The Effects of Oil Price Shocks on the UK Economy

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Abstract

This thesis examines the impact of oil price movements on the UK economy. To this end, it is composed of three chapters which use different approaches in order to assess the causes and the consequences of oil price shocks on the main UK macroeconomic fundamentals.

In Chapter 1, we analyse the impact of oil price fluctuations on the UK economy using a two-stage method. This empirical strategy allows us to decompose oil price changes depending on the underlying source of the shock. In line with previous studies, our results show that, since the mid-1970s, oil price movements have been mainly associated with shocks to oil demand rather than oil supply. We contribute to previous literature by finding that the consequences of oil price changes on UK macroeconomic aggregates depend on the different types of oil shocks. Thus, for instance, increases of global real economic activity do not depress the domestic economy in the short run. Conversely, shortfalls in crude oil supply cause an immediate fall of UK GDP growth. As a consequence, the Bank of England sets the nominal interest rate depending on the nature of the shock hitting the oil market. Our results also show that domestic inflation increases following a rise in the real oil price. Finally, we find that in response to oil price increases, although UK macroeconomic fundamentals worsen, the government deficit reduces.

In Chapter 2, we develop and estimate, using Bayesian methods, an open economy two-bloc DSGE model in order to analyse the responses of the UK economy and the rest of the world to different sources of oil price shocks. We consider the period in which the UK was a net oil exporter that also corresponds to the Non-Inflationary, Consistently Expansionary (NICE) decade (1990-2005). In line with previous literature, our findings confirm that global oil shocks are mainly responsible for UK oil price changes. Our impulse response analysis shows that a drop in the oil price stimulates UK GDP and reduces domestic inflation inducing the BoE to lower the nominal interest rate. In contrast to previous studies, we find that the UK exchange rate responds differently according to the

source of oil price shocks. In particular, a positive shock to foreign oil intensity induces an appreciation of the Pound. Conversely, a positive shock to foreign oil supply causes a depreciation of the British Sterling. Generally, a fall in the oil price worsens the UK trade balance, since UK is a net oil exporter. Finally, our historical decomposition analysis contributes to previous literature by showing that episodes of sharp increases in the oil price are associated with falls in the UK output and rises in the domestic inflation.

In Chapter 3, we study the main transmission channels of oil price fluctuations for the UK economy and the consequences of oil price changes on its public finances. Our model is estimated with Bayesian techniques over the same sample period as in Chapter 2. In line with previous literature, our results show that foreign oil demand and supply shocks are the main factors explaining the UK oil price volatility. In contrast to existing studies we find that the variation of UK government debt is broadly explained by oil price fluctuations related to changes in the foreign oil intensity. We extend the previous literature by estimating the parameters of several fiscal policy rules. In particular, we find that the response of petroleum revenue tax to oil price changes is stronger than the response of fuel duty tax to domestic oil demand. In line with Chapter 2, our impulse response analysis indicates that a decrease in the oil price positively affects the UK economy inducing an increase in its GDP and a fall in the domestic inflation. However, the drop in the oil price generates a negative effect on the UK trade balance. In contrast to Chapter 2, we find that a positive foreign oil intensity shock causes depreciation in the Pound. The latter effect occurs as the decrease in the UK VAT causes a reduction in the price of domestic consumption goods. Finally, we are able to quantify the size of the responses of UK public finances to oil price shocks. Our results indicate that a fall in the oil price induces a reduction in UK total tax receipts and, in turn, causes the rise in the government debt. Thus, for example, we find that a positive shock to foreign oil intensity increases UK government debt by £ 700 millions during the first year and £ 1100 millions in four years.

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Dedicated to my mother.

"*Fatti non foste a viver come bruti, ma per seguir virtute e conoscenza.*"
"You were not formed to live the life of brutes, but virtue to pursue and knowledge high."
Dante Alighieri

"*It is a sad thing to think of, but there is no doubt that genius lasts longer than beauty.*"
Oscar Wilde

"*Felix, qui potuit rerum cognoscere causas.*"
"Fortunate who was able to know the causes of things."
Virgil

Declaration

I declare that, except where explicit reference is made to the contribution of others, that this dissertation is the result of my own work and has not been submitted for any other degree at the University of Glasgow or any other institution.

Signature:

Printed name: Marco Lorusso

Preface

Oil and its refined components are crucial resources in the modern economy. Therefore, media, policy makers, and economists have been constantly interested in understanding causes and effects of large fluctuations in oil price. A common view is that sharp and persistent oil price upswings have been responsible for some serious economic recessions, periods of excessive inflation, reduced productivity and lower economic growth. On the other hand, periods of low oil prices have been considered as a boost for the economic performance.

Recent economic research made considerable advances in understanding the causes and the consequences of oil price shocks. In particular, most recent studies have shown that oil price fluctuations do not derive exclusively from exogenous shocks, such as supply disruptions due to political conflicts or coordinated supply constraints in producing nations, but can also be driven by endogenous changes in global macroeconomic aggregates, including factors such as economic expansion, existing inflation, currencies' fluctuations or changes in interest rates (see for example, Bernanke, 2004; Barsky and Kilian, 2004; Kilian, 2008a and 2008b; Balke et al., 2010). In other words, the real oil price ought to be considered as endogenous to economic fundamentals. Accordingly, in order to fully understand the economic effects of oil price shocks, it is necessary to analyse the origins of oil price fluctuations.

The majority of papers analysing the relationship between oil and the macroeconomy have studied the US case, with only a few studies focusing on the UK economy (see for example, Harrison et al., 2011; Millard, 2011; Millard and Shakir, 2013). However, the UK is a very interesting case study because it is a developed economy which has transitioned from being a net oil importer in 1970s to a net exporter in the 1980s and early 1990s and returned to be a net importer again in mid-2000s. Therefore, the main objective of the present thesis is to fill this gap. In particular, from different perspectives, each chapter aims to analyse the causes and the effects of oil price fluctuations on the UK economy.

