main stream of causality between CPI and NER- the shock has a simultaneous effect on both variables, which moves CPI in the same direction (falling CPI) as NER.

Let us look at ERPT sign now. On impact, both price and NER fall entailing a positive ERPT degree in the short-run. Over the time, exchange rate needs to converge to its steady-state to satisfy PPP condition. Thus, the nominal exchange rate has to keep decreasing as CPI declines. ERPT degree is still positive in the long-run. In contrast with productivity shock, CPI and nominal exchange rate move in the same direction throughout the simulation period. Therefore, there is no switch in the sign of ERPT degree.

In terms of pass-through coefficient, ERPT to CPI is larger than ERPT to import prices [5]. The reason is due to the aggregate demand channel that puts additional downward pressure on CPI.

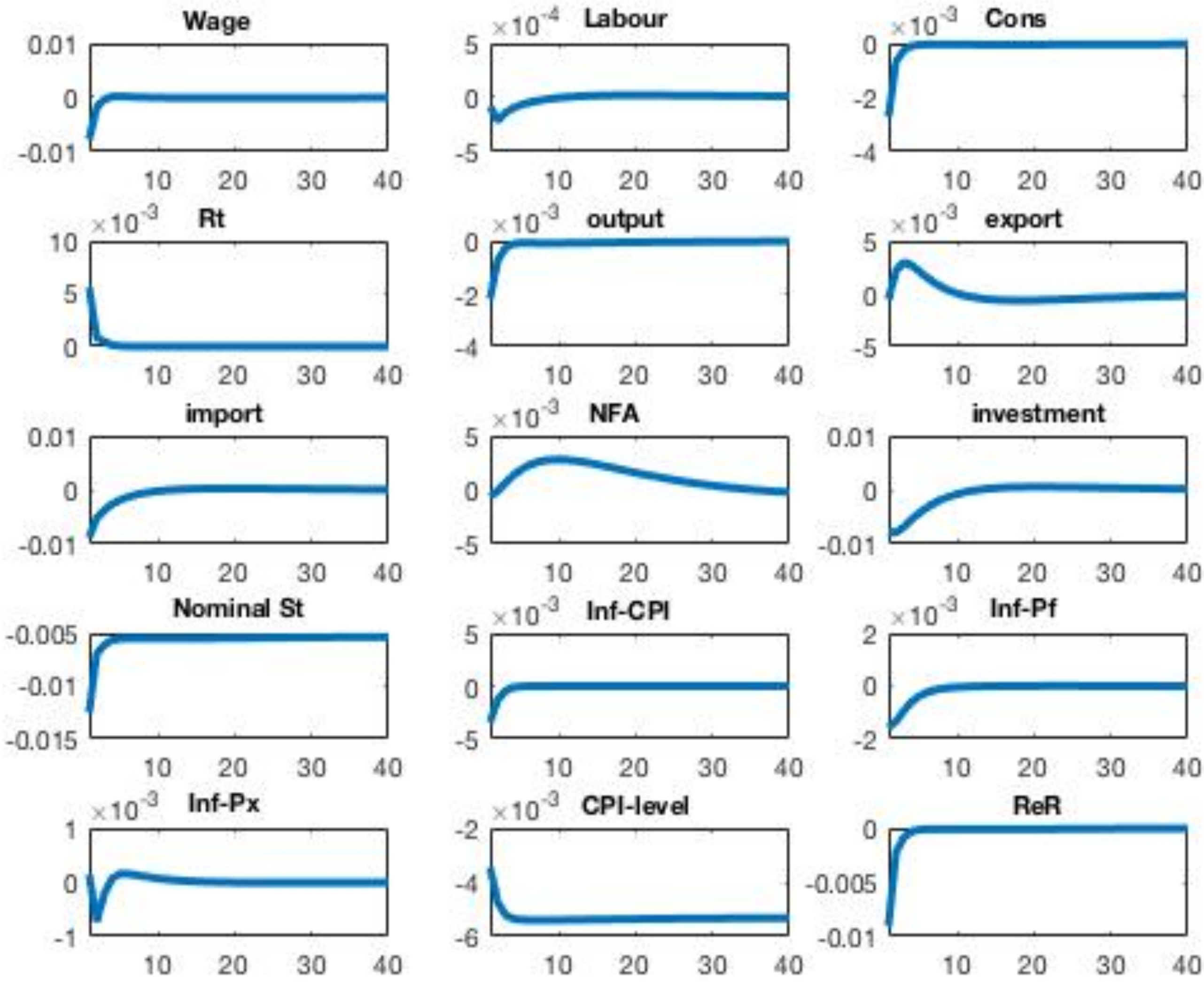

Figure 7.2: Response to 1% Monetary policy shock

[5]Not displayed in the graph but IRF for CPI level is -0.0035 but for import price is -0.0015

7.3 Foreign interest rate shock

In the model, the foreign interest rate shock is equivalent to the UIP shock to the exchange rate. Hence, in response to positive shock on foreign interest rate the nominal exchange rate depreciates. The real depreciation boosts the export of domestic goods while decreasing imports due to a subsequent rise in relative import prices. Consequently, the current account improves. Aggregate demand increases due to a significant upswing in trade balance despite falling consumption and investment (due to rising interest rate). The elevated demand then pushes up consumer inflation as there is excess demand. As the UK is assumed to exhibit perfect capital mobility, policy-makers have to increase the nominal rate to preserve the real interest rate close to its foreign counterpart. In addition, rising output and falling CPI inflation reinforce the behaviour of the nominal interest rate. In the labour market, employment rises both on the supply and demand side, and real wages go up as demand dominates the supply effect. Therefore, a rise in marginal cost puts additional upward pressure on CPI including the main channel through import prices.

In contrast to a monetary policy shock, foreign interest rate shock is persistent[6]. Therefore, the convergence rate of variables to their steady-state has a longer horizon. Another distinguished behaviour of the nominal exchange rate is its size of a change, as it greatly surpasses that of two previous shocks. In fact, its magnitude is even larger than the shock itself[7]. The reason is the economy that expects a persistent rise in foreign interest rate starts purchasing foreign capitals thereby significantly appreciating the exchange rate. The expectation about future depreciation significantly affects today's rate.

The dynamics of CPI and nominal exchange rate is different than two other shocks. A rise in foreign nominal interest rates generates capital outflow, which causes nominal depreciation. This in turn affects CPI directly through import prices and indirectly via aggregate demand conditions. That is, output demand increases due to rising net exports. Thus, the main causality streams from NER to CPI, unlike the previous

[6] persistence is 0.875

[7] 4 times to be specific

two cases. In regard to ERPT sign, NER and CPI move in the same direction at the time of impact, eg. nominal exchange rate depreciates and CPI increases. Thus, the sign is positive. In the long-run, both variables keep moving in the same direction to satisfy PPP condition and hence, ERPT sign remains positive.

Comparing all three shocks, we conclude that pass-through depends on the type of shock that is hitting the economy. Firstly, the sign of ERPT degree on impact is positive for monetary policy and foreign interest rate shocks but negative for productivity shock. The sign of ERPT on impact depends on the behaviour of NER- it is negative if PPP conditions are not satisfied in the short-run[8] so that NER both depreciates and appreciates during the simulation period. Technically speaking, if the main causality streams from CPI to NER, then the sign is always negative and positive otherwise. Nevertheless, in the long-run the sign is positive in consistent with the literature. Secondly, the dynamics of CPI and NER varies along with different shocks, which is actually the main reason for a different pass-through degree. For instance, a major effect of productivity shock falls on CPI and then on NER, implying that the main causality runs from CPI to NER. Contrarily, under foreign interest rate shock, the primary effect of shock resides on NER and then on CPI; and simultaneously on both variables under monetary policy shock. Thus, we can make the following conclusion. Unlike the literature on a partial equilibrium where the ERPT degree is estimated from regressing CPI on NER (causality runs from NER to CPI), in general equilibrium, the causality runs in both directions. Nevertheless, there is the main flow of effect of shock. And this flow runs from NER to CPI and vice versa (or simultaneous), which helps to identify ERPT sign. Now, in the next sub-section, I will explore the magnitude of ERPT under different shocks. And to do that, it is essential to perform the analysis on the price level and exchange rate separately.

[8]CPI and NER moves in different direction

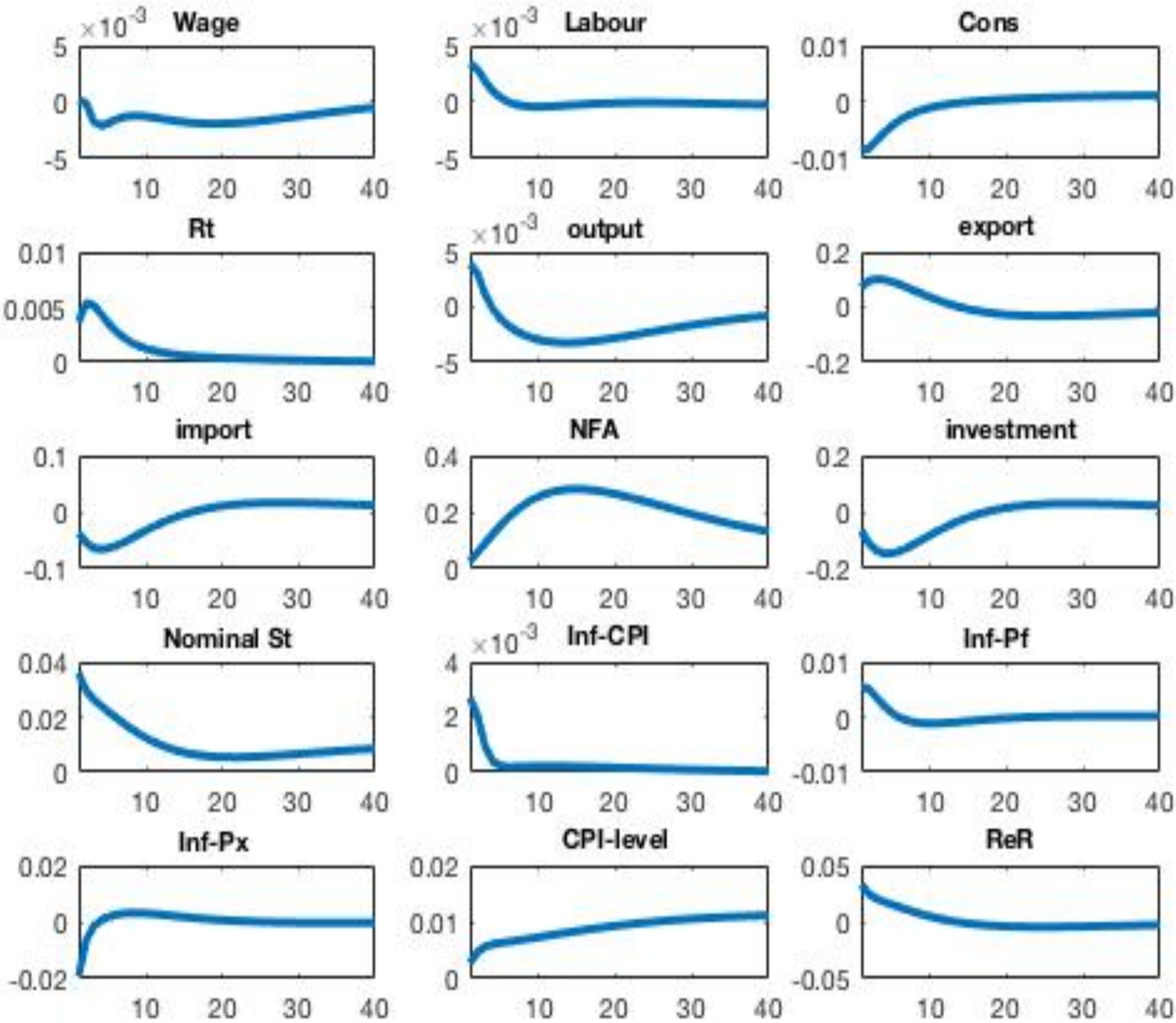

Figure 7.3: Response to 1% Foreign interest rate shock

7.4 Investment-specific shock

This section covers the impulse response function of the main variables to positive investment shock. The variance decomposition in Chapter 8 reveals that investment shock is responsible for the most variation observable in CPI price level, nominal exchange rate and output, which are the base variable for the auxiliary model. Therefore, the aim is to see how the dynamics work when the economy is subject to this shock.

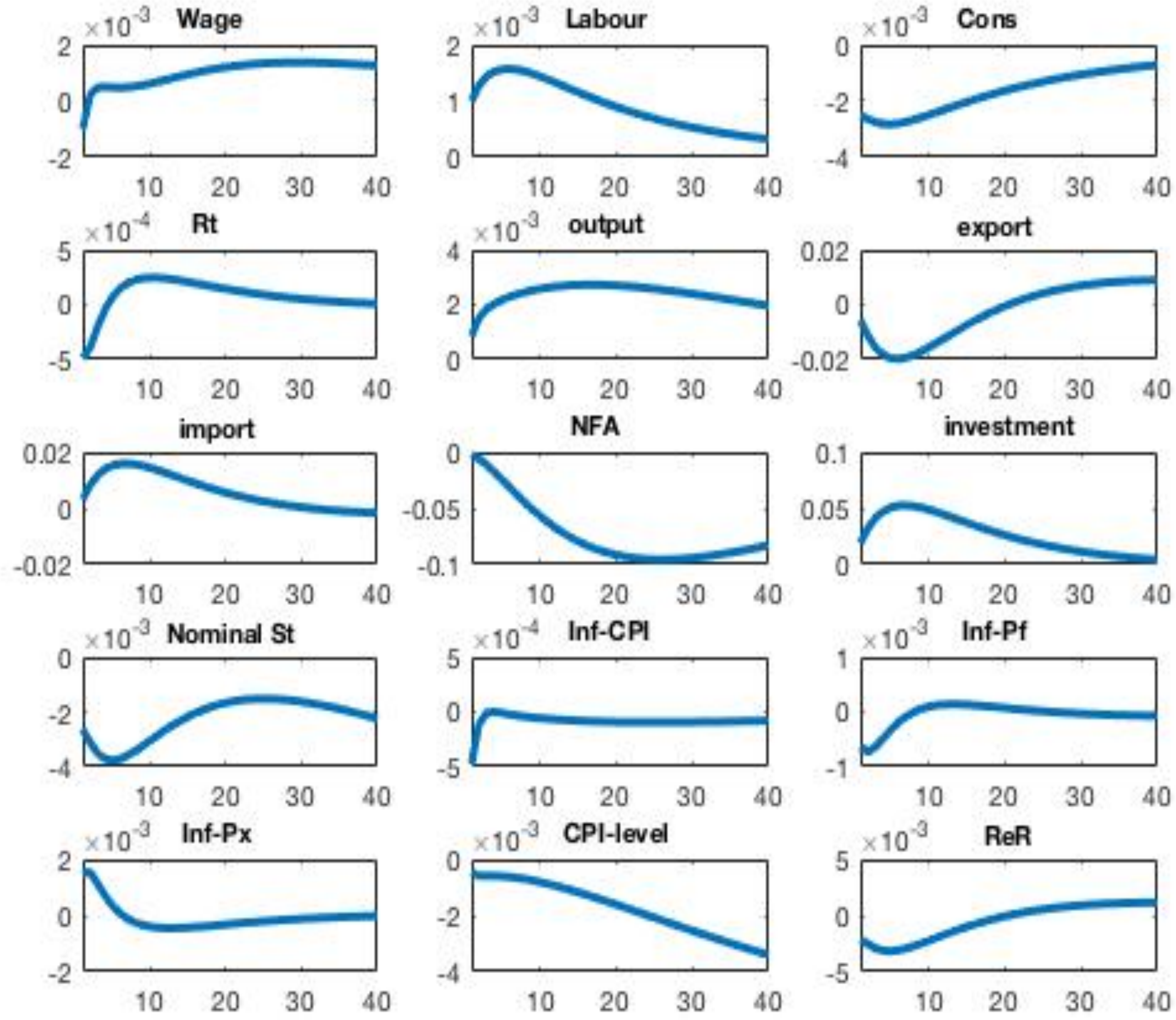

Figure 7.4: Response to 1% investment-specific shock

Similar to foreign interest rate shock, investment-specific shock is highly persistent. Thus, the effect of the shock is long-lasting. A positive one standard deviation investment shock increases investment and consequently aggregate demand. At the same time, aggregate supply also goes up due to rising capital stock and employment. Consequently, CPI inflation falls as changes in supply exceed a change in demand. In addition, due to the open economy feature of the model, the movement in CPI is also triggered by a fall in local import prices. A nominal appreciation due to rising investment puts downward pressure on export volume. The imports, on the other hand, increases due to increasing national income. As a result, the economy experiences a current account deficit. Despite expansionary monetary policy in response to deflation, consumption falls. This is due to rising investment and deteriorating net foreign asset position, where the latter is an additional source of income financing household consumption. Thus, a reduction in consumption partly offsets some domestic demand effects.