In Chapter 1, we use an empirical framework based on a two-stage method in order to assess the impact of oil price fluctuations on the UK economy depending on the underlying source of the shock. Chapter 2 develops an open economy Dynamic Stochastic General Equilibrium (DSGE) model of the UK economy in order to evaluate the economic repercussions of oil price fluctuations. In Chapter 3, we extend the open economy DSGE model in order to analyse the specific effects of oil price movements on UK fiscal variables and, in particular, how quickly oil price changes work through the economy into UK public finances.

In the first chapter we aim to answer the following question: what are the effects of oil price movements on the UK economy conditional on the nature of the underlying shock? To do so we estimate our model in two different steps. In the first step, following the framework of Kilian (2009), we use a structural vector autoregression (VAR) in order to assess the causes of oil price changes. In particular, we identify three types of underlying source for oil price movements: crude oil supply shocks, aggregate demand shocks and oil market-specific demand shocks. An oil supply shock is defined as an exogenous shift in supply, independent from any change in the macroeconomic environment. Demand-driven shocks can either reflect an increase in global real economic activity (aggregate demand shock), or an increase in precautionary demand for oil associated with the uncertainty about future supply (oil market-specific demand shock). In the second step, we assess the effects of these structural shocks on several UK macroeconomic aggregates such as output growth, CPI inflation, nominal interest rate and government deficit.

The sample of our analysis covers the period 1976-2014.[1] In general, our estimated results indicate that, since the mid-1970s, shortfalls in crude oil supply

[1] As we will describe below, this sample period is longer than the ones we will consider in Chapter 2 and 3. Our choice is motivated by two main reasons. Firstly, the empirical framework of Chapter 1 requires an extended sample period with sufficient variation in all oil demand and supply shocks in order to provide accurate estimated results. As argued by Kilian (2014), the estimated responses converge to the expected or average responses only if the sample period is large. Secondly, our sample covers the period analysed by Kilian (2009). Therefore, we are able to compare our estimated results concerning the causes of oil price shocks with Kilian's findings.

have a small effect on oil price movements. On the contrary, we find that major changes of real oil price are associated with shifts in the precautionary demand for oil. These changes in precautionary demand are mainly caused by expectations on future oil supply. Such expectations are linked to exogenous events (such as military conflicts or political decisions) in the Middle East and generate large fluctuations in the real oil price. For example, we find that the surge in the real oil price between 2011 and mid-2014 was driven primarily by a sustained increase in oil-market specific demand. In particular, precautionary demand for oil was pushed up by the political and social turmoil in North African regions and Middle East countries together with the worsening of the financial crisis.

As concerns the consequences of oil price fluctuations, we find that UK macroeconomic fundamentals react differently to the three types of shocks. More specifically, UK GDP growth falls immediately after a shortfall in crude oil supply. On the other hand, expansions of global real economic activity initially have negligible effects on UK output growth although, in the long term, high oil prices tend to depress domestic GDP growth. In general, we find that increases in the real oil price are associated with a rise in domestic inflation. Our estimated Impulse Response Functions (IRFs) also indicate that the Bank of England[2] tends to increase its policy rate in response to positive oil demand shocks. The opposite occurs in the case of oil supply disruptions. Finally, in line with previous literature (see for example, Powell and Horton, 1985; Hall et al., 1986; Young, 2000; OECD Economic Surveys, 2002; OBR, 2010; Barrel et al., 2011), we find that an increase in the real oil price reduces the domestic government deficit reflecting the UK's condition as an oil producer country.

We argue that the empirical framework developed in Chapter 1 substantially contributes to our understanding of the causes and effects of oil price shocks on the UK economy. However, there are three main shortcomings that limit this

[2]More specifically, only in May 1997 the UK government granted the Bank of England operational independence allowing it to set domestic interest rates. Before that date, the chancellor and governor held a monthly meeting during which they agreed the set up of interest rates.

approach. Firstly, although our estimated results, on average, correctly represent the historical behaviour of UK economic fundamentals, they cannot be interpreted as actual responses of these variables at specific points in time. Indeed, our empirical approach is not able to capture the structural changes (for example, shifts in monetary and fiscal policy) that occurred to UK macroeconomic aggregates between 1976 and 2014. On the other hand, we cannot shorten or split our sample because our VAR model needs a long sample period in order to accurately estimate the structural shocks.

Secondly, our empirical model is not able to reflect the geographic origin underlying oil shocks. However, according to the report of the Office for Budget Responsibility (2010), there are different economic effects on the UK economy depending on whether the oil shock is global or UK specific. Similarly, Kilian (2014) argues that it is deeply misleading to treat an oil shock caused by, say, the expansion of aggregate demand in China as identical to a crude oil supply shock originating in the Middle East.

Thirdly, our structural VAR model cannot include a rich shock structure given the joint demands of robust estimation and identification. For example, it is not able to distinguish between different demand shocks. Thus, for instance, it cannot recognize if an oil demand shock is driven by a change in foreign productivity or a change of foreign monetary policy.

Recent advances in DSGE modelling of oil price shocks allow us to overcome such limitations. Indeed, it is feasible for global DSGE models to include a variety of shocks and where the oil market is one of many markets with endogenously determined oil prices. In particular, the DSGE framework allows economists to differentiate between fiscal and monetary policy shocks as well as productivity and oil intensity shocks, for example. That distinction is one of a number that will turn out to be important. Similarly, the DSGE framework provides the possibility of disentangling the shocks according to their geographic origins. In this regard, this kind of model represents an ideal tool for macroeconomic policy analysis.

Therefore, in Chapter 2, we develop an open economy two-bloc DSGE model in order to study the transmission and impact of oil shocks on the UK economy and the rest of the world. Our sample choice encapsulates the Non-Inflationary, Consistently Expansionary (NICE) decade and corresponds to the period in which UK was a net oil exporter.

Our quantitative theoretical framework builds on the papers of Bodenstein and Guerrieri (2011) and Bodenstein et al. (2012) who, in turn, drew upon the insights of Backus and Crucini (2000) to develop a DSGE model with an endogenous real price of oil. It also draws upon to the works of Barsky and Kilian (2004) and Kilian (2008a) to incorporate an important demand-side channel to characterise oil shocks over the sample period.

All these papers have exclusively studied the effects of oil price fluctuations on the US economy. Therefore, in Chapter 2 we contribute to this literature by assessing whether a small oil exporter economy, such as the UK, reacts differently from an oil importer country in response to global price fluctuations.

We estimate our model via Bayesian technique using observed data series for the UK economy and the rest of the world over the sample period 1990-2005. More specifically, observed variables for the foreign bloc are constructed using the Loretan (2005) technique of trade weights and aggregating data of the main trading partners of UK.

In line with the findings of the papers analysing the US case (see, for example, Barsky and Kilian, 2002; Kilian, 2008a and 2009; Lippi and Nobili, 2012; Kilian and Murphy, 2012; Kilian and Hicks, 2013; Baumeister and Peersman, 2013), our estimated results show the overall importance of global oil demand and supply factors for the UK economy. More specifically, the source of oil price shocks matters. Accordingly, we find that foreign oil intensity is the main cause of UK oil price variation.

In this regard, we define oil intensity as the measure of oil efficiency in a given economy. In turn, oil efficiency can be seen as the goal to reduce the amount of oil required to provide products and services. Thus, for example, oil efficiency is related to better methods of transportation and conservation efforts. Therefore, in a given country, positive shocks to oil intensity imply the improvement of its oil efficiency and the reduction in its oil demand. In our theoretical framework, oil intensity is modeled as an exogenous shock that affects the functions of production goods and consumption goods. Accordingly, a positive oil intensity shock induces a fall in the oil demanded by the firms that produce both production goods and consumption goods.

Our findings also indicate that foreign technology shocks and foreign oil supply shocks contribute significantly to UK oil price fluctuations. Moreover, our estimated results show a strong persistence of oil shocks. The latter aspect implies that the decrease of UK oil price is more intense in the case of a positive foreign oil intensity shock.

We analyse the effects of oil price shocks on the UK economy through our estimated IRFs. In line with the estimated responses of Millard (2011) for the UK economy, we find that the lower oil price pushes down the costs of firms using oil as production input. This tends to increase profits, stimulating employment and, thus, real GDP. Moreover, the fall in the oil price translates into lower retail prices. This boosts real incomes and therefore stimulates consumer spending. Given the inflation target, the UK nominal interest rate falls. Regarding nominal rigidities, we find high values for the Calvo (1983) re-pricing parameter and also for the wage setting parameter. On the other hand, the data indicate a low degree of price and wage indexation, implying that prices and wages are not significantly linked to past inflation. We also find a negligible response of wage inflation to oil price shocks.

Contrary to previous literature (see, for example, Hall et al., 1986 and Young, 2000) that predicted a depreciation of the Pound against other currencies in the presence of a drop in the oil price, we find something different. British Sterling appreciates against other currencies in the presence of a positive foreign oil intensity shock while the opposite occurs after a positive oil supply shock and a negative foreign technology shock. Moreover, our estimated responses show that positive shocks to foreign oil supply and intensity imply the deterioration of UK trade balance reflecting the UK's position as net oil exporter.

An additional contribution of Chapter 2 is that we identify the main drivers in the movements of UK GDP and inflation for the period 1990-2005. In this regard, the historical decompositions of these two variables show the strong influence of oil price fluctuations on the UK economy. In particular, we find that the sustained increases in the oil price during the periods 1990:Q3-1992:Q3 and 1999:Q1-1999:Q3 were largely responsible for the relative GDP reductions. Moreover, the rise in the real oil price during the second half of 1990 induced a sustained increase in UK inflation.

Although the theoretical framework adopted in Chapter 2 captures the main features of the UK economy, it does not reflect the impact of oil shocks on fiscal variables. Previous studies on the UK economy have stressed the importance of considering the impact of oil price changes on the domestic public sector (see, for example, Powell and Horton, 1985; Hall et al., 1986; Young, 2000; OECD Economic Surveys, 2002; OBR report, 2010; Barrel et al., 2011) but they have been unable convincingly to quantify such effects. In particular, since the UK is an oil producer, oil price fluctuations influence directly the revenues coming from oil sales.

Therefore, in Chapter 3, we model in detail the UK fiscal sector considering government oil revenues and their relationship with overall UK public finances. More specifically, in the third chapter, we estimate an open economy DSGE model in order to evaluate how oil price fluctuations impact on the UK economy and which fiscal variables are most affected.

Our theoretical framework extends the one presented in Chapter 2 and, in particular, it assumes the endogenous determination of real oil price and a world economy model in a new Keynesian framework. From a theoretical point of view, Chapter 3 presents two main contributions over to Chapter 2. Firstly, we assume that domestic households and firms face several distortive taxes. Secondly, we set up a detailed fiscal sector which includes several policy rules for these distortive taxes.

Our model is estimated using Bayesian techniques over the sample 1990-2005. Therefore, it includes the NICE decade and corresponds to the period in which the UK was a net exporter of oil. In order to estimate our model, we use data for the United Kingdom and the rest of the world. The observed time series for the foreign bloc are constructed as before using the Loretan (2005) method.

The third chapter extends the existing literature by showing that foreign oil intensity shocks contribute significantly to the variation of UK government debt. The main reason is that the foreign oil intensity shock is the most relevant source of oil price fluctuations. Accordingly, relevant changes in oil price imply more volatile oil tax and fuel duty revenues and, in turn, substantial fluctuations of government debt.