In regards to the pass-through degree, the sign of ERPT is positive since both the nominal exchange rate and CPI price level are falling. The initial impact of the shock transmits to the price level and nominal exchange rate through demand conditions. Thus, the causality runs simultaneously. However, unlike monetary policy shock, the ERPT sign is positive both at the time of impact and in the long-run.

7.5 Pass-through analysis

The dynamics of nominal exchange rate and CPI price level in the DSGE model. The sign of ERPT degree. Before commencing a study on pass-through degrees, I would like to review the dynamics of key variables by summarising IRFs. Let us start with domestic supply shocks such as productivity, labour supply or markup shocks. These shocks trigger movement in aggregate supply through marginal cost, which in turn shifts the price level. The causality then runs from price level to exchange rate via Taylor rule and UIP equations, respectively. Although changes in NER bring out second round movement in the price level, we are concerned with the predominant effect of shock. Let us now consider the monetary policy shock. The shock simultaneously changes NER through UIP equation and price level through demand conditions (consumption and investment). Finally, a shock to foreign interest rate has a direct effect on NER, which in turn alters price level via import prices and domestic demand. Hence, we conclude that import prices, as well as aggregate demand and supply conditions, determine price level whereas NER is defined through UIP equation in the short-run. In the long-run, NER must satisfy PPP rule.

Shocks	**Main causality**	**ERPT sign**
Monetary policy	Simultaneous	+
Productivity	CPI $\rightarrow NER$	-
Government spending	CPI $\rightarrow NER$	-
Foreign interest rate	NER $\rightarrow CPI$	+
Export demand/Foreign price Markup	CPI $\rightarrow NER$	-
Preference	Simultaneous	-
Investment	Simultaneous	+

Table 7.1: Dynamics of CPI and NER under different shocks

Table 7.1 outlines the transition of shock effects and ERPT sign. The major effect of shock might transit from NER to CPI and vice versa. There are also cases when the main effect of shock has a simultaneous impact on CPI and NER. For instance, let us consider monetary policy shock, which triggers a movement in nominal interest rate. The major impact is on NER directly via UIP rule and CPI through demand (investment and consumption) conditions. In contrast, under productivity shock, the principal effect is on CPI and then on NER. Similarly, the same dynamics can be observed under government spending shock. Now, a contrasting episode arises under foreign interest rate shock. The principal effect of this shock befalls on NER and then on CPI through demand conditions.

The last column of Table 7.1 shows the sign of ERPT degree on impact. The analysis shows that the sign of ERPT is mostly negative; only three out of fifteen shocks exhibit a positive ERPT degree. This is because the remaining twelve cases involve causality streaming from price to NER- CPI moves interest rate in the same direction (Taylor rule) and interest rate shifts NER in opposite direction (UIP). As a result, CPI and NER shifts in a different direction leading to a negative ERPT. In contrast, if the effect of shocks befalls on NER before hitting CPI, then ERPT sign is positive as transition goes through import prices and aggregate demand that moves CPI in uni-direction. Lastly, when the effect of shock has a similar impact on NER and CPI then everything depends on the type of shock (positive for monetary policy shock but negative for preference shock). The illustration in Table 7.2 summarises the behaviour of key variables in determining the sign of ERPT degree.

Shocks	**Interest rate**	**Exchange rate**	**CPI level**
Productivity	r↓	S↑	P↓
Labour supply	r↑	S↓	P↑
Preference shock	r↑	S↓	P↑
Government spending	r↑	S↓	P↑
Import price markup	r↑	S↓	P↑
Monetary policy	r↑	S↓	P↓
Investment*	r↓	S↓	P↓
Foreign interest rate	r↑	S↑	P↑
Export demand	r↑	S↓	P↑
Import demand	r↓	S↑	P↓
Domestic price markup	r↑	S↓	P↑
Export price markup	r↓	S↑	P↓
Foreign price	r↑	S↓	P↑
Foreign output	r↑	S↓	P↑

Table 7.2: The dynamics of nominal interest rate, nominal exchange rate and CPI level at the time of impact

To sum up, the sign of ERPT degree can be both negative and positive under different shocks. In most cases, it is negative due to the main causality flowing from CPI to NER, the presence of UIP condition and the nature of monetary policy in the model. This result also explains the outcome of past literature on the significance of monetary policy on a pass-through degree. Secondly, the short-run dynamics of CPI is determined in demand and supply conditions as well as the impact that comes from exchange rate movements through import prices. Therefore, the factors that determine the ERPT degree are current and future demand and supply conditions, and the nature of the monetary policy. This affirmation is similar to the one emphasized by K. Forbes, Hjortsoe, and Nenova (2018), that the reason behind shock-dependent ERPT is due to firms adjusting their price and markups differently under a different state of the economy. This is because they consider factors such as current and future demand conditions and marginal cost as well as competitor's prices.

Definition of pass-through. The literature defines pass-through as a percentage change in the price level over a percentage change in the exchange rate. Previously I have noted that the pass-through degree is shock-dependent and the reason for various pass-through estimates are due to transmission channels. Therefore, the structure of the model plays a significant role in the pass-through analysis. To understand the various degree of pass-through we will define pass-through as a percentage change in the short-run over long-run effect. That is

$$Pass-through \quad for \quad CPI = \frac{\triangle P^{SR}}{\triangle P^{LR}} \tag{7.1}$$

Similarly for exchange rate:

$$Pass-through \quad for \quad exchange \quad rate = \frac{\triangle S^{SR}}{\triangle S^{LR}} \tag{7.2}$$

However, to generate common pass-through degree utilised in the literature, we could use the following:

$$Pass-through = \frac{\triangle P^{SR}}{\triangle S^{SR}} = \frac{\triangle P^{SR}}{\triangle S^{SR}} * \frac{\triangle P^{LR}}{\triangle S^{LR}} = \frac{\triangle P^{SR}/\triangle P^{LR}}{\triangle S^{SR}/\triangle S^{LR}} \tag{7.3}$$

The above expression uses the fact that ratio of long-run pass-through equals to one.

According to equation (7.3), the pass-through degree is broken into price and exchange rate dynamics. This arrangement helps us to identify the reason behind different values of pass-through degree: whether it is due to a small or large response of price and exchange rate under different shocks hitting the economy.

Pass-through of the exchange rate to CPI price level. In the previous section, we consider the sign of ERPT degree. Let us now examine the magnitude. In the literature review, I have reported the magnitude of pass-through degree for the UK is based on both OLS and SVAR estimates. The results vary along with methodology and sample period. The economists argue that pass-through degree is non-constant-it changes over time. Thus, the sample period is crucial in estimating pass-through degree.

Table 7.3 shows the pass-through degree for the UK for both short and long-run periods where short-run ranges up to four quarters whereas long-run involves at least 20 quarters. It is clear that pass-through estimates vary with methodology and sample periods. For instance, Choudhri and Hakura (2006) reports estimates for 1979-2000 and use simple regression analysis. The analysis closest to my sample period is K. Forbes, Hjortsoe, and Nenova (2018). They implement SVAR and simple regression for 1993-2015, which produces different results under two methodologies. In contrast, L. S. Goldberg and José Manuel Campa (2006) document estimates for 1975-2003 with similar results between SVAR and simple regression. This corroborates my point about the literature that model assumptions, estimation methods and sample periods all matter in estimating pass-through. Here I set up a DSGE model with a unified theory (nominal rigidity) and test it rigorously against the fullest sample of data available; as noted, the model fits this data well.

Table 7.3: ERPT degree for UK from literature review

Authors	Model type	Short-run (1Y)	Long-run (4Y or full sample)
Choudhri and Hakura (2006)	Regression	0.02	0.03
K. Forbes, Hjortsoe, and Nenova (2018)	Regression	-0.01	-0.07
K. Forbes, Hjortsoe, and Nenova (2018)	SVAR	-	-0.13
J. E. Ihrig, Marazzi, and Rothenberg (2006)	Regression	-	0.04
L. S. Goldberg and José Manuel Campa (2006)	Regression/SVAR	-0.05	-0.11

Now, let us compare the literature estimates with the ones derived in this thesis. The table 7.4 below shows that pass-through from exchange rate to price level is different for different shocks in the short-run under estimated coefficients that include autoregressive parameters. From this table we conclude that short-run ERPT degree varies along with different shocks, eg. larger for monetary policy and productivity shocks while smaller for foreign interest rate shock. On the impact of shock, the highest ERPT degree is exhibited by productivity shock (-0.56) whereas the lowest is by foreign interest rate shock (0.08). The reason is that the domestic cost-push disturbance is the most costly shock in terms of the size and persistence of the inflationary impulse. Therefore, despite a gradual adjustment in prices, there is a higher expectation about future inflation, which in turn increases the total exchange rate pass-through.

Shocks	**On impact**	**1 year (avg)**	**Time to full ERPT**
Monetary policy	0.27	0.7	6 quarters
Productivity	-0.56	>1.0*	Long-run
Foreign interest rate	0.08	0.18	Long-run

Table 7.4: ERPT from nominal exchange rate to CPI

The change in nominal exchange rate is negligible compared to price level

The table also illustrates that within a year's time, the pass-through becomes over one for productivity shock since the movement in price exceeds the change in NER. In contrast, the ERPT degree for the other two shocks remains below one consistent with other literature. The magnitude of ERPT is larger for monetary policy shock than for foreign interest rate shock. The reason is NER fluctuates immensely under foreign interest rate shock implying a smaller pass-through degree. In terms of convergence to full ERPT, monetary policy shock converges faster than other shocks.

Table 7.5 shows the ERPT degree for the majority of structural shocks in the current model and confirms that ERPT degree varies with shocks. The highest pass-through degree on impact is generated by cost-push shocks followed by domestic demand shocks including preference and government spending. It is important to emphasise that all highest ERPT degrees on impact are of negative sign. However, over time, there is a sign change in ERPT due to long-run PPP conditions imposed on the model. Another interesting point is that ERPT degree is over one within 4 quarters for some shocks. This is due to near zero change in the nominal exchange rate, which makes a ratio of pass-through degree to be large- price level fluctuates more than the nominal exchange rate in medium run[9]. The magnitude of ERPT degree on impact for invest-

[9]The nominal exchange rate experiences depreciation after appreciation (or vice

ment shock is 0.17 and 0.18 in four quarters. These values are similar to estimates reported by other literature based on SVAR models. Another point to highlight from table 7.5 is that the convergence rate of ERPT to full pass-through is very slow for most of the shocks except for monetary policy and preference shocks. This analysis signifies the importance of model estimation while doing a study on a pass-through degree as the calibration or even more the simple regression may result in misleading conclusion.

*

Shocks	On impact	1 year (avg)	Time to full ERPT
Productivity	-0.56	>1.0*	Long-run
Labour supply	-0.62	>1.0*	Long-run
Preference shock	-0.6	>1.0*	6 quarters
Government spending	-0.47	>1.0*	Long-run
Import price markup	-0.52	0.93	9 quarters
Monetary policy	0.27	0.7	6 quarters
Investment	0.17	0.18	Long-run
Foreign price	-0.1	-0.1	Long-run
Foreign interest rate	0.08	0.17	Long-run
Export demand	-0.2	-0.14	Long-run

Table 7.5: ERPT from nominal exchange rate to CPI

The change in nominal exchange rate is negligible compared to price level

In contrast to past estimates, the size of the pass-through degree is significantly higher in the short-run (on impact as well). In the long-run, however, the model assumes that pass-through degree is one as price becomes flexible. Nevertheless, shocks such as foreign interest rate, investment and foreign price produce similar results as studies conducted by other authors. Then, I can conjecture that one or a combination of these shocks could be a dominant source of fluctuations in UK history during the period of consideration, 1989-2017. And similar to the literature, the convergence rate of the pass-through degree to CPI is gradual.

Figure 7.5 shows the evolution of pass-through degree over the simulation period. First, the pass-through degree on impact is negative for productivity shock while positive for the other three shocks. Second, the adjustment rate to full pass-through of one occurs gradually over

versa) and hence, changes will be zero at some point making ERPT degree more than one the long-run except for monetary policy shock. In the latter case, the shock effect is absorbed completely in 4-6 quarters (IRFs confirm this fact as well) and there is a one-to-one relationship between two variables. Finally, the behaviour of pass-through degree with investment and foreign interest rate shocks are quite similar: the estimate is low in the short-run while steadily converges to unity in the long-run.

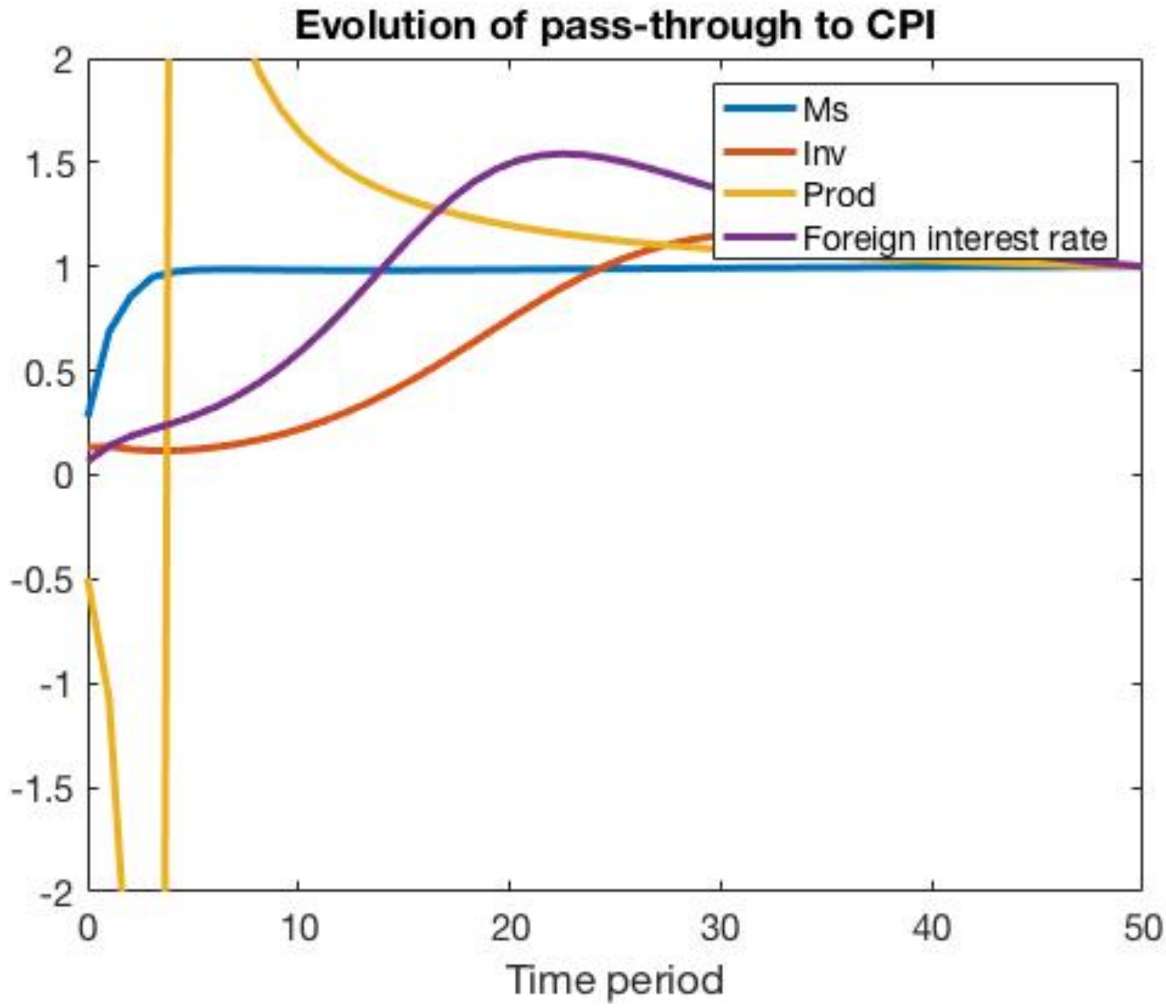

Figure 7.5: Pass-through to CPI

To understand the logic behind different ERPT degrees under different shocks, we need to split our pass-through degree into its price and exchange rate counterpart (equation 7.3). Figure 7.6 depicts the convergence rate of the price level and exchange rate to their respective steady-states over the simulation period. The left graph shows that CPI responds optimally under monetary policy shock as the impact value is quite close to its steady-state (0.65). However, the other two shocks exhibit modest movement in price level-when there is a shock, the CPI level is quite far from its long-run value.