In line with the findings of the second chapter, the estimated results of Chapter 3 show that foreign oil demand and supply shocks explain most of the variation of UK oil price. We also find a significant effect of foreign technology shocks on UK oil price variation.

One of the main contributions of Chapter 3 is that we are able to estimate the fiscal policy rules of our model. In this regard, we find that the fuel duty tax rate responds only moderately to UK oil demand whilst the petroleum revenue tax rate responds more strongly to oil price variations.

In general, the results of our impulse response analysis are in line with those of Chapter 2. More specifically, in response to an oil price decrease, we find an increase in UK GDP and its major components. Similarly, domestic hours worked tend to increase. Moreover, we observe a decline in UK inflation that induces the monetary authority to reduce its policy rate.

Since the UK is a net oil exporter, the reduction in oil price implies a worsening in its oil trade balance inducing the UK overall trade balance to fall. Similarly to Chapter 2, we find a depreciation of the Pound in response to both positive foreign oil supply shocks and negative foreign technology shocks. Differently from the second chapter, we find that an increase in oil intensity abroad causes a depreciation in the Pound. Indeed, the response of UK taxation to this shock causes a reduction in the domestic price of consumption goods relative to imported goods.

Finally, Chapter 3 contributes in quantifying the effects of oil price shocks on the UK public finances. In this regard, our analysis presents several advantages over previous papers that have investigated this issue (see, for example, Powell and Horton, 1985; Hall et al., 1986; Young, 2000; NIESR, 2000; OECD Economic Surveys, 2002; OBR, 2010; Barrell et al., 2011a and 2011b). Firstly, our study takes into account several sources of oil price shocks. Indeed, the particular implications of an oil price shock for the UK public finances differ depending on whether the shock is global or UK specific. Similarly, the effects implied by oil demand shocks are different from the ones generated by oil supply shocks. Secondly, the impact of oil price fluctuations on the UK public finances also depends significantly on how long the oil price change lasts. Accordingly, our empirical strategy allows us to estimate directly the persistence of the exogenous shocks affecting the oil price. Thirdly, the effects of oil price movements on the UK public finances are related to the size of the UK price elasticity of oil demand. Thus, we estimate the latter using Bayesian techniques. Fourthly, our theoretical framework allows us to consider the response of the UK fiscal variables in the case of actual and potential economy.

Our results show that, although overall UK economic performance improves after a fall in the real oil price, domestic public finances deteriorate. Indeed, the negative direct effect on Petroleum Revenue Tax (PRT), Value Added Tax (VAT) and fuel duty tax receipts more than offset the positive indirect effect on the other tax revenues. Accordingly, we find that following a positive shock to foreign oil intensity, UK government debt increases by £ 700 millions during the first year and it reaches £ 1100 millions in four years.

Chapter 1: Causes and Consequences of Oil Price Shocks on the UK Economy

1.1 Introduction

Since the dramatic oil price spikes of the 1970's, and the consequent global recession, economists have analysed oil price fluctuations in order to understand their economic impact. In this regard, a large number of studies have investigated the macroeconomic effects of oil price shocks (see, for example, Hamilton, 1983 and 2003; Burbidge and Harrison, 1984; Bernanke et al., 1997; Papapetrou, 2001; Lee and Ni, 2002; Bernanke, 2004; Barsky and Kilian, 2004; Peersman, 2005; Blanchard and Galí, 2007; Kilian, 2008a and 2009; Peersman and Van Robays, 2009; Lombardi and Van Robays, 2011).

Although these studies have found a negative correlation between oil price increases and economic performance, a strong divergence appeared in the analysis of the causes of oil price fluctuations. In particular, Hamilton (2003) has assumed the exogeneity of the oil price to economic fundamentals without distinguishing between the different sources of oil price fluctuations. However, Kilian (2009) has shown that this assumption is inappropriate for two main reasons. Firstly, there exists a reverse causality from macroeconomic aggregates to oil prices. Secondly, oil prices are driven by structural demand and supply shocks which have direct effects on the macroeconomy as well as indirect effects operating through the price of oil. Hence, Kilian (2009) concludes that the real oil price ought to be considered as endogenous with respect to global macroeconomic conditions.

In the present paper we aim to analyse the impact of oil price changes on the UK economy. We do this by using a structural vector autoregression (VAR) approach to estimate these effects. In particular, we adopt a two-stage method in order to estimate our model. In the first stage, we assess the causes of oil price changes depending on the underlying source of the shock, that is, whether the oil price has been driven by a supply or a demand disturbance. In the second stage, we examine the effects of the structural shocks estimated in stage 1 on a set of UK macroeconomic aggregates such as output growth, CPI inflation, nominal interest rate and government deficit.

The empirical strategy adopted in the present chapter is in line with the approach of Kilian (2009) and is fully consistent with our theoretical models developed in Chapters 2 and 3. In particular, as we will show in the next two chapters, it justifies our adoption of a macroeconomic model that endogenizes the price of oil rather than relying on the assumption of exogenously given oil prices.[3]

Moreover, the empirical analysis developed in this paper focuses on the demand side of the oil market. In particular, it shows that the traditional emphasis on physical oil supply shocks in explaining oil price fluctuations is misplaced.[4] This outcome confirms the results of our estimated DSGE models of Chapters 2 and 3 in which, as we will see, the demand side of the oil market is the most important source of oil price variation.

Hitherto most of the papers analysing the relationship between oil and the macroeconomy have focused on the United States. There have also been a few cross-country studies. For example, Cunado and Perez de Gracia (2003) showed that oil price fluctuations significantly affected industrial production in European countries. Jimenez-Rodriguez and Sanchez (2004) compared the effects of oil price shocks between US, Euro Area and Japan. They found that the impact of oil price increases on GDP was larger for the US than for the Euro Area and Japan. Baumeister et al. (2010) found a smaller effect on Euro Area GDP of oil supply shocks than in the United States, although similar effects in the two areas from oil shocks driven by world activity.

In contrast to the above literature, this chapter focuses on the response of the

[3] In particular, we can mention several recent papers based on DSGE models such as Backus and Crucini (2000), Bodenstein et al. (2008), Nakov and Pescatori (2010b), Nakov and Nuño (2011), Bodenstein et al. (2011), Bodenstein and Guerrieri (2011) and Bodenstein et al. (2012).

[4] In this regard recent economic literature provides a large number of studies such as Barsky and Kilian (2002), Kilian (2008a), Apergis and Miller (2009), Basher et al. (2012), Kilian and Murphy (2012) and (2014), Kilian and Hicks (2013), Baumeister and Peersman (2013).

UK macroeconomy to global oil price changes. In particular, we aim to analyse how the effects of oil price fluctuations on the UK economy may depend on the nature of the underlying shock. More specifically, our structural VAR model distinguishes between oil price changes caused by exogenous disruptions in oil production, oil demand shocks driven by global real economic activity and oil market-specific demand shocks associated with the uncertainty about future supply.

The sample of our analysis covers the period 1976-2014.[5] In this regard, an additional contribution of the present chapter is that we estimate our model with monthly data. Indeed, as we will explain below, our empirical set up heavily relies on delay restrictions that are economically plausible only at monthly frequency.

As far as the causes of oil price shocks are concerned, in general, our estimated results confirm the findings of Kilian (2009) for the sample 1976-2007. However, as our sample runs to end 2014, we are able to explain oil price variation in recent years.

More specifically, we find that most large and persistent fluctuations in the real price of oil since the mid-1970s have been associated with the cumulative effects of oil demand rather than oil supply shocks. The fact that flow supply disruptions have had small effects on the real oil price does not mean that political events in the Middle East do not matter. On the contrary, these events have affected the real oil price by shifting expectations about future shortages of oil supply relative to oil demand. In our model these expectations are captured by shocks on precautionary demand for oil.

A meaningful example is given by the large increase in the real oil price between 2011 and mid-2014. Indeed, during this period, there was a sustained increase in oil market-specific demand that pushed up the oil price. This rise of

[5] As we explained earlier, this sample period is longer than the ones of Chapter 2 and 3. Indeed, the empirical framework of the present chapter requires an extended sample period with sufficient variation in all oil demand and supply shocks in order to provide accurate estimated results. Moreover, our sample covers the period analysed by Kilian (2009). Therefore, we are able to compare our estimated results concerning the causes of oil price shocks with Kilian's findings.

precautionary demand for oil occurred for two main reasons. Firstly, during the so-called Arab Spring, social and political instability in the Middle East and North African regions created worries of supply disruptions and possible oil shortage. Secondly, as documented by Barrell et al. (2011b), the worsening of the financial crisis caused a sharp increase in investors' demand for a safe haven asset, such as oil, rather than complex financial assets.

Turning to the consequences of oil price shocks on the UK economy, we find that oil supply disruptions induce an immediate fall in domestic GDP growth and cause a sustained increase in domestic inflation. Moreover, our estimated results show that increases in aggregate demand, initially, have a negligible effect on UK output growth but in the long run they tend to depress it. Although the overall performance of the UK economy deteriorates, after an increase in the oil price, UK public finances improve. Indeed, our IRFs show that, in response to negative shocks to crude oil supply, the domestic government deficit decreases because of the rise in oil revenues. Our impulse response analysis also indicates that the Bank of England responds differently to oil price fluctuations associated with unanticipated booms in oil demand compared to oil price changes due to unexpected oil supply disruptions. Indeed, the nominal interest rate increases after both aggregate demand shocks and oil market-specific demand shocks, whereas negative shocks to the oil supply induce the Bank of England to loosen its monetary policy.

The rest of the paper is structured as follows. In the next section we discuss the empirical framework describing the two different stages used to estimate the effects of different shocks (all of which affect the price of oil) on the UK economy. Section 3 discusses the estimated results distinguishing between the causes of oil price changes and the effects of oil price fluctuations on the UK economy. Section 4 concludes.

1.2 The Empirical Framework

As we mentioned above, we estimate our model in two distinct stages. In stage 1, we adopt the framework of Kilian (2009) to capture supply and demand conditions in the oil market using a SVAR and applying the identifying assumptions on the relationships between the world variables to recover three structural shocks affecting oil prices: oil supply shocks, aggregate demand shocks and oil market-specific demand shocks (or precautionary demand shocks). In what follows we describe each of these shocks. Firstly, oil supply shocks are shocks to current availability of crude oil. Secondly, aggregate demand shocks are shocks to the current demand for crude oil coming from changes in the global business cycle. Thirdly, oil market-specific demand shocks are shocks driven by shifts in the precautionary demand for oil. These shocks come from the uncertainty about shortfalls of expected supply relative to expected demand. Thus, they include the holdings of oil inventories as insurance against oil supply disruptions.

In stage 2, we assess the impact of structural innovations, estimated in stage 1, on several UK macroeconomic aggregates such as real GDP growth, CPI inflation, the nominal interest rate and the real government deficit. The use of two-stage procedure presents two advantages. First, our approach enables us to keep the number of variables in our SVAR manageable (less than four) given the computational requirements associated with estimating larger VARs. Second, as we will explain below, separating the process of identifying structural shocks in the oil market removes the need to employ further identification restrictions on the UK equations.

1.2.1 Modelling the Causes of Oil Price Shocks: a World SVAR

Data. In the first stage, we consider monthly data for the sample period 1976:1-2014:12.[6] In order to estimate the world structural VAR we use the following data series.[7] The percentage change of global crude oil production ($\Delta prod_t$) is obtained by the log differences of world crude oil production in millions per barrels pumped per day (averaged by month).