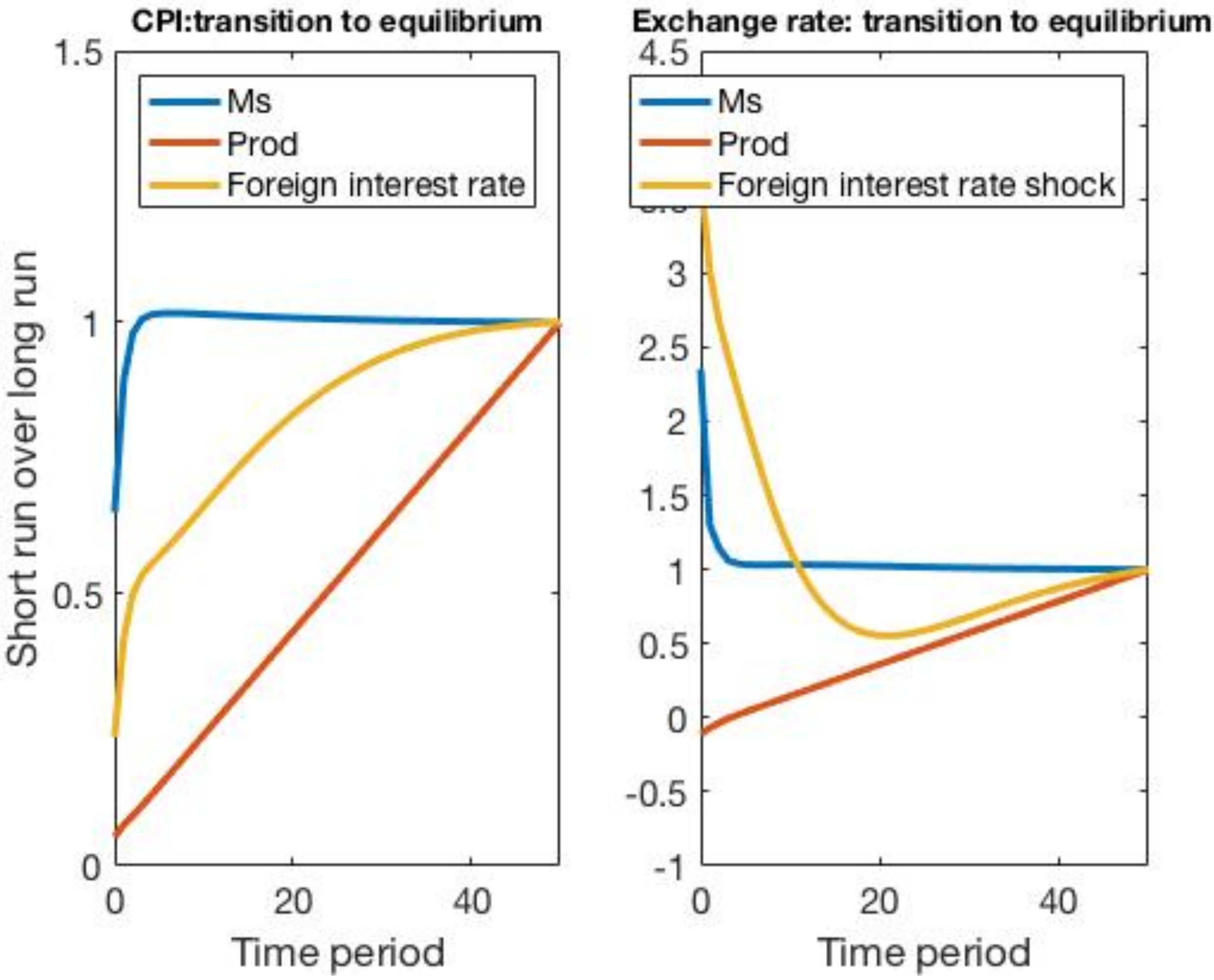

Figure 7.6: Pass-through to CPI and Exchange rate

Let us look at the dynamics of the nominal exchange rate from the right graph. Firstly, we can observe that NER changes sign under productivity shock as we have appreciation followed by depreciation. This implies a short-run negative ERPT degree as discussed above. Secondly, the response of nominal exchange rate is similar under the monetary policy and productivity shocks but we observe different ERPT degrees. This implies that a larger ERPT degree under monetary policy shock is due to larger movement in CPI level. Lastly, negligible size of ERPT degree with foreign interest rate shock is due to both larger response of nominal exchange rate and smaller movement in CPI [10].

[10]Larger response means further apart from optimal level and vice versa

In summary, we can confirm that ERPT degree is shock-dependent. The sign of ERPT degree in the short-run depends on the dynamics of the nominal exchange rate as aforementioned. The past literature with a positive ERPT degree is based on the assumption that PPP conditions are always satisfied implying that CPI and NER move in the same direction. This causes ERPT degree to be positive at all times. However, in general equilibrium, the short-run movement in NER is not determined by PPP conditions but in the UIP equation.

The size of ERPT degree, on the other hand, depends on relative movements of CPI and exchange rate to its corresponding steady-states. For instance, we observe lower ERPT under foreign interest rate shock due to negligible shift in CPI versus exchange rate, while higher ERPT degree under productivity shock mainly due to minor movement in NER.

The next question is why these variables move differently under various shocks? The primary cause lies in different behaviour of individuals to different shocks. For instance, firms adjust their prices more in response to monetary policy and government spending shocks than to foreign interest rate shock. Similarly, the nominal exchange rate fluctuates a lot under foreign shocks than under domestic supply shocks. Thus, as the shock varies then so is the feedback on the exchange rate and price level, which generates different pass-through degrees.

This different behaviour of the economy technically can be reflected in causality running between CPI and NER in both directions. In simple regression, a disturbance term does not implicate different ERPT degrees. In contrast, in general equilibrium, the ERPT degree is specific to certain disturbances. For instance, foreign interest rate shock hits nominal interest rate, which in turn adjusts movement in demand conditions and hence price level (causality from NER to CPI), where the latter eventually perturb nominal interest rate again (causality from CPI to NER). This is a key explanation as to why ERPT is shock-dependent.

Summary on pass-through degree. The analysis confirms that the pass-through degree is shock-dependent. The different magnitude of ERPT degree reflects the different behaviour of the economy under the different distribution of macroeconomics shocks. In other words, the demeanor of firms that set different prices in response to shocks and the type of regime pursued by monetary authority determines the pass-through degree. From a technical perspective, the relative movement of CPI to NER varies along with shocks. It varies because the causality between these variables flows in both directions unlike in a simple regression.

The sign of ERPT degree on impact also varies along with shocks but strictly positive in 4 quarters. The past literature with positive ERPT degree depicts the situation where PPP conditions are always satisfied [11] where CPI and NER move in the same direction. In the current paper, however, short-run NER is determined in the UIP equation while demand and supply conditions along with the exchange rate channel stipulate the price level.

[11] Since regression represents average ERPT degree over all time horizon

Chapter 8

Shock processes

In general, structural residuals in the DSGE model are serially correlated. There are fifteen auto-regressive disturbances in the model. Twelve of them are in structural equations while the remaining three are exogenous variables representing foreign economy. And one of the structural errors is non-stationary (technology shock). According to the setup, since structural errors are not directly observable, they are backed from the model equations using both data and estimated parameters. If the the expectational term enters the equation, then expectational variable is estimated using a robust instrumental variable technique from Wickens (1982). They are basically the one step ahead forecasts from estimated VECM.

If the shock process is stationary then its form takes the following equation:

$$\epsilon = \alpha + \rho\epsilon_{t-1} + \gamma t + \eta_t \tag{8.1}$$

where τ_t is i.i.d. mean zero innovation term. If γ is non-zero then the shock is trend stationary. The innovations are derived from fitted version of equation (8.1), from fitted residuals. These innovations are used to bootstrap the model.

The Solow residual is a unit root process taking the following form:

$$A_t = \alpha + A_{t-1} + \rho(A_{t-1} - A_{t-2}) + \eta_t^a \tag{8.2}$$

In the long-run, when all innovations are ceased to exist, the growth rate of technology converges to a constant. As a result, all model variables grow at a same constant rate along a balanced growth path (BGP). This growth rate is a function of deterministic trend in the residual (technology process).

Now let us look at the estimated parameters of shock processes (estimated by IIW), which is displayed in Table 8.1. The reported parameters are then being tested by Augmented Dickey-Fuller (ADF) and Kwiatkowski-Phillips-Schmidt-Shin (KPSS) tests. The null hypothesis is that structural disturbances have a unit root, $AR(1) = 1$ or shock process ϵ_t $I(1)$, with a confidence level of 5%. The table shows that all shocks are stationary except Solow residual, which contains a stochastic trend. These results are in line with initial model expectations- apart from technology shock, the other exogenous disturbances are assumed to be stationary (or trend stationary). The deterministic component of the technology stochastic process generates balanced growth path (BGP). After the model is simulated, the pure effect of shocks adds to the BGP. And that is how we compare the properties of unfiltered sample data and data derived from the model equations.

Shock processes			
Shock	Process	AR(1)	Standard deviation
Labour supply	Stationary	0.95	0.04
Preference	Stationary	0.79	0.003
Monetary policy	Stationary	-0.2	0.007
Investment	Stationary	0.96	0.05
Gov spending	Stationary	0.61	0.04
Export demand	Stationary	0.94	0.08
Productivity	Non-stationary	0.01	0.007
Import demand	Stationary	0.83	0.04
Markup domestic price	Stationary	0.97	0.01
Markup import cons price	Stationary	-0.32	0.02
Markup import input price	Stationary	0.32	0.01
Markup export price	Stationary	0.95	0.03
Foreign int rate	Stationary	0.87	0.006
Foreign output	Stationary	0.94	0.01
Foreign price	Stationary	0.96	0.004

Table 8.1: Stationary features are tested by ADF and KFSS tests

8.1 Historical shock decomposition

In general, fluctuations in macroeconomic activity are explained in terms of various shocks. In this section, I turn to investigate how the historical contribution of each of seven groups of shocks -shocks to labour supply, demand shocks, monetary policy, investment, productivity shock and foreign shocks - to the sterling exchange rate and CPI over 1989Q1 - 2016Q4. This assessment helps to understand the relative importance of different shocks over time.

The historical decomposition of the shocks to the nominal exchange rate is displayed in Figure 8.1[1]. Looking at the graph, I can deduce that there are some similarities as well as differences in the source of exchange rate movements[2]. The shift in the policy of the Bank of England towards a lower targeting inflation rate in 1998 appreciated the exchange rate significantly, which was mainly associated with monetary policy and investment shocks. At the end of 2008, UK experienced a large current account deficit initiating a sharp depreciation in the sterling exchange rate. The dominant effect is coming from domestic demand (except investment shock) and labour supply shocks that made a major contribution to the exchange rate movements. After the financial crisis, another contrast in exchange rate movement is observed between 2013-2015- appreciation with significantly a larger role belonging to investment shock. Although the efforts on stabilising exchange rate level prior to the crisis period had been successful till 2016, sterling repeatedly depreciated to a record level against top trading partners after the Brexit referendum vote in the third quarter of 2016. The departure from the European Union imposed uncertainty on the UK's future trading policy, generating a lack of confidence in businesses. And the largest share of uncertainty taken by investment shock. To sum up, a movement in sterling since 1989 was due to different sources of uncertainties. However, the investment shock seems to be the main contributor in recent years in fluctuating exchange rates about its trend.

[1]The vertical axis shows the share of each shock in levels

[2]Demand shocks include model's four demand shocks excluding investment shock; markup includes all markups; foreign shocks include all three foreign shocks

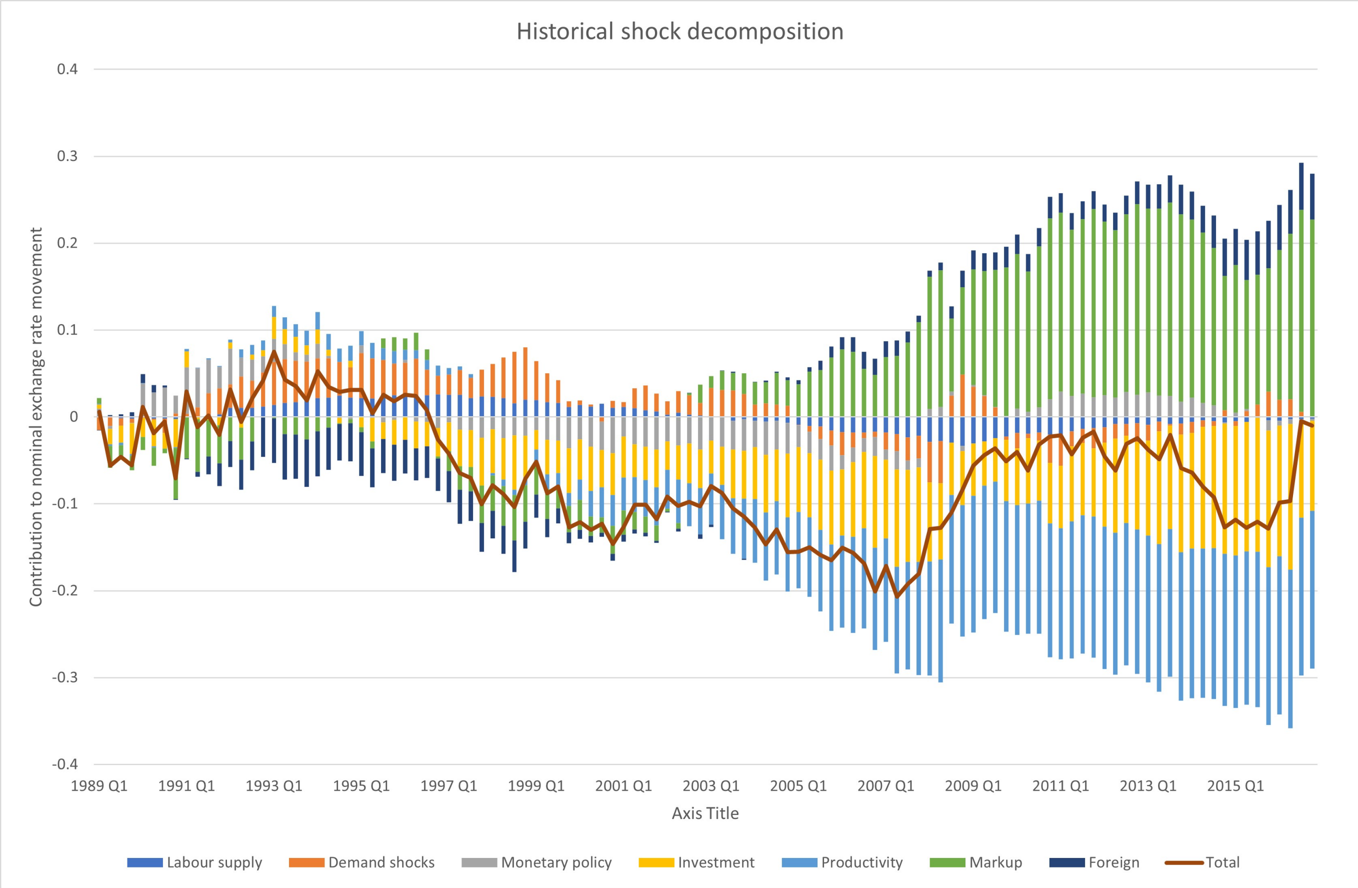

Figure 8.1: Historical decomposition for nominal exchange rate

Figure 8.2 decomposes the movement in CPI price level into the corresponding contributions from the seven shocks during three recent events in the UK economy[3]. First, the graph depicts that price was mainly driven by markup and monetary policy shocks prior to 1998. Second, we observe that the consumer price level has been constantly declining since 1997. A switch in the monetary policy regime successfully decreased the price level as inflation rate subsided greatly over these years. However, the price level has increased slightly during the financial crisis. Although the contribution of investment shock is the most discernible, we observe that an increase happened due to fading effect of other demand and labour supply shocks (orange line disappears whereas blue line shrinks). A negative impact of technology shock during this period was offset by markup and foreign shocks. Between 2013-2015, similar to the exchange rate, the price level recovers its prior crisis trend and hence starts to decline steadily. The productivity shock is the one that aids the drop in CPI level during this period along with a negative

[3]The vertical axis shows the share of each shock in levels

contribution of investment shock. Nevertheless, positive markup shocks partly counterweight this negative effect. The next contrast movement in CPI level occurs during the Brexit event in 2016, where the level starts to increase.

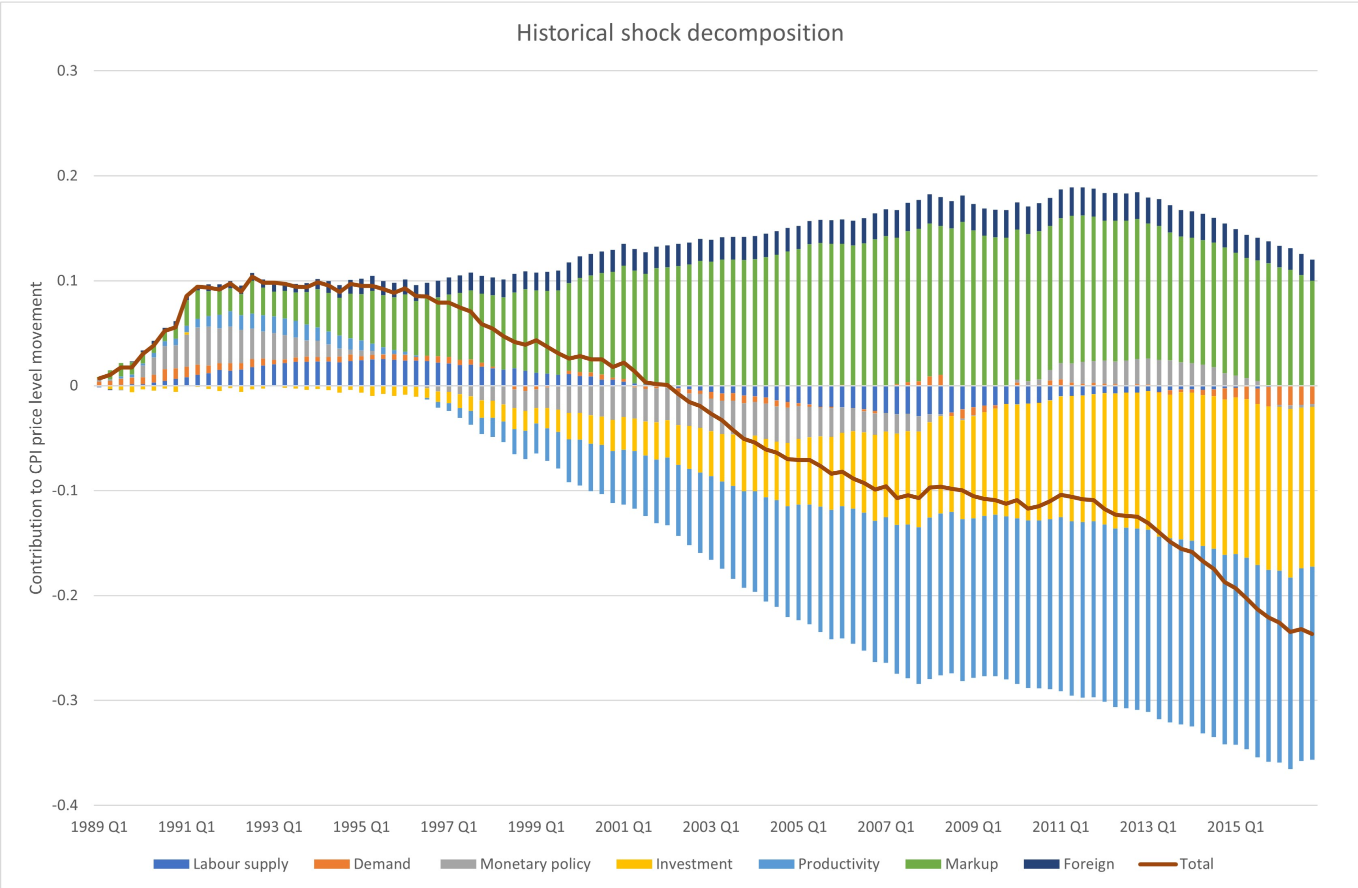

Figure 8.2: Historical decomposition for CPI price level

In conclusion, the sources of fluctuations in CPI and nominal exchange rate are different within the same period (and clearly over time). Therefore, we cannot deduce which shock was the root of higher or lower pass-through during a certain point of time in UK history. The reason is simple: the model is a general equilibrium- where the causality runs in all directions- with all shocks present in the economy at all times. We could do so if the same shock was the largest source of movement in all variables, which is unfortunately not the case here[4]. This is in contrast to previous literature, which derived conclusions based on historical shock decomposition. We could still emphasize that in recent years the contribution of investment shock has been a major trigger

[4]Appendix G presents historical decomposition for output

in movements of both CPI and nominal exchange rate in recent years. However, I cannot conclude that investment shock was a source of lower pass-through degree in UK history[5]. This is because investment shock was not the only source of fluctuation in all major macroeconomic variables.

8.2 Variance decomposition

In this section, I attempt to answer the question of what are the main drivers of the sterling exchange rate and CPI level between 1989 and 2016. Variance decomposition is a method to quantify how important each shock is in explaining the variation in each of the variables in the reduced form of the structural model over all periods.

Variance decomposition 1989Q1:2016Q4				
Shocks	Exchange rate	CPI level	Output	Interest rate
Labour supply	5.1	4.75	3.04	1.5
Demand shocks	1.08	0.63	0.52	13.6
Monetary policy	2.7	2.25	0.1	10.0
Investment	72.0	77.0	86.0	19.0
Productivity	1.05	0.88	5.53	1.13
Markup	9.34	8.0	4.0	23.0
Foreign shocks	8.84	6.54	1.0	30.0

Table 8.2: Variance decomposition for NER, CPI level, Output and Interest rate

The table 8.2 shows the variance decomposition of the sterling exchange rate, CPI level, output and nominal interest rate with estimated parameters and observed data. It can be seen that around 72 % of the sterling exchange rate variation is due to the investment shock. This could be due to investment demand being financed by net foreign assets, which in turn affects the exchange rate dynamics. The next largest contributor belongs to markup and foreign shocks, each having a share of 10%. Note that the former includes import, export and domestic markup shocks. Unexpectedly, foreign shocks explain a minor fraction of the total variations in all variables in contrast to previous literature

[5]Table 7.5 shows that pass-through degree on impact is 0.17 and 0.18 in the long-run for investment shock

on VAR analysis[6]. The result is quite similar to historical shock decomposition where the results report the significance of investment shocks in recent years.

Similarly, the table illustrates that investment shock accounts for more than 77% of the error variance of CPI level. The next bulk of variation comes from markup shocks as the CPI level is a weighted average of domestic and import prices. Lastly, all demand shocks such as government spending and import demand together contribute only 1% of variation. A similar conclusion can be drawn on output level where the largest share goes to investment shock. A quite distinct result is observed on the nominal interest rate. Over the whole period, a movement in nominal interest rate can be explained by fluctuations in foreign and markup variables (together they contribute 50% of variation). The next largest contributor relates to investment and monetary policy shocks.

Summarising the outcome of shock processes we might conclude that investment shock, in general, is the main cause of fluctuations in the variables of interest. The lower pass-through degree in the UK might be partly explained by investment shock. However, as I stated in chapter 7, the lower pass-through degree mainly is due to model structure. In this thesis, a lower pass-through degree is due to nominal rigidities. And I assume that the pass-through degree remains constant throughout the period. And the model with these assumptions was tested by a powerful Indirect Inference test. Since the model passed the test, the presence of nominal rigidity and a constant pass-through is valid for the UK economy for the period of estimation. Thus, the nominal rigidity is the source of the sluggish response of prices to exchange rate movements. In addition, there could be other reasons such as the presence of non-tradable goods in the economy (home intermediate goods) as this specification was also included in the model.

[6] K. Forbes, Hjortsoe, and Nenova (2018)

Chapter 9

Policy analysis

Chapter 6 described the transmission channels of the economy between exchange rate and inflation. Due to the open economy part of the model, there are additional channels for the transmission of monetary policy via the exchange rate: the sensitivity of net exports to the exchange rate and the direct effect of the exchange rate on import prices.

The discussion about the relationship between exchange rate and inflation in UK policy debates has evolved with different monetary policy regimes. According to Kara and Nelson (2003), in 1976, the Government assumed that 10% depreciation in sterling leads to 2.9% change in retail price annually[1]. During UK's early membership in Exchange Rate Mechanism (ERM), the Government strongly argued that there is a strong correlation between exchange and inflation and hence, there is no room for independent movement in the cost of production[2]. On the other hand, the debate on the relationship between exchange rate and inflation has been in discord in the aftermath event of the UK returning to a floating exchange rate. Some advocated in favour of weak correlation[3] while Bank of England (Inflation Report of February 1994) reported on full pass-through to import prices (one-to-one relationship). These observations might indicate that the pass-through degree is dependent on the monetary policy.

The literature on optimal monetary policy under imperfect pass-

[1] Written answer in Parliament by Edmund Dell on behalf of the Chancellor of the Exchequer, House of Commons Hansard, 24 March 1976, p. 215

[2] HM Treasury, 1992, p. 8

[3] HM Treasury, 1993, p. 24

through is extensive. The majority supports the idea that policy is endogenous to a pass-through degree. There are two classifications of studies that relate policy regimes to a pass-through degree. The first strand examines the impact of the inflation environment on the pass-through. The Bank of Canada's November 2000 report states that "the low inflation environment itself is changing price-setting behaviour. When inflation is low, and the central bank's commitment to keeping it low is highly credible, firms are less inclined to quickly pass higher costs on to consumers in the form of higher prices". The literature on this subject commences from the study by Taylor (2000), who argues that nominal anchor in the inflation targeting regime significantly reduces the responsiveness of price level. In addition, with the forward-looking nature of the model, real shocks arising from various channels (demand or foreign interest rate shock) will also have a limited effect on the price level.

The statement by a central bank to maintain low and stable inflation helps to explain a low pass-through degree we find in the data. Another literature by Carriere-Swallow et al. (2016) found that greater credibility of monetary policy acts to reduce the degree of exchange rate pass-through to consumer prices in a sample of 62 economies. The decision of price-setting firms about whether to transmit changes in their cost to domestic consumers due to exchange rate movements is likely to be forward-looking. Indeed, Taylor's argument for endogenous pass-through originates from the idea that pricing decisions will depend on the inflation shock persistence, which is in turn linked to the degree of anchoring of inflation expectations. Thus, the expectation about future inflation is informative for pass-through dynamics.

The impact of monetary policy on pass-through has also been analysed by J. E. Gagnon and J. Ihrig (2004). Their contribution is the formal derivation of the linkage between monetary policy and exchange rate pass-through to consumer prices. This hypothesis was tested in 20 countries between 1971 and 2003 including the UK. They found a statistically significant link between the pass-through estimate and inflation variability. The estimate of the pass-through degree tends to decline in countries with regimes shifted towards inflation targeting, supported by the evidence of an increase in the responsiveness of policy rate to expected inflation. The paper develops a theoretical model that explains how regime change influences inflation expectations and consequently pass-through.

The second strand of literature examines the type of optimal monetary policy that minimizes the welfare loss associated with nominal rigidity under imperfect pass-through. In other words, policy authorities are looking for a target variable they should pursue to optimise welfare. The monetary policy under discretion has been studied by Smets and Raf Wouters (2002) whereas Monacelli (2005) resorts to commitment. Monacelli articulates that under commitment central bank trades off some volatility in output gap in favour of stronger stabilization of LOP (law of one price) gap and in turn a stable inflation rate. The intuition is that policy authorities can manipulate future private sector's expectations, which gives rise to gains from commitment relative to discretion.

The literature on the closed economy shows that the welfare implications of monetary policy are to target consumer-based price index (Goodfriend and King (2001)). A similar result holds for the open economy case (Monacelli (1999), Clarida, Gali, and Gertler (2001)). In contrast, Sutherland (2005) shows that domestic inflation stabilisation rather than CPI stabilisation is optimal under full pass-through degree when import prices are fully flexible. He reasons that flexible price outcome is restored when policy regime targets sticky home prices. This idea is also confirmed by Friedman (1967) concluding that the central bank can achieve a flexible price efficiency level by targeting inflation in the rigid price sector. Another example is M. Devereux (2001) who finds that stabilising sticky non-traded goods inflation rate performs the best in particular if pass-through is less than unity. The paper's welfare judgement, though, is based on an ad hoc examination of the volatility of output, inflation, and consumption. In general, the problem with sticky prices is that the real side of the economy does not immediately respond to money or productivity shocks as they would in a flexible price environment. If the authority targets home price, then it will stabilise the economy by setting interest rate such that domestic price always equals marginal cost. However, the case gets complicated if the economy observes rigidity in both domestic and import sectors.

Under full pass-through, which is widely used in the literature, movements in nominal exchange rates bring out real short-term adjustments. The point is that monetary policy relies on nominal exchange rate adjustment in the presence of macroeconomic shocks. The movements in the exchange rate achieve a necessary change in relative prices (Friedman (1967)). Consequently, the flexible price equilibrium is attainable if the exchange rate is employed as a part of monetary policy. However, if pass-through is incomplete due to prices being rigid in local markets the same real adjustment requires a larger change in the nominal exchange rate. The movements in the exchange rate have a limited effect on prices faced by consumers, the so called "expenditure switching effect" (the ability of nominal exchange rate to adjust relative prices) may be negligible. Consequently, the outcome predicted by flexible price models would no longer be feasible (Smets and Raf Wouters (2002)).

The model in this thesis exhibits both import and domestic price stickiness implying limited pass-through. Monacelli (2005) states that in this situation with imperfect pass-through flexible price allocation is no longer feasible and hence the monetary authority faces a trade-off between stabilising inflation and stabilising the output gap or LOP gap. For instance, when there is a productivity shock, the exchange rate depreciates to accommodate the rising supply. However, depreciation causes inflation in the import sector and consequently distortions in output due to staggered price-setting in this sector (Smets and Raf Wouters (2002)). Nevertheless, a stable CPI inflation can alleviate some inefficiency despite having the relative price distortion that occurs due to both rigid domestic and import prices. This idea stems from Woodford (2001). He argues that in a model with nominal rigidities, where deviations between sticky and flexible prices occur, the distortions in the relative price of goods can be minimised by keeping the general price level stabilised. Stabilisation of CPI inflation reduces uncertainty about future consumption, which is welfare improving for the model.

Smets and Raf Wouters (2002) analyse the implication of sticky home and import prices for optimal monetary policy in the calibrated DSGE model. They also verify that flexible price outcome is infeasible. The reason is that incomplete pass-through limits the effectiveness of the exchange rate channel. As a result, more adjustment is required in the interest rate channel which primarily affects domestic demand.

Nevertheless, there are studies that confirm that estimates of pass-through degree have a low correlation with the nature of the monetary policy. Kara and Nelson (2003) is one such example. The paper reports that the inflation and exchange rate relationship in the UK is robust to the monetary policy regime. In other words, the relationship between consumer price inflation and the exchange rate tends to be quite weak across regimes. Secondly, they conclude that the pass-through to import price is high in the UK in the last four decades, even though exchange rate changes and CPI are weakly correlated. This also confirms the fact that there is much more pass-through of exchange rates to imported goods prices than to final consumer prices.

The empirical findings for the UK reveal that pass-through to domestic prices has declined in 1992. The change in the rate of pass-through has been attributed to increased emphasis on inflation stabilisation by the Bank of England. When the central bank aggressively stabilises domestic inflation, it tightens policy to offset any inflationary stimulus from a rise in import prices. In such an environment, firms are less likely to direct fluctuations in their input prices to output prices, both because the central bank applies countervailing pressure and because firms believe that the authorities will be successful in stabilizing inflation. This analysis explains why inflation or price targeting creates a lower pass-through degree in comparison to nominal GDP targeting.

The causality between pass-through degree and monetary policy might run in a different direction. That is, knowing the pass-through degree alters the decision on policy to be conducted. Despite ambiguous arguments in the literature, being aware of pass-through degrees is important for policy-makers. Thus, most of the central banks try to estimate the rate of pass-through degree. According to K. Forbes, Hjortsoe, and Nenova (2018), the economists suggest that policy-makers should not calculate pass-through degree using “rules-of-thumb” (simple regression) to predict how an exchange rate movement will affect prices. Instead, they should use a general equilibrium framework to capture the entire dynamics of the economy.

The objective of this chapter is to evaluate the welfare effects of alternative policy regimes. The thesis aims to see if new regimes still operate according to the data and if we could observe a similar behaviour with other monetary policies under the DSGE model. In this thesis, the model with the consumer price inflation targeting rule has been estimated and tested. Since the model passed the Indirect Inference test, it is the "correct" model for policy analysis. I use the estimated structural parameters along with alternative monetary regimes as this complies with the Lucas critique (that structural parameter estimates should be used in policy evaluation). I expect the pass-through to change with new rules and the thesis shows how exactly the change will occur.