The index of global real economic activity (rea_t) is a measure of the component of worldwide real economy activity that drives demand for industrial commodities in global markets (Kilian, 2009). This index is based on dry cargo single voyage ocean freight rates. As argued by Klovland (2004), world economic activity is the most important determinant of the demand for transport services. Thus, following the original idea of Kilian (2009), increases in freight rates are indicators of strong cumulative global demand pressures.

The real price of oil (rpo_t) is obtained from the series of the US crude oil imported acquisition cost by refiners. In our analysis, we prefer to focus on the latter series rather than using the Europe Brent spot price. As we can observe from Figure 1.1, the Europe Brent spot price and US crude oil imported acquisition cost by refiners have very close patterns during the period considered.

Hence, we decide to focus our analysis on the series of US crude oil imported acquisition cost by refiners because of the availability of this series at monthly frequency back to January 1974. Indeed, as we will explain below, the monthly frequency of this data series is crucial for the identification assumptions of our structural VAR. Moreover, the longer sample size of this series allows us to consider the relevant episodes that occurred during the 1970's.

[6] We use the sample period 1974:1-1975:12 as training sample for our estimates.

[7] See Appendix A for a detailed description of data sources and the construction of the series used to estimate the world structural VAR.

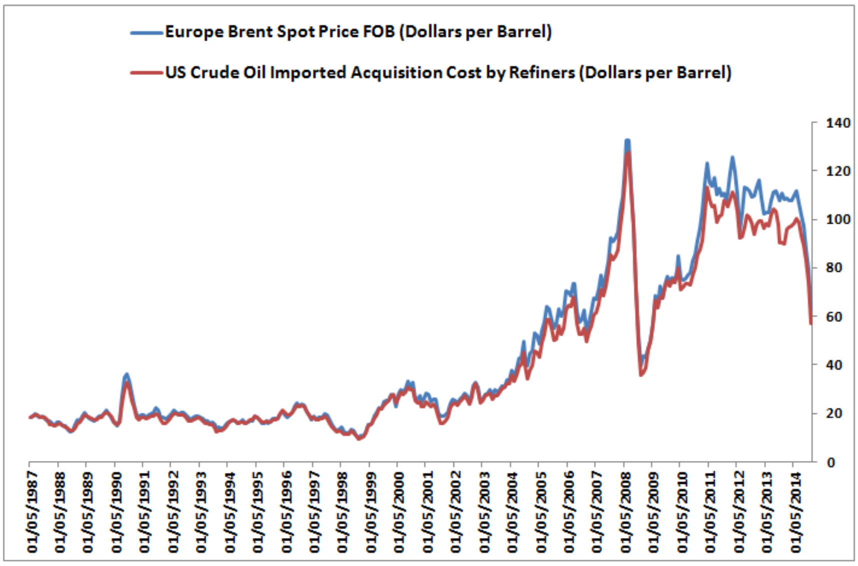


Figure 1.1: US Crude Oil Imported Acquisition Cost by Refiners and Europe Brent Spot Price, May 1987 to December 2014

Source: US Department of Energy.

Figure 1.2 shows the nominal and real oil price series at monthly frequency from the period January 1974 to December 2014. As we can observe from Figure 1.2, the crude oil price rose persistently from the end of 1970's to the mid 1980's. Except for the peak episodes observed in 1990-1991 and 1999-2000, the oil price remained fairly stable at around \$20 per barrel from 1986 until the end of 2001. Later that year the path of oil price steepened sharply until the end of 2008. This surge in the oil price was followed by an even more spectacular collapse. In 2011 the oil price went back to the level achieved in 2007-2008. Finally, we observe a plunge in the oil price at the end of 2014.

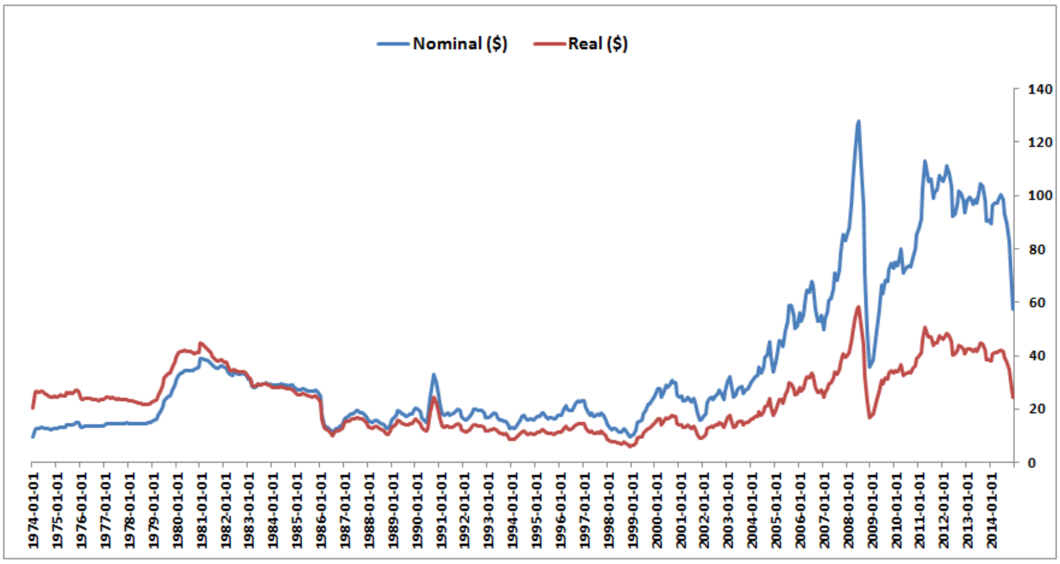


Figure 1.2: Real and Nominal Oil Prices (US Crude Oil Imp. Acq. Cost by Refiners)

Source: US Department of Energy and US Bureau of Economic Analysis.