9.1 Core inflation targeting

This section explores the performance of the model under core inflation targeting in the Taylor rule. The literature argues that CPI may not be the best measure of inflation for policy purposes. Thus, they tend to focus on more persistent movements in prices, core inflation. The intuition is that monetary authorities may be less concerned with fluctuations in prices, but rather target the underlying trend. The core inflation reflects this general trend in inflation. The core inflation is a measure of inflation that excludes short-run fluctuations and it represents changes in prices that are not a direct concern of monetary authority. The idea is that policy-makers may prefer not to react to certain fluctuations in prices just because they may assume that the deviation from target inflation may quickly reverse on its own. Therefore, core inflation attempts to abstract from noises such as seasonality or the timing of particular price changes. In addition, there could be other short-term movements beyond the control of policy authorities. These shocks to price level are idiosyncratic in nature and can be regarded as relative price shifts. Examples include changes in supply and demand such as shifts in tastes or indirect taxes. The modified Taylor rule then takes the following form:

$$r_t = \mu r_{t-1} + (1-\mu)(r_p \pi_t^{core} + r_y y_t) + r_{\triangle\pi}(\pi_t - \pi_{t-1}) + r_{\triangle y}(y_t - y_{t-1}) + ln\varepsilon_t^r \tag{9.1}$$

where $\pi_t^{core} = \pi_{t-3} + \pi_{t-2} + \pi_{t-1} + \pi_t)/4$ is core inflation. The aim of this section is to examine the pass-through degree and welfare implications under alternative monetary policy regime.

9.1.1 Pass-through degree

Before commencing analysis on pass-through degree, I will illustrate the impulse response of key variables to macroeconomic shocks as the IRFs are used to estimate the pass-through degree.

Figure 9.1 shows the IRFs for non-stationary productivity shock to intermediate goods production. The dynamics of key variables are consistent with the case of the standard Taylor rule except for the nominal interest rate that actually rises on impact. The intuition is that monetary policy does not have to respond directly to falling inflation by reducing the interest rate since policy-makers care about average inflation only. The nominal interest rate actually rises to offset rising expected inflation by increasing the current output gap.

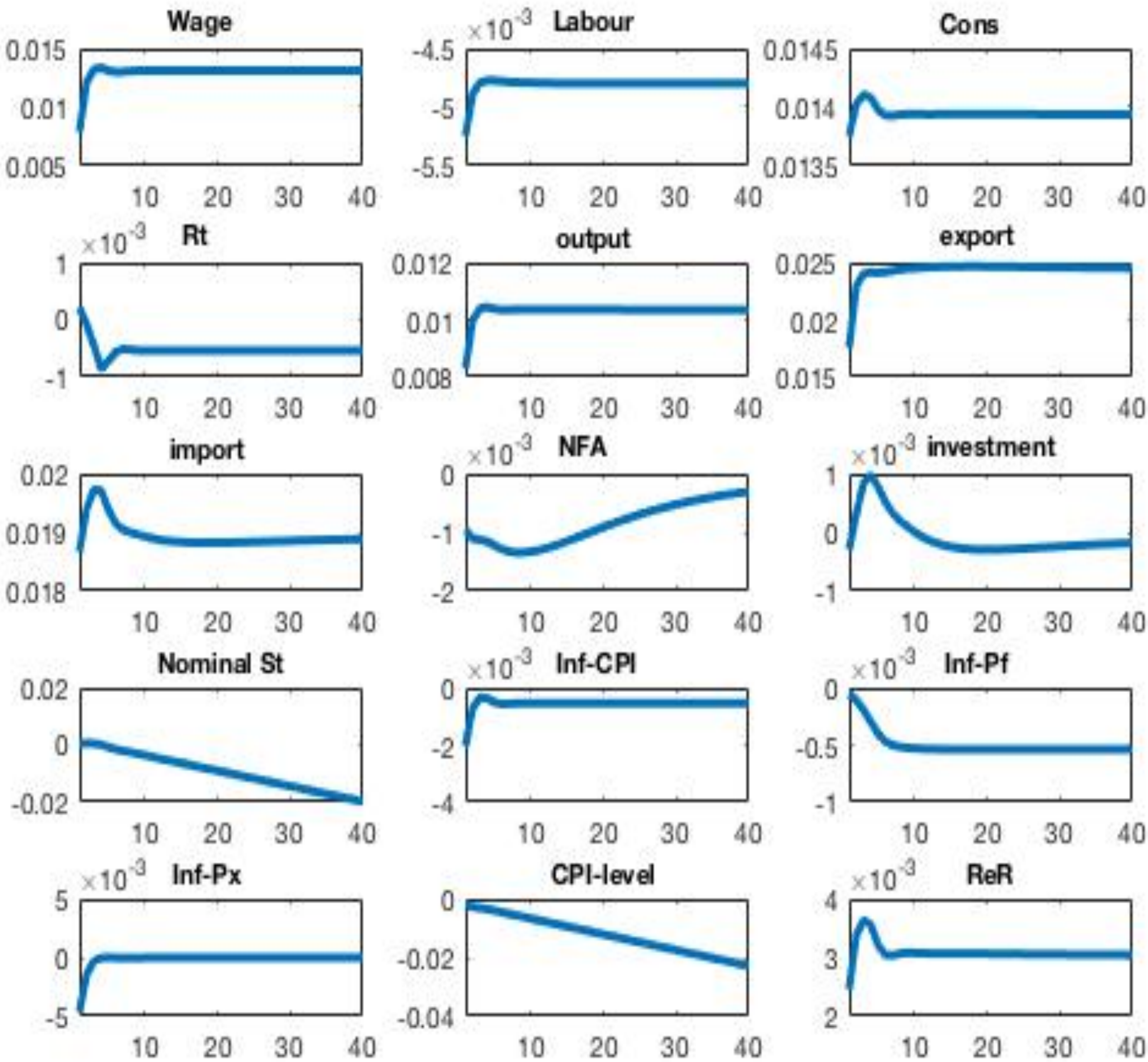

Figure 9.1: Response to 1% Productivity shock under core inflation targeting

Similarly to productivity shock, the behaviour of key variables is similar to the inflation targeting case. The graphs can be found in Appendix B at the end of this thesis.

Pass-through The pass-through degree for shocks is displayed in Table 9.1. As noted in chapter 7, a sign of ERPT degree is similar to the inflation targeting case. However, the magnitude is larger in the current situation. To identify the reason, let us look at Figure 9.2 that displays the dynamics of CPI and NER to their steady-state. The comparison of this graph to the one under IT regime reveals that, on average, under core inflation the price level moves optimally (close to its long-run value)[4]. For instance, both monetary policy and foreign interest rate induce a larger movement in price. On the other hand, the movement in NER is shock-dependent- a higher response under the monetary policy but lower for Euler shocks. To sum up, ERPT degree is similar under two policy regimes. Albeit there are few shocks where pass-through degree significantly increases due to more optimal response of price level.

*

Shocks	**On impact**	**1 year (avg)**	**Time to full ERPT**
Productivity	>-1.0	>-1.0*	Long-run
Labour supply	>-1.0	>1.0*	Long-run
Preference shock	-1.31	>-1.0	7 quarters
Government spending	-0.67	0.67	Long-run
Import price markup	-0.75	-0.75	12 quarters
Monetary policy	0.25	0.79	3 quarters
Investment	0.17	0.18	Long-run
Foreign price	-0.11	-0.11	Long-run
Foreign interest rate	0.09	0.19	13 quarters
Export demand	-0.23	-0.23	Long-run

Table 9.1: ERPT from nominal exchange rate to CPI under core inflation targeting

The change in nominal exchange rate is negligible compared to price level

[4]For some shocks such as productivity, the dynamics of the price level is similar to IT regime case

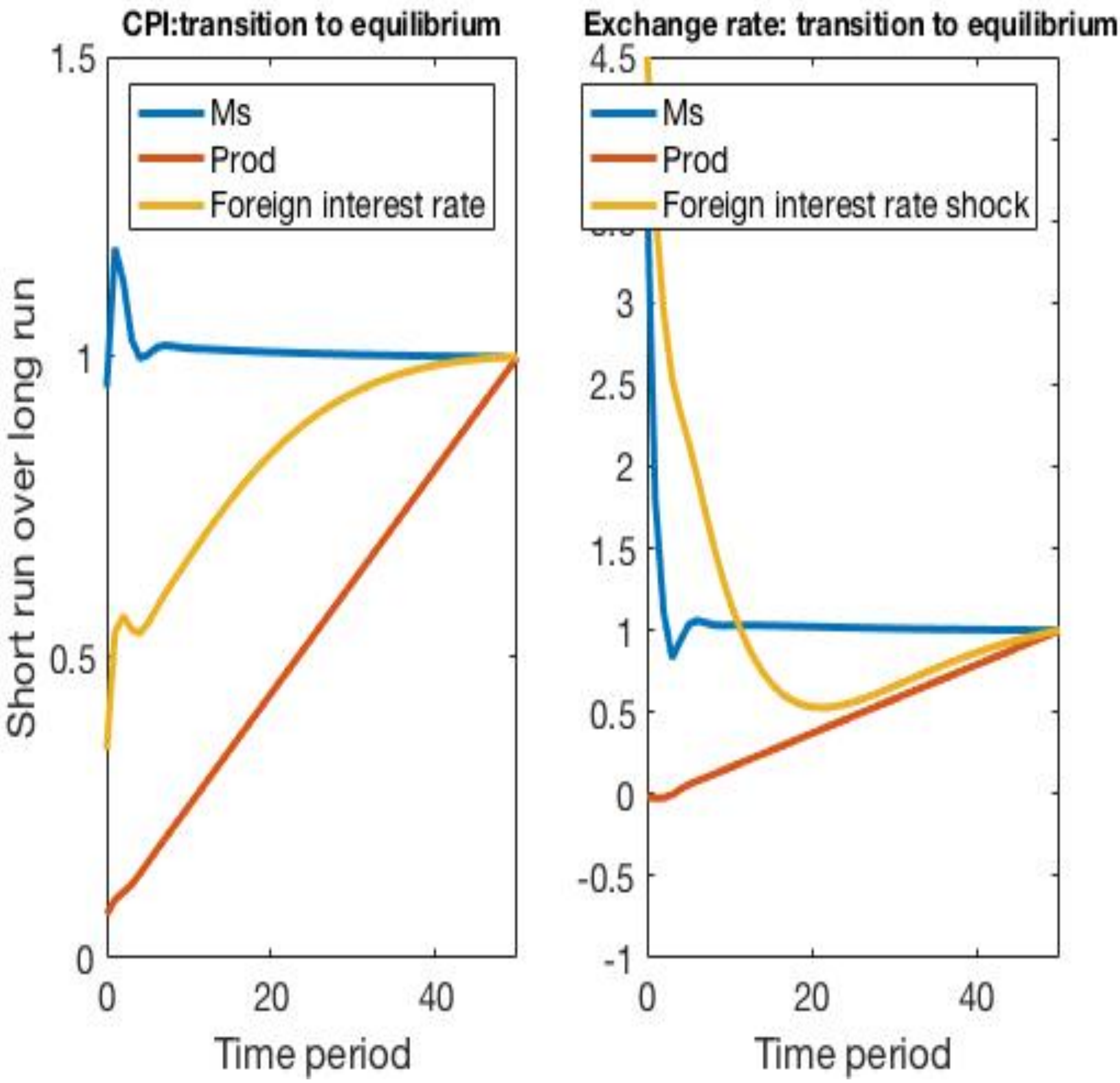

Figure 9.2: Response to 1% Transition to steady-state for CPI and NER under core inflation targeting

9.2 Price targeting

The fundamental difference between price and inflation targeting is the consequence of missing the target. For instance, if inflation is high today, this would be followed by below the average inflation under price targeting in order to return the price level to the target. This is because the central bank has to counterbalance past inflationary shocks making the price targeting regime "history dependent" (Woodford (2004)). On the other hand, inflation targeting policy is obliged to keep inflation around average regardless of the level of current and past inflation rates.

The advantage of price-level targeting over inflation targeting can be explained by the following example when the economy is affected by negative demand shock. Under price-level targeting, this creates a future expected inflation above the target, which in turn decreases real interest rate today and hence stimulates the economy. In addition, the New Keynesian features of the model allow an increase in current inflation. In contrast, the inflation targeting regime anchors expected inflation around the target. Hence, cutting the interest rate is the only remaining option to overcome the effect of a negative demand shock. Thus, we may conclude that welfare gains are larger under price tarting than inflation targeting when the economy hits the zero lower bound. Hatcher and Minford (2016) argues that price targeting outperforms inflation targeting in the New Keynesian macro model with rational expectations when policymakers commit to Taylor-type rules. In general, rules are more relevant for central bank policies in practice unlike optimal policies such as commitment and discretion since they are easy to implement and robust across alternative models.

The modified Taylor rule then takes the following form:

$$r_t = \mu r_{t-1} + (1-\mu)(r_p p_{tt} + r_y y_t) + r_{\triangle\pi}(\pi_t - \pi_{t-1}) + r_{\triangle y}(y_t - y_{t-1}) + ln\varepsilon_t^r \tag{9.2}$$

9.2.1 Pass-through degree

Before beginning analysis on pass-through degree, I will illustrate the impulse response of key variables to macroeconomic shocks as the IRFs are used to estimate the pass-through degree.

Productivity shock. Figure 9.3 depicts the IRFs for non-stationary productivity shock to intermediate goods production. The behaviour of most variables are identical to inflation targeting rule. However, there are noticeable difference in the behaviour of NER and CPI price level.

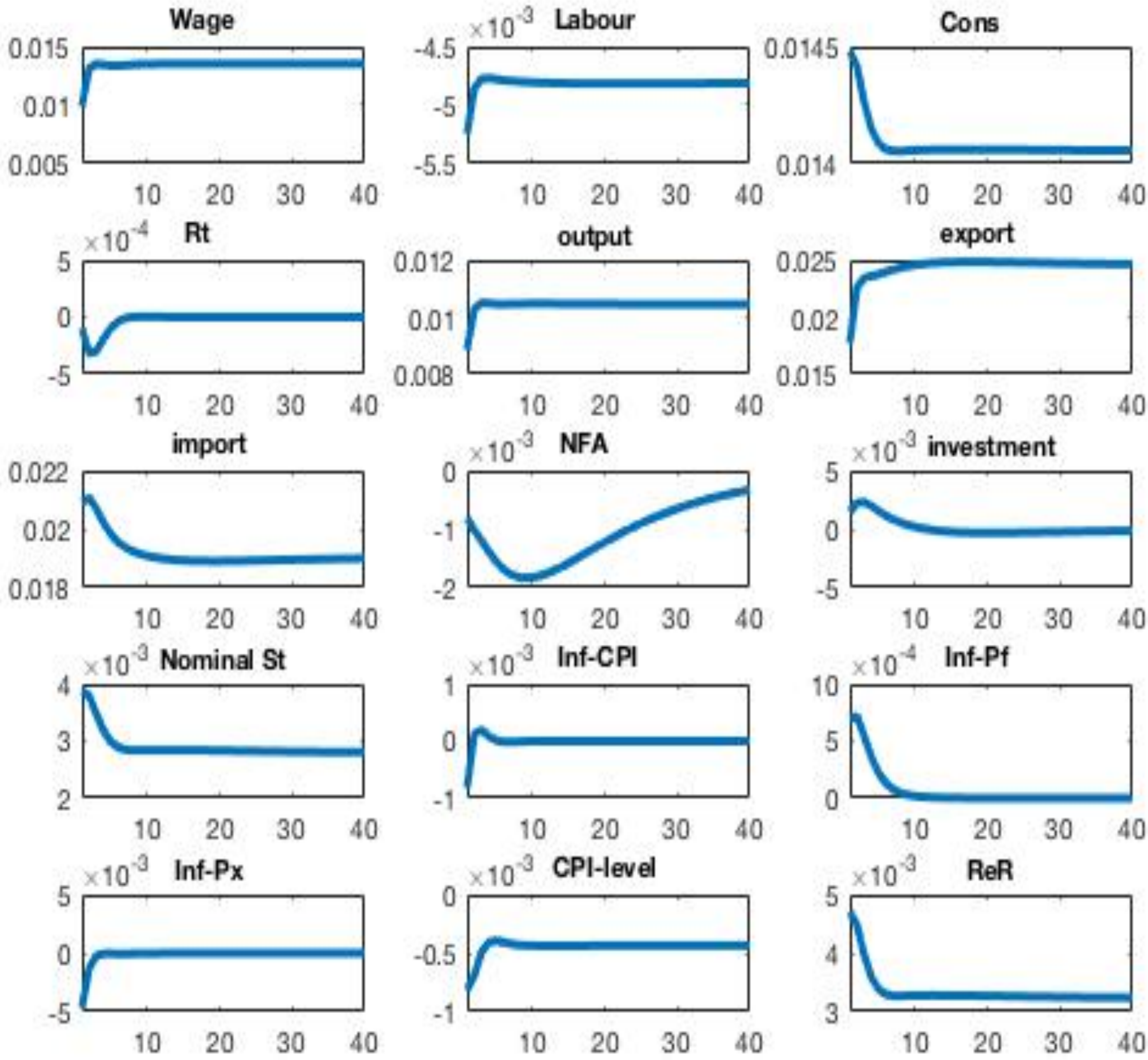

Figure 9.3: Response to 1% Productivity shock under price level targeting

The positive shock to supply exerts negative pressure on CPI inflation. The price level targeting creates an automatic expectation of future inflation as the price level falls and hence, we observe positive expected inflation as shown in the graph. In effect, the total sum of inflation has to be zero over the simulation period (deflation followed by inflation so that changes in CPI level remain zero). Note that, positive expected inflation partially offsets declining nominal interest rates.