Specification and Identification of the Model. As a benchmark specification for our model we adopt a structural VAR, whose reduced form is defined by the following dynamic equation:

$$\mathbf{B}_0\mathbf{y}_t = \mathbf{c}_t + \sum_{l=1}^{24} \mathbf{B}_l\mathbf{y}_{t-l} + \mathbf{u}_t \tag{1.1}$$

where $\mathbf{y}_t = (\Delta prod_t, rea_t, rpo_t)'$ indicates the three-variable vector of variables specified above, $\mathbf{c}_t$ is a vector of constants and $\mathbf{u}_t$ denotes the vector of reduced-form innovations. As an identification strategy, we adopt a Cholesky factorization so to recover the vector of structural shocks $\boldsymbol{\varepsilon}_t$ from the reduced-form error $\mathbf{u}_t$ in (1.1), according to the following scheme:

$$\boldsymbol{\varepsilon}_t = \begin{bmatrix} \varepsilon_t^{\Delta prod} \\ \varepsilon_t^{rea} \\ \varepsilon_t^{rpo} \end{bmatrix} = \begin{pmatrix} \alpha_{11} & 0 & 0 \\ \alpha_{21} & \alpha_{21} & 0 \\ \alpha_{31} & \alpha_{32} & \alpha_{33} \end{pmatrix} \begin{bmatrix} u_t^{oil\ supply\ shock} \\ u_t^{aggregate\ demand\ shock} \\ u_t^{oil\ market\text{-}specific\ demand\ shock} \end{bmatrix} \tag{1.2}$$

The Cholesky ordering in (1.2) corresponds to assuming the following set of conditions. Firstly, crude oil supply shocks are defined as unpredictable innovations to global oil production, that is, oil demand shocks ($u_t^{aggregate\ demand\ shock}$ and $u_t^{oil\ market\text{-}specific\ demand\ shock}$) do not influence crude oil supply ($u_t^{oil\ supply\ shock}$) in the same month. That assumption is plausible since adjusting oil production is costly for oil producer countries and because the state of the crude oil market is difficult to forecast in the very short run. Hence, oil producer countries tend to respond slowly to oil demand shocks.

Secondly, shocks to global real economic activity that are not explained by oil supply shocks are identified as shocks to global demand for industrial commodities. We simply define these shocks as aggregate demand shocks. We assume that shocks to oil market-specific demand ($u_t^{oil\ market\text{-}specific\ demand\ shock}$) do not influence global real economic activity ($u_t^{aggregate\ demand\ shock}$) in the same month. In general, our assumption is reasonable because global real economic activity responds with a delay to oil price increases.

Finally, shocks to the real oil price that are not explained by oil supply shocks or aggregate demand shocks by construction reflect changes in the demand for oil in contrast to changes in the demand for all industrial commodities. We simply define these shocks as oil market-specific demand shocks. In particular, these shocks represent the fluctuations in precautionary demand for oil due to uncertain future oil supply.

We estimate our VAR reduced-form equation (1.1) using least squares. The resulting estimates are used to construct the structural VAR representation of the model. We adopt the inference method used by Gonçalves and Kilian (2004) which implies a recursive-design wild bootstrap with 2,000 replications.[8]

[8] This method is successful in dealing with conditional heteroskedasticity of unknown form in autoregressions. In particular, it is well known that there is evidence of conditional heteroskedasticity in the residuals of many estimated dynamic regression models involving monthly data. In general, standard residual-based bootstrap methods of inference for autoregressions are invalidated by conditional heteroskedasticity. Therefore, Gonçalves and Kilian (2004) propose the recursive-design wild bootstrap method. The latter tends to be much more accurate than standard methods when it is applied to the residuals of the dynamic regression

1.2.2 Modelling the Consequences of Oil Price Shocks on the UK Economy

Having identified the shocks and obtained the responses of our world variables to these shocks, we then estimate the impact of structural innovations in model (1.1) to the growth rate of UK real GDP (Δy_t), UK CPI inflation (π_t), the UK short-term nominal interest rate (Δr_t) and the UK real government deficit (d_t).[9] In particular, we measure the effects of oil supply shocks, aggregate demand shocks and oil specific demand shocks on these UK macroeconomic aggregates adopting the following regressions:

$$\begin{aligned} \Delta y_t &= \alpha_j + \sum_{i=1}^{12} \gamma_{ji} \hat{\lambda}_{jt-i} + z_{jt} \\ with &: \; j = 1, 2, 3 \end{aligned} \tag{1.3}$$

$$\begin{aligned} \pi_t &= \delta_j + \sum_{i=1}^{12} \eta_{ji} \hat{\lambda}_{jt-i} + \upsilon_{jt} \\ with &: \; j = 1, 2, 3 \end{aligned} \tag{1.4}$$

$$\begin{aligned} \Delta r_t &= \theta_j + \sum_{i=1}^{12} \iota_{ji} \hat{\lambda}_{jt-i} + s_{jt} \\ with &: \; j = 1, 2, 3 \end{aligned} \tag{1.5}$$

model.