Thus, a decrease in the nominal interest rate is smaller than the inflation targeting case. The next apparent observation is that NER always appreciates in contrast to the previous case with expected nominal depreciation. This implies a negative ERPT degree both in the short and long-run. In the long-run, PPP must be satisfied. The economy that expects the price level to return its deterministic trend, does not exert a negative impact on the current nominal exchange rate. This is in contrast with inflation targeting rule, where constantly falling price level entails future nominal depreciation.

Pass-through The pass-through degree for three shocks is displayed in Table 9.2 [5]. The magnitude of the ERPT degree is smaller for all three shocks, particularly, for productivity shock. In terms of convergence of ERPT degree to the perfect pass-through, the time horizon is getting shorter (except for foreign interest rate shock). The result is quite striking. Although pass-through degree has declined on impact under price-level targeting, the adjustment speed to complete pass-through has rapidly increased.

To understand the reason behind a lower pass-through degree under price-level targeting regime, the dynamics of the price level and the exchange rate have been broken down into two graphs as displayed in Figure 9.4. A lower pass-through degree with productivity shock is mainly due to optimal response of price level (impact value is close to long-run value or change is small). It is also worth to note that nominal exchange rate movement is also around its long-run trend compared to the inflation targeting regime. Similarly, a slightly lower pass-through degree under the other two shocks is due to dynamics of price level: a relative change in price level is lower than the nominal exchange rate. Nevertheless, the volatility of the nominal exchange rate under foreign shock remains larger regardless of the monetary policy regime.

[5] Since price level and nominal exchange rate are stationary under price-level targeting, equation (7.3) no longer holds. This is because the change in levels in the long-run is zero making the pass-through degree value significantly large. Therefore, the pass-through degree is commonly measured as the short-run value of price level over nominal exchange rate

Shocks	On impact	Time to full ERPT
* Monetary policy	0.20	5 quarters
Productivity	-0.20	8 quarters
Foreign interest rate	0.04	Long-run

Table 9.2: ERPT from nominal exchange rate to CPI under price level targeting

The change in nominal exchange rate is negligible compared to price level

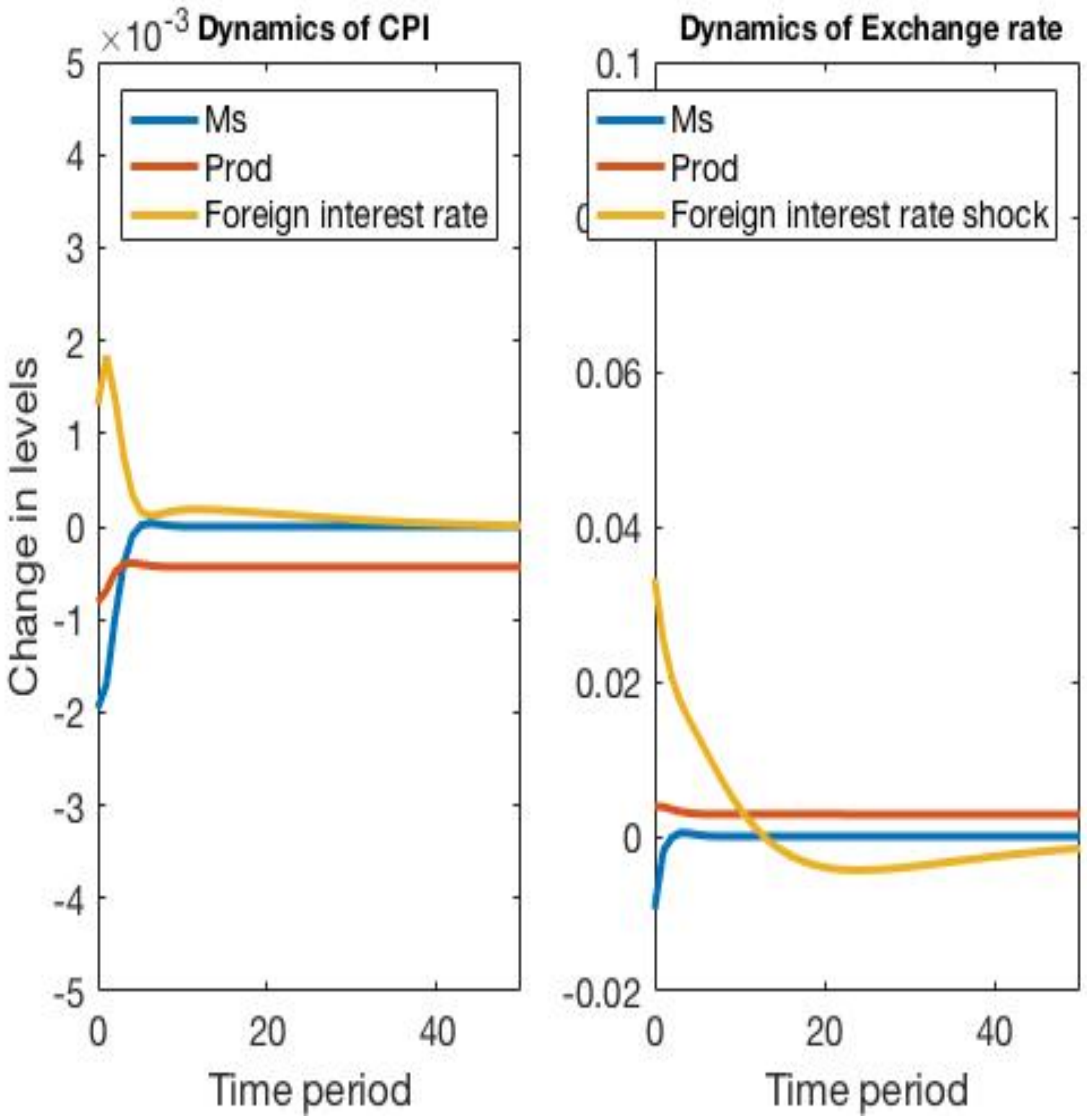

Figure 9.4: Response to 1% Transition to steady-state for CPI and NER under price level targeting

Table 9.3 summarises the majority of ERPT degrees on impact and the convergence rate of the pass-through degree to its long-run value of one. There is a striking difference in pass-through degree compared to the original Taylor rule case. First, the convergence rate of the pass-through degree to unity is significantly faster. The latter observation fits the theory well as the price-level targeting regime requires the convergence of price level whereas the PPP conditions ensure that the path of nominal exchange rate follows CPI. In summary, under price-level targeting the pass-through degree is observed to be low because the monetary policy forces the variables of interest (CPI and NER) to converge. As a result, a change in these variables is low leading to a lower pass-through degree. In addition, due to the credibility of the central bank and the expectational terms of the model, the economy will anticipate a faster convergence and price stability making the pass-through degree even lower.

Shocks	**On impact**	**Time to full ERPT**
Productivity	-0.2	8 quarters
Labour supply	-0.24	10 quarters
Preference shock	-0.25	6 quarters
Government spending	-0.23	8 quarters
* Import price markup	-0.2	10 quarters
Monetary policy	0.2	5 quarters
Investment	0.13	4 quarters
Foreign price	-0.06	5 quarters
Foreign interest rate	0.04	Long-run
Export demand	-0.11	8 quarters

Table 9.3: ERPT from nominal exchange rate to CPI under price level targeting

The change in nominal exchange rate is negligible compared to price level

9.3 Welfare analysis

The aim of this section is to investigate the effects of different monetary policy configurations on social welfare. The majority of the existing literature follows the seminal work of Rotemberg and Woodford (1997). The paper derives its econometric specification from an explicit model of intertemporal optimisation- a second-order approximation of representative consumer's loss of utility. The analysis of optimal monetary policy builds upon a utility-based measure of deadweight loss associated with price level instability, and parameters of the loss function can be determined from estimated structural equations.

Another traditional approach is to use a standard quadratic loss function where the policymaker aims to minimise the deviations of a set of variables from their target values. M. Devereux (2001) shows that the second-order approximation of a household's utility function can be approximated by a quadratic loss function of inflation deviation from zero and output deviation from potential level. This methodology, however, differs from the structural approach. The relative weights on each target variable are exogenously imposed, rather than being dependent on the model's structural parameters.

Rotemberg and Woodford (1997) also shows that maximisation of the household's welfare indeed implies the minimisation of the variances of inflation and the output, where the relative weights on inflation and output stabilisation are determined by the model's structural parameters. On the other hand, the ad-hoc method implemented here has been criticised by Walsh (2005). The author is against the use of exogenously specified policy objectives to analyse the monetary policy, especially when assessing the robustness of alternative policy rules. Indeed, much current research has used an approximation to the representative agent's loss function to derive optimal policies.

Despite this criticism, even though this loss function does not capture the welfare of consumers in the model, it is still likely to be a close approximation. The nominal price staggering in the model creates costs of inflation, which can be captured by the term in inflation. The majority of studies confirm that the weight on inflation in loss function far exceeds the one on the output gap (Yağcıbaşı Özge and Yıldırım Mustafa (2017), De Paoli (2009), Paez-Farrell (2014)). Moreover, these papers calibrated their structural model and hence, in essence, the weights on target variables have also been exogenously determined.

M. Devereux (2001) finds that a rule stabilising sticky non-traded product prices delivers the best performance, especially with an imperfect pass-through degree. And their judgement is based on ad hoc examination of the volatility of inflation, output and consumption. However, the author examines the optimal monetary policy only with external (world) shocks. A corollary of their findings is that inflation targeting is less costly with limited pass-through. This is because inflation can be stabilised by allowing a significant degree of nominal exchange rate volatility. In general, the economy with staggered price setting suffers from welfare loss due to dispersion in relative goods prices and hence, the inefficient allocation of resources.

According to M. Devereux (2001), the derivation of the structural welfare function is quite complicated if there are multiple sectors and imperfect pass-through. The paper conjectures that inferences about desirable policies can be made without complete knowledge about weight parameters policy-makers put on inflation and output volatility in the loss function. The quantitative results show that when the pass-through degree is incomplete, the markup rule dominates the fixed exchange rate rule. However, markup rule, price-level targeting rule and standard inflation targeting Taylor rule produce similar welfare loss. For instance, price-level targeting is superior to the Taylor rule only for 0.0012 points whereas the markup targeting rule performs better than the Taylor rule for 0.0025 standard deviation points. Finally, the paper shows that nominal exchange rate volatility increases with a limited pass-through degree in contrast to a full pass-through case, which confirms the analysis made by Smets and Raf Wouters (2002).

Based on the arguments above, we implement ad-hoc quadratic loss function. The welfare measurement is based on a weighted average of resource cost due to price variability and output variability:

$$L_t = \omega(\pi_t - \pi^*)^2 + (1-\omega)(y_t - y^*)^2 \tag{9.3}$$

The weight, ω, which takes a value between zero and one, reflects the preferences of policymakers whose aim is either to stabilise the inflation or stabilise the output. If the weight is close to one then monetary policy authorities place no value in output stabilisation. The weight on inflation is given a fixed value of 0.8 whereas the output is 0.2[6]. The loss

[6]Since the data on output is larger than inflation and UK is concentrated on

function, L_t, is minimised so that desired loss is zero when both inflation and output gap are at their respective natural levels. The equation (9.4) is analogous to the following equation, which I use as a reference to calculate welfare loss:

$$L_t = \omega\sigma_t^{\pi} + (1-\omega)\sigma_t^{y} \tag{9.4}$$

where σ_t^{π} and σ_t^{y} are standard deviation of inflation and output, respectively. Bootstrapping the simulation data 20,000 times we yield the following results:

Welfare analysis			
Monetary policy regime	σ_t^{π}	σ_t^{y}	Loss function value
Standard Taylor rule	0.0063	0.0656	0.0181
Core inflation targeting	0.0069	0.0656	0.0186
Price targeting	0.0058	0.0662	0.0178

Table 9.4: Welfare analysis under different monetary policy regime

Table 9.4 shows the result of the simulation and reports the standard deviation of inflation, output, and value of loss function. The welfare implication under inflation targeting with different kinds of inflation (core inflation versus CPI inflation) results in a similar loss function. The difference is 0.0005 higher for core inflation targeting. This value might be interpreted as the average standard deviation for output and inflation. In contrast, the loss function under price-level targeting is slightly lower mainly due to the lower volatility of inflation. The difference is 0.0003 points lower for the price-level targeting regime. In terms of welfare loss, the table concludes that none of the policy regimes are superior to another.

To sum up, the thesis illustrates that monetary policy has an impact on a pass-through degree. Although the estimates for ERPT degree are similar for standard Taylor rule and core inflation targeting, the outcome under price-level targeting is significantly lower. This result is expected because the pass-through degree involves price level and the central bank is committed to keeping the price level stable. That is, in

inflation targeting, the weight on inflation is larger the long-run, the price level converges to its target level while making the inflation rate equal to zero. Moreover, the inflation rate has to offset any past history to ensure stable prices (total sum of inflation over the time horizon has to be zero). According to PPP conditions imposed in the model, the nominal exchange rate has to follow the path of price level. In addition, the expectation of price level and the credibility of the central bank allows the volatility of inflation to be low (Table 9.4). All these arguments lower the pass-through degree.

In terms of the welfare implication of monetary policy, I conclude that all three policies- standard Taylor rule, core inflation targeting, price level targeting- yield similar social welfare loss. Therefore, none of these policies are superior to another. This result replicates the outcome achieved by M. Devereux (2001). I regard this as a result solidly based on my empirically-tested model.

Chapter 10

Conclusion

The open economy DSGE model with imperfect pass-through on UK data was estimated and the model passed the test. In addition, pass-through analysis has been done using estimated structural parameters and Impulse Response Functions. The paper verifies the outcome of the past literature that pass-through degree is incomplete and is shock-dependent. In contrast to prior studies, the paper tries to explain the reason behind such different magnitudes under different shocks. This is the second major contribution of the paper.

The thesis reports that pass-through degree in the short-run is incomplete and it has different signs and magnitude depending on the distribution of macroeconomic shock. The sign of ERPT degree in the short-run depends on the the dynamics of nominal exchange rate. The past literature with a positive ERPT degree is based on the assumption that PPP conditions are always satisfied implying that CPI and NER move in the same direction. This causes ERPT degree to be positive at all times. However, in general equilibrium, the short-run movement in NER is not determined by PPP conditions but in the UIP equation.

The size of ERPT degree, on the other hand, depends on relative movements of CPI and exchange rate to its corresponding steady-states. In order to understand this phenomenon, I have explored the dynamics of the price level and nominal exchange rate separately. Unlike in partial equilibrium analysis where causality streams from exchange rate to price level, in general equilibrium the causality flows in both directions. Note that in the DSGE model, the short-run nominal exchange rate is determined in the UIP equation while CPI price level is defined from supply and demand conditions as well as a direct impact from importing sector. This implies that the behaviour of individuals plays a major role in estimating pass-through degrees. In other words, a pass-through degree is different for different shocks because households, firms and monetary authorities respond differently under a different state of the economy, eg. firms set prices differently whether the shock comes from demand or foreign suppliers. Similarly, the nature of the monetary policy is a crucial aspect in assessing the pass-through degree. This different behaviour of the economy technically can be reflected in causality running between CPI and NER in both directions.

For the UK economy, the highest pass-through is inherent to domestic supply shocks, preference and government spending shocks. By the definition, ERPT degree is defined as a percentage change in the price level over the nominal exchange rate. Therefore, the magnitude of the coefficient depends on how close the short-run value of price and exchange rate is from their corresponding equilibrium levels. For instance, we have shown that ERPT degree is high for domestic supply shocks due to negligible response by exchange rate relative to price level movements. On the other hand, lower ERPT degree by foreign interest rate shock is generated by enormous movement in the exchange rate. In other words, under this shock, the short-run level of the exchange rate is too far away from its long-run equilibrium level.