[9] Appendix A provides a detailed description of data sources and the construction of the series used to estimate the UK regression model.

and:

$$\begin{aligned} d_t &= \varphi_j + \sum_{i=1}^{12} \varkappa_{ji}\hat{\lambda}_{jt-i} + w_{jt} \qquad (1.6) \\ with &: \; j = 1, 2, 3 \end{aligned}$$

Our regression model is based on quarterly data for Δy_t, π_t, Δr_t, and d_t. Thus, in equations (1.3)-(1.6) $\hat{\lambda}_{jt}$ represents the measure of quarterly shocks (estimated in model (1.1)) constructed by averaging the monthly structural innovations for each quarter:

$$\begin{aligned} \hat{\lambda}_{jt} &= \frac{1}{3}\sum_{i=1}^{3} \hat{u}_{j,t,1} \qquad (1.7) \\ with &: \; j = 1, 2, 3 \end{aligned}$$

where $\hat{u}_{j,t,1}$ indicates the estimated residual for the jth structural shock in the ith month of the tth quarter of the sample.[10] In equations (1.3)-(1.6) the impulse response coefficients correspond to γ_{ji}, η_{ji}, ι_{ji}, and $\varkappa_{ji}$, respectively. The number of lags is determined by the maximum horizon of the impulse response function, that is set to twelve quarters. Finally, in equations (1.3)-(1.6) z_{jt}, v_{jt}, s_{jt} and w_{jt} are potentially serially correlated errors. In order to deal with possible serial correlation in the error term we use block bootstrap methods. Following the empirical strategy of Kilian (2009), all our estimated results are obtained with block size 4 and 20,000 bootstrap replications.

Our regression model (1.3)-(1.6) holds under the identifying assumption that within a given a quarter there is no feedback from Δy_t, π_t, Δr_t, and d_t to $\hat{\lambda}_{jt}$, $j = 1, 2, 3$. Thus, these shocks can be treated as exogenous and we can assess their effects on UK macroeconomic aggregates. The assumption that $\hat{\lambda}_{jt}$, $j = 1, 2, 3$ are exogenous to UK GDP growth, CPI inflation, nominal interest rate and government deficit can be defended as follows. We assume that the United

[10] These quarterly averages are not exactly uncorrelated but their correlation is so low that they can be treated as uncorrelated.

Kingdom is "small" in the sense that movements in UK variables have no effects on world variables. Although the United Kingdom produces oil, its average share of oil production in the period 1976-2014 was 3% with a peak of 5% from 1984 to 1986 and it was 1% in 2014 according to the statistics of US Energy Information Administration (Monthly Energy Review). Similarly, UK petroleum consumption has been on average 3% of world consumption during the period 1976-2014 (US Energy Information Administration - Monthly Energy Review). Given these data, our assumption that oil supply shocks, aggregate demand shocks and oil market-specific demand shocks are exogenous to UK macroeconomic aggregates seems justified.

1.3 Results

In this section, we show the estimation results of our empirical model. Firstly, we start by discussing the results concerning the causes of oil shocks (stage 1). Secondly, we focus on the consequences of oil shocks on the UK economy (stage 2).

1.3.1 Causes of Oil Shocks: Estimates

Figure 1.3 shows the historical evolution of the structural shocks considered in our model for the period 1976-2014. Our analysis focuses on the episodes associated with the major changes in the real oil price. In general, our estimated results confirm the findings of Kilian (2009) for the sample 1976-2007. However, as our sample runs to end 2014, we are able to explain oil price variation in recent years.

In particular, from Graph (a), we do not observe any oil supply disruption corresponding to the Iranian Revolution occurring in 1978-1979. Accordingly, our interpretation is that the reductions of oil supply due to the Iranian Revolution were more than offset by increases in production from other oil producer countries. Moreover, we note that during the Iran-Iraq War in 1980 there is evidence of oil supply disruption.

Graph (b) shows that repeated large positive shocks to global aggregate demand occurred in 1978, 1979 and 1980. Moreover, from Graph (c), we observe a large unanticipated increase of oil market-specific demand during 1979. Indeed, in that year the Iranian Revolution, the Iranian hostage crisis and the Soviet invasion of Afghanistan all created concern about the future availability of oil supply from the Middle East. Thus, these episodes induced a higher precautionary demand for oil.

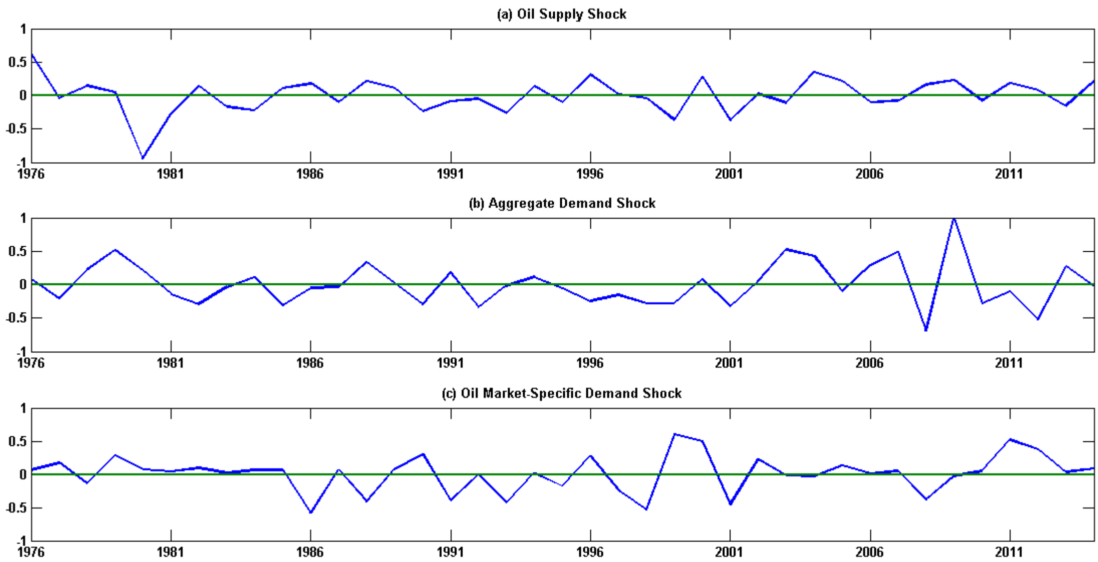


Figure 1.3: Historical Evolution of the Structural Shocks, 