Finally, we have performed welfare analysis on different monetary policies including standard Taylor rule, core inflation targeting and price-level targeting. The thesis concludes that these regimes yield similar welfare loss functions implying none of the policies are superior to another. In regard to pass-through analysis, the outcome under two inflation targeting is similar. On the other hand, under price-level targeting the pass-through degree is significantly lower in the short-run and the adjustment to complete pass-through is also fast. Under price-level targeting the pass-through degree is observed to be low because the monetary policy forces the variables of interest (CPI and NER) to converge. As a result, a change in these variables is low leading to a lower pass-through degree. In addition, due to the credibility of the central bank and the forward-looking nature of the model, the economy will anticipate a faster convergence and price stability making the pass-through degree even lower.

These arguments clearly imply that the structure of the model being implemented plays a crucial role in the pass-through analysis. Thus, the model requires to be estimated and tested before proceeding with pass-through estimates. The pass-through estimates from partial equilibrium analysis and calibrated models can be taken as a reference only but cannot be used for policy implementation as these results are misleading.

Chapter 11

Appendix

11.1 Appendix A

In this appendix, I report the log-linearised representation of structural model.

$$lnw_t = \gamma lnN_t + \sigma lnC_t + lnP_t - lnP_{dt} + ln\varepsilon_t^{Ns} \tag{11.1}$$

$$lnC_t = E_t lnC_{t+1} - \frac{1}{\sigma}(r_t - E_t\pi_{t+1}) + \frac{1}{\sigma}ln\varepsilon_t^b \tag{11.2}$$

$$lnN_t = (1 + \frac{\psi'(1)}{\psi"(1)})rk_t - lnw_t + lnK_{t-1} \tag{11.3}$$

$$r_t = \mu r_{t-1} + (1-\mu)(r_p\pi_t + r_y y_t) + r_{\triangle\pi}(\pi_t - \pi_{t-1}) + r_{\triangle y}(y_t - y_{t-1}) + ln\varepsilon_t^r \tag{11.4}$$

$$lnI_t = \frac{1}{1+\beta}lnI_{t-1} + \frac{\beta}{1+\beta}E_t lnI_{t+1} + \frac{1}{(1+\beta)\Gamma"(1)}(lnQ_t + lnP_t - lnP_{ht}) + ln\varepsilon_t^I \tag{11.5}$$

$$lnK_t = (1-\sigma)lnK_{t-1} + \sigma I_t \tag{11.6}$$

$$Q_t = \beta E_t \frac{\lambda_{t+1}}{\lambda_t}(Q_{t+1}(1-\delta) + \frac{P_{dt+1}}{P_{t+1}}[rk_{t+1}u_{t+1} - \psi(u_{t+1})]) \tag{11.7}$$

$$lnY_t = \frac{C}{Y}lnC_t + \frac{I}{Y}lnI_t + \frac{G}{Y}ln\varepsilon_t^G + \frac{X}{Y}lnX_t - \frac{M}{Y}lnM_t + rk^{ss}\frac{K}{Y}\frac{\psi'(1)}{\psi"(1)}rk_t \tag{11.8}$$

$$lnS_t = E_t S_{t+1} - r_t + r_t^* - \phi f_{t-1} \tag{11.9}$$

$$lnX_t = lnY_t^* - \rho_f(lnP_{xt} - lnP_t^*) + ln\varepsilon_t^x \tag{11.10}$$

$$lnY_t = \phi_y(\alpha lnK_{t-1} + (1-\alpha)lnN_t + \alpha\frac{\psi'(1)}{\psi"(1)}rk_t + lnA_t) \tag{11.11}$$

$$lnM_t = (1-\omega)\frac{C}{Y}\frac{Y}{M}\left[lnC_t - \rho(lnP_{ft} - lnP_t) + ln\varepsilon_t^{cf}\right] + \frac{1-\upsilon}{\upsilon}\frac{Y}{M}(lnY_t - \frac{X}{Y}lnX_t) \tag{11.12}$$

$$f_t = \frac{1}{1+g}[f_{t-1}(1+r) + fr_{t-1}^*] + \frac{X}{Y}(lnS_t + lnP_{xt} + lnX_t - lnP_t) - \frac{M}{Y}(lnP_t^M + lnM_t - lnP_t) \tag{11.13}$$

$$\pi_t = P_t - P_{t-1} \tag{11.14}$$

$$lnP_t = \omega P_{ht} + (1-\omega)P_{ft} \tag{11.23}$$

$$lnP_t^M = \theta P_{ft} + (1-\theta)P_{mt} \tag{11.24}$$

$$lnr_t^* = \rho_{rf} lnr_{t-1}^* + ln\varepsilon_t^{rf} \tag{11.25}$$

$$lny_t^* = \rho_{yf} lny_{t-1}^* + ln\varepsilon_t^{yf} \tag{11.26}$$

$$lnp_t^* = \rho_{pfo} lnp_{t-1}^* + ln\varepsilon_t^{pfo} \tag{11.27}$$

11.2 Appendix B

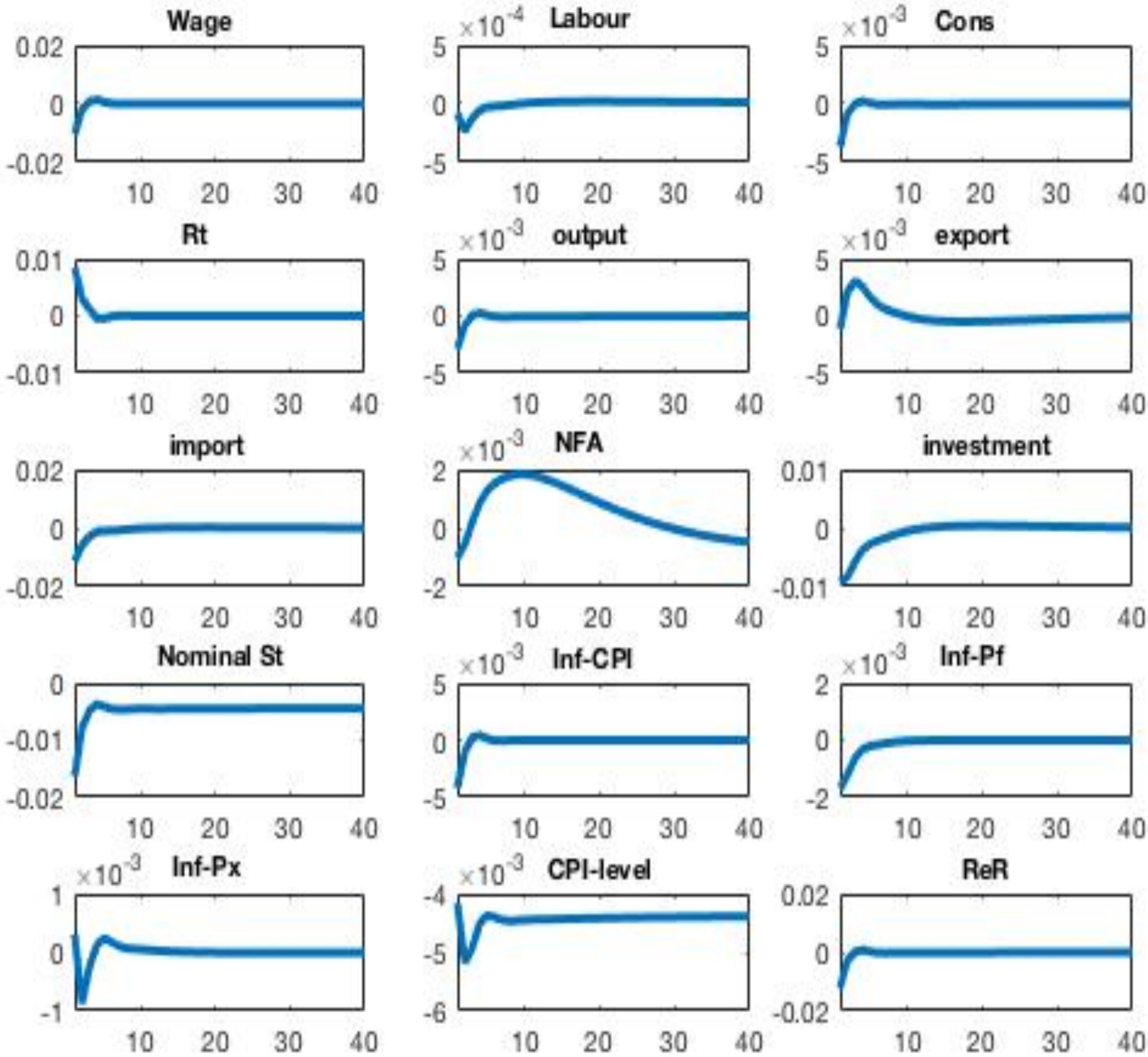

Figure 11.1: Response to 1% Monetary policy shock under Core inflating targeting

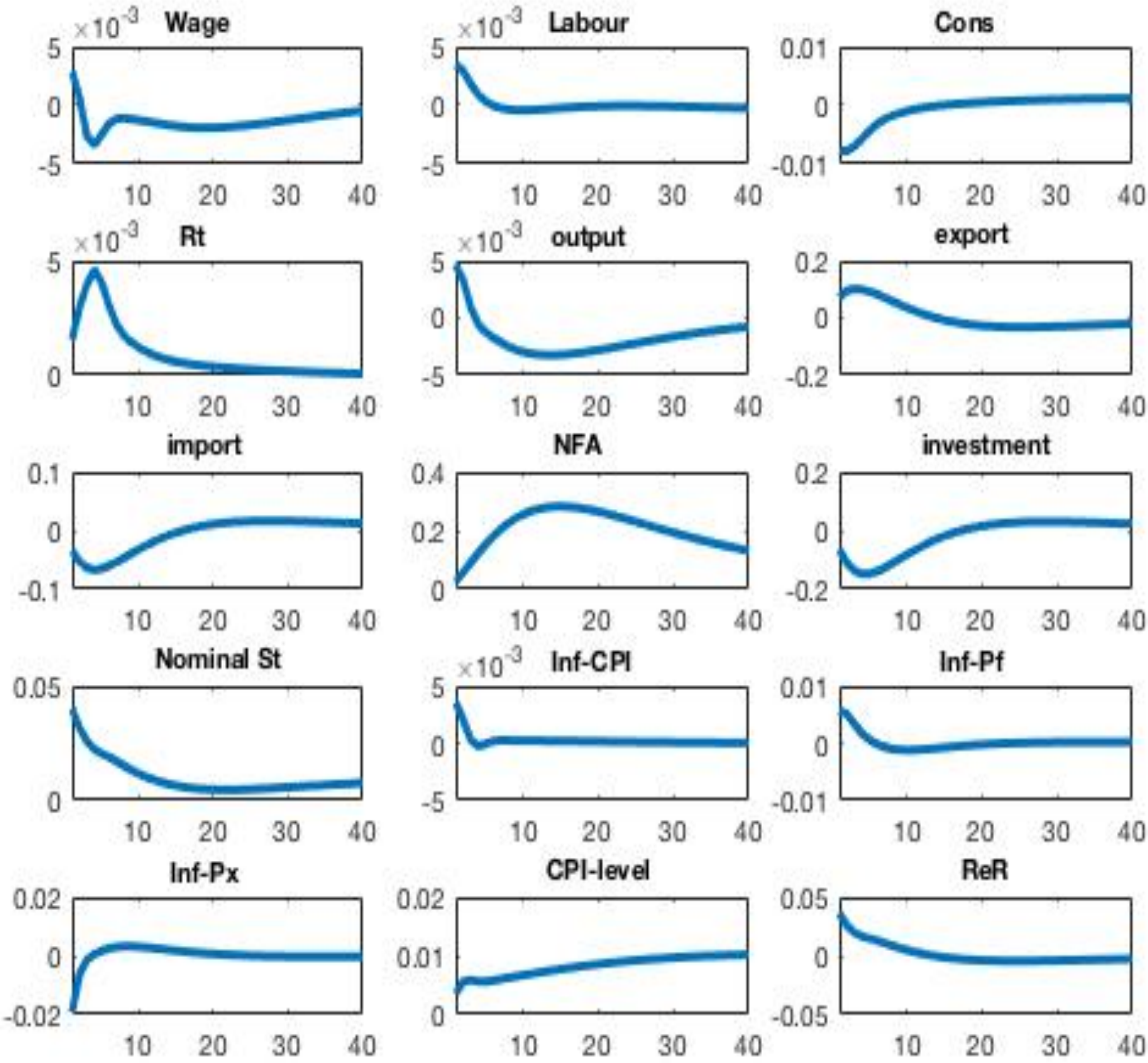

Figure 11.2: Response to 1% foreign interest rate shock under Core inflating targeting

11.3 Appendix C

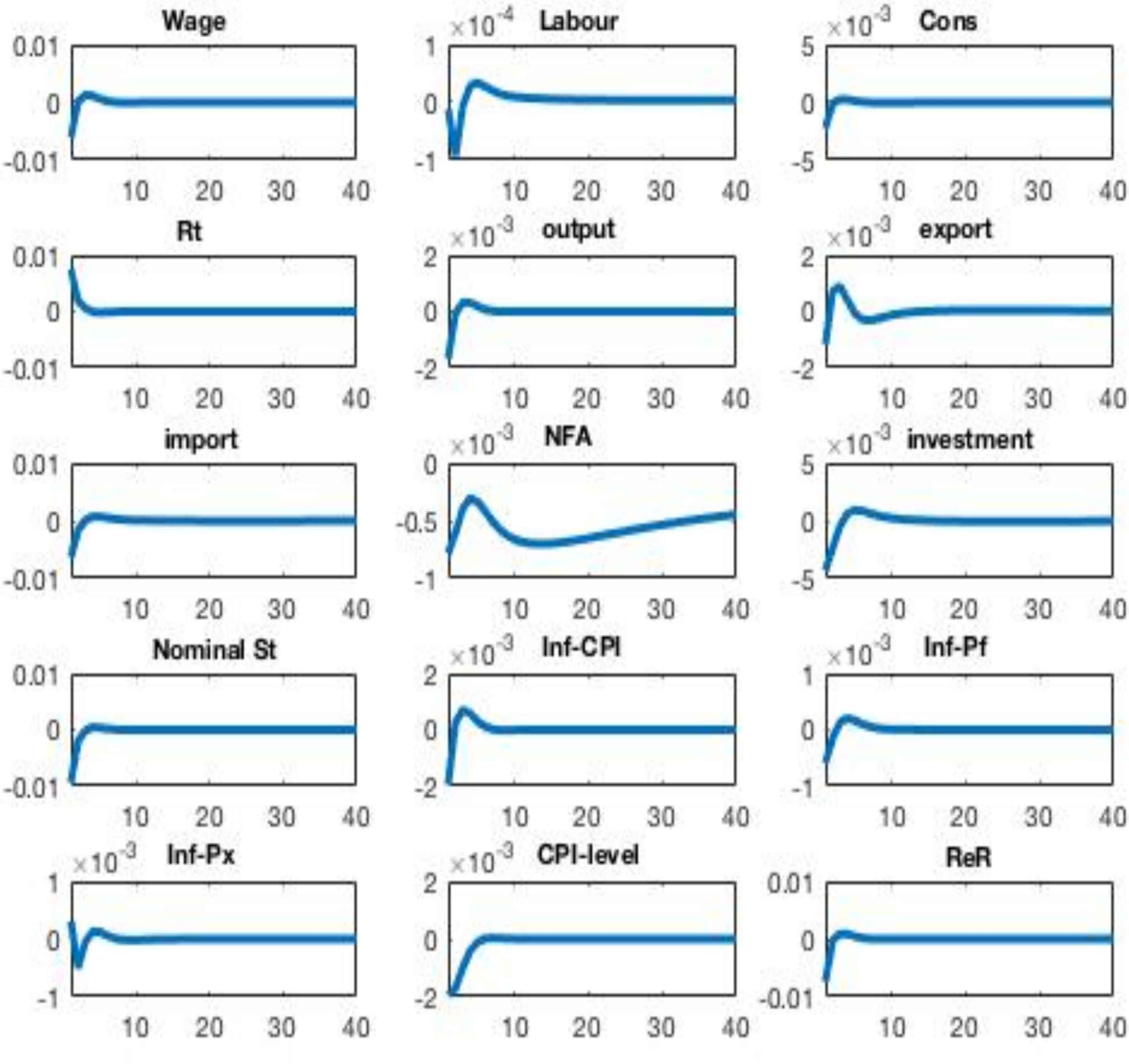

Figure 11.3: Response to 1% Monetary policy shock under price level targeting

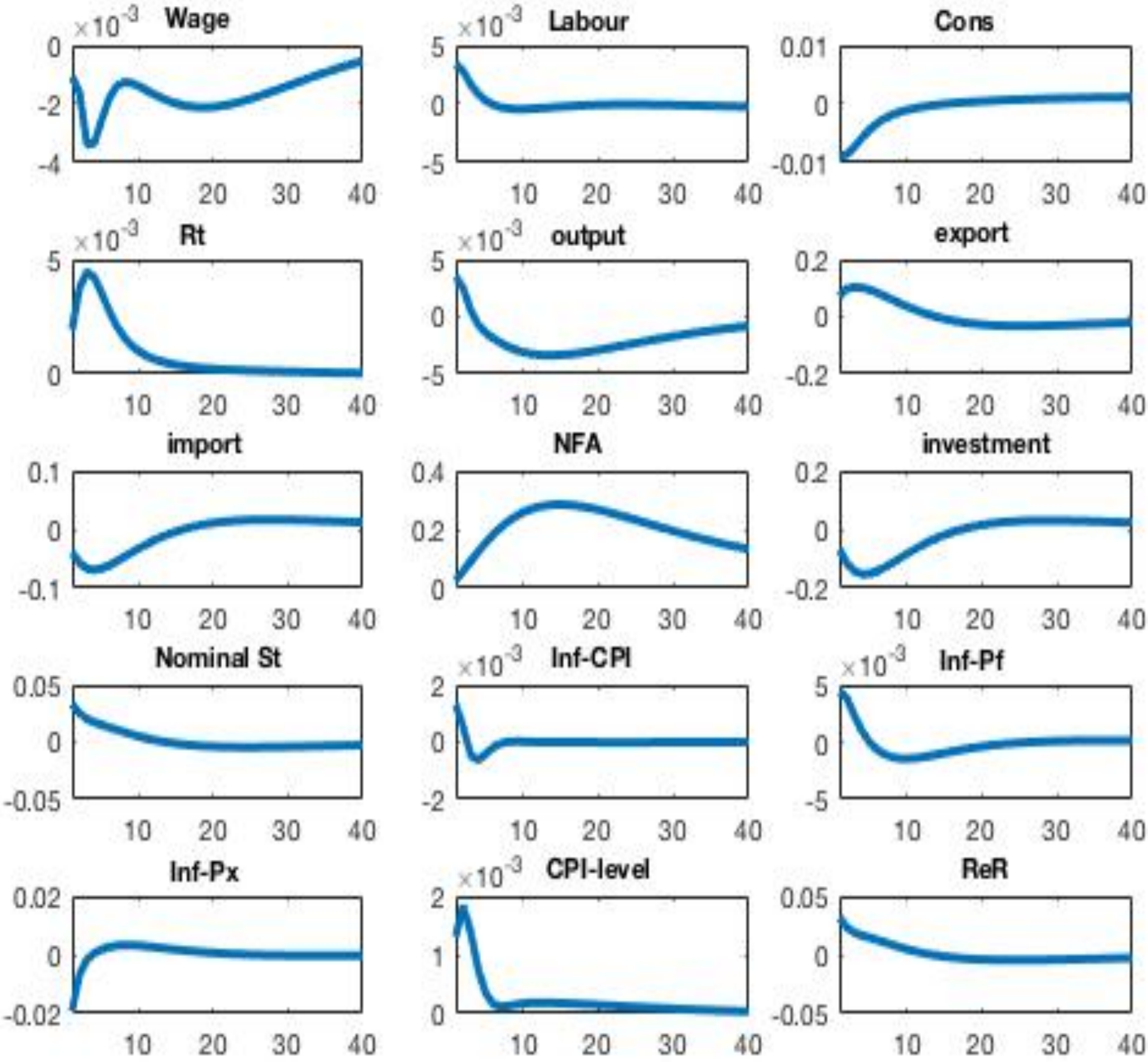

Figure 11.4: Response to 1% Foreign interest rate shock under price level targeting

11.4 Appendix D

The data period is 1989Q1-2016Q4 including the following variables: output, interest rate, inflation, consumption,nominal exchange rate, capital, government spending, wage, labour, investment, Tobin's Q, rental rate, export, import, foreign debt to gdp ratio, import and domestic price levels, and foreign variables. The variables are expressed as per capita basis. Most of variables are in natural logs except rates such as inflation, nominal interest rate and foreign debt to output ratio.

Description of data calculated from model equations:
Deriving capital stock data Capital is derived from capital accumulation equation using data on investment:

$$\frac{K_t}{Y_t} = (1-\delta)\frac{K_{t-1}}{Y_{t-1}}\frac{Y_{t-1}}{Y_t} + \frac{I_t}{Y_t}$$

Using the growth rate of output, g yields:

$$K_t = \frac{1-\delta}{1+g}K_{t-1} + I_t$$

Log-linearising equation and using the fact that in steady-state $\frac{I}{K} = \frac{g+\delta}{g+1}$:

$$lnK_t(1 - \frac{1-\delta}{1+g}L) = \frac{\delta+g}{1+g}lnI_t$$

Here$L$ is lag operator. Using the property of geometric sequence:

$$lnK_t = \sum_{i=0}^{\infty}\frac{1-\delta}{a+g}(\frac{\delta+g}{1+g}lnI_{t-i}$$

Re-arranging this equation:

$$lnK_t = \frac{\frac{\delta+g}{1+g}lnI_t}{1 - \frac{1-\delta}{1+g}\frac{1}{\rho}}$$

where we use $I_t = \rho I_{t-1} + \epsilon$.

Derivation of Tobin's Q The log-linear equation of Tobin's Q is:

$$lnQ_t = \beta E_t\frac{\lambda_{t+1}}{\lambda_t}Q_{t+1}(1-\delta) + \beta rk^{ss}E_t rk_{t+1} - rr_t$$

where rk^{ss} is steady-state rental rate and rr_t is real interest rate. Applying the lag operator:

$$lnQ_t(1-\beta(1-\delta)L^{-1}) = -rr_t + +\beta rk^{ss}E_t rk_{t+1}$$

Then

$$lnQ_t = \sum_{i=0}^{\infty}(\beta(1-\delta))^i(-rr_{t+i} + \beta rk^{ss}E_t rk_{t+1+i})$$

Expanding sequence and rearranging yields:

$$lnQ_t = \frac{-rr_t}{1-\beta(1-\delta)\rho_{rr}} + \beta rk^{ss}\frac{rk_{t+1}}{1-\beta(1-\delta)\rho_{rk}}$$

Here we apply $rr_t = \rho_{rr}rr_{t-1} + \epsilon$ and $rk_t = \rho_{rk}rk_{t-1} + \epsilon$

Data description			
Symbol	Variable	Description	Source
w	real wage	weekly wage and salaries	ONS;(ROYJ/(YBUS*CPI)
C	Consumption	Household final consumption expenditure	ONS (ABJR)
N	Labour	Number of hours per person weekly	ONS (YBUS/MGRZ)
r	Nominal interest rate	BoE	3-months average sterling bill/4
I	Investment	Total gross fixed capital formation+changes in inventories	ONS (NPQS)
K	Capital stock	Derived from capital accumulation equation	Calculation
Q	Tobin's Q	Derived from Tobin's Q equation	Calculation
rk	Rental rate	Derived from labour demand equation	Calculation
S	Nominal exchange rate	Inverse of sterling effective exchange rate	BIS (www.bis.org/statistics)
X	Export volume	Total Exports	ONS (IKBK)
Y	Output	Gross Domestic Product	ONS
M	Import volume	Total imports	ONS (IKBI)
F	Foreign debt to GDP ratio	Foreign debt to GDP ratio	ONS (AA6h)
P	Consumer price index	Consumer price index	FRED[1]
Ph	Domestic producer price	GDP deflator	ONS (L8GG)
Pd	Domestic intermediate goods price	All manufacturing price excluding duty	ONS
Pf	Imported consumption goods price	Consumer good prices other than cars	ONS (BQMC) [2]
Pm	Imported intermediate goods price	Imports manufacturing goods	ONS
Px	Export price	Weighted average of foreign import prices (LCP)[3]	ONS
P_t^M	Total import price	Total import deflator	ONS
r*	Foreign nominal interest rate	Weighted average of nominal interest rate	Federal Statistics Office, Cabinet Office,FRED
y*	Foreign output	Weighted average of foreign outputs	Federal Statistics Office, Cabinet Office,FRED
p*	Foreign price	Weighted average of foreign	Federal Statistics

11.5 Appendix E

The derivation of optimal demand of imported and domestic intermediate goods. Let us do it for home good. Similar procedure is for imported good. The profit maximisation is:

$$\max_{Y_{dt}(j)} P_{dt}\left[\int_0^1 (Y_{dt}(j))^{\frac{\chi_d-1}{\chi_d}} dj\right]^{\frac{\chi_d}{\chi_d-1}} - \int_0^1 P_{dt}(j)Y_{dt}(j)$$

The first order condition is:

$$\frac{P_{dt}(j)}{P_{dt}} = \left[\int_0^1 (Y_{dt}(j))^{\frac{\chi_d-1}{\chi_d}} dj\right]^{\frac{1}{\chi_d-1}} [Y_{dt}(j)]^{-\frac{1}{\chi_d}}$$

Hence, the optimal demand for each intermediate home good is:

$$Y_{dt}(j) = [\frac{P_{dt}(j)}{P_{dt}}]^{-\chi_d} Y_{dt}$$

11.6 Appendix F

Derivation of Phillips Curve

Each period, only random fraction $(1-\xi)$ of firms are able to reset their price. The remaining firms index their price to previous inflation rate. For simplicity, let us drop all subscripts for four different price levels. Then, using

$$P_t = \left(\int_0^1 P_t(j)^{1-\lambda}\right)^{\frac{1}{1-\lambda}}$$

Since Calvo assumes that probabilities also represents share of firms:

$$\begin{aligned} P_t^{1-\lambda} &= \int_0^{1-\xi} P_t^{\sharp 1-\lambda}(j).dj + \int_{1-\xi}^{1}\left([\frac{P_{t-1}}{P_{t-2}}]^{\varphi} P_{t-1}(j)\right)^{1-\lambda}.dj \\ &= (1-\xi)P_t^{\sharp 1-\lambda} + \xi[\frac{P_{t-1}}{P_{t-2}}]^{\varphi(1-\lambda)} \end{aligned}$$

Then, price level will be a weighted average of reset and non-reset prices:

$$P_t^{1-\lambda} = (1-\xi)P_t^{\sharp 1-\lambda} + \xi\big[(\frac{P_{t-1}}{P_{t-2}})^{\varphi} P_{t-1}\big]^{1-\lambda}$$

The optimisation problem is:

$$Max \sum_{t=0}^{\infty}(\beta\xi_d)^t\Lambda_t[(P_{dt}^{\sharp}\prod_{k=1}^{t}\pi_{k-1}^{\varphi_d} - mc_t^N)Y_{it}^d] + \sum_{t=0}^{\infty}(\beta\xi_x)^t\Lambda_t[(S_tP_{xt}^{\sharp}\prod_{k=1}^{t}\pi_{k-1}^{\varphi_x} - mc_t^N)X_{it}]$$

subject to

$$Y_{dt}(j) = (\frac{P_{dt}^{\sharp}\prod_{k=1}^{t}\pi_{k-1}^{\varphi_d}}{P_{dt}})^{-\chi_d}Y_{dt}$$

$$X_t(j) = (\frac{P_{xt}^{\sharp}\prod_{k=1}^{t}\pi_{k-1}^{\varphi_x}}{P_{xt}})^{-\chi_x}X_t$$

Here the term $\prod_{k=1}^{t}\pi_{k-1}^{\varphi_d}$ is related to partial indexation of non-resetting firms:

$$\prod_{k=1}^{t}\pi_{k-1} = \frac{P_{t+k-1}}{P_{t-1}}$$

Substituting and taking derivative of optimisation function with respect to $P_t^{\sharp}$ yields:

$$P_t^{\sharp} = \frac{\lambda}{\lambda-1}\frac{\sum_{s=0}^{\infty}(\beta\xi)^s\lambda_{t+s}y_{t+s}P_{t+s}^{\lambda}MC_{t+s}(\prod_{k=1}^{t}\pi_{k-1}^{\varphi_d})^{-\lambda}}{\sum_{s=0}^{\infty}(\beta\xi)^s\lambda_{t+s}y_{t+s}P_{t+s}^{\lambda}(\prod_{k=1}^{t}\pi_{k-1}^{\varphi_d})^{1-\lambda}}$$

Since in the right hand side no variation between firms,j, $P_t^\sharp$ is the same for all firms. Log-linearising numerator and denominator of equation separately around zero steady-state inflation generates:

$$p_t^\sharp - \varphi p_{t-1} = (1-\beta\xi)\sum_{s=0}^{\infty}(\beta\xi)^s(mc_{t+s} - \varphi p_{t+s-1})$$

So, the price is equal to lagged price plus the sum of current and future marginal costs. By "reverse engineering" this equation (opening the summation brackets and cancelling terms) and combining with third equation (log-linearise this equation as well) we derive the NKPC.

Log-linearising method description

$$lnf(x_t) = lnf(x^*) + \frac{f'(x*)}{f(x*)}x^*(lnx_t - lnx^*)$$
$$f(x_t) = f(x^*) + f'(x*)x^*(lnx_t - lnx^*)$$

11.7 Appendix G

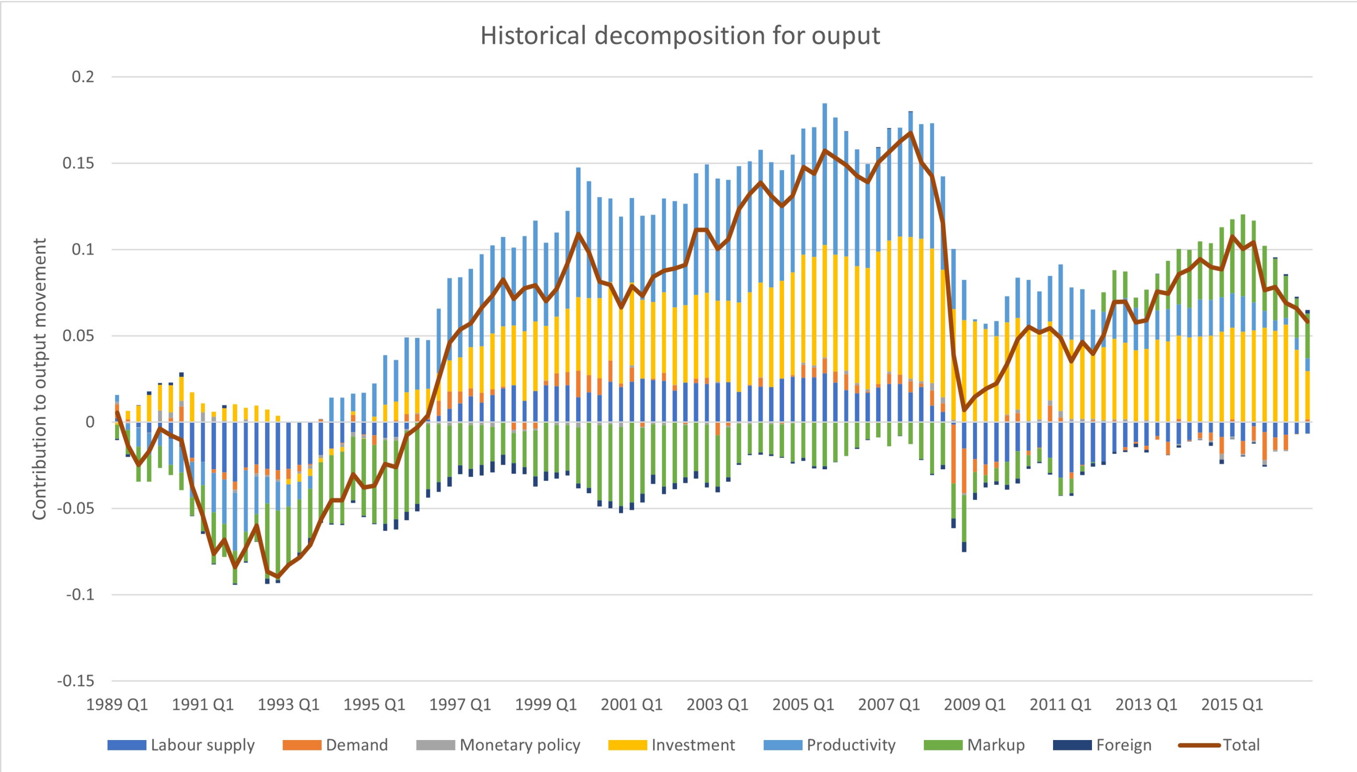

Figure 11.5: Historical decomposition for output level

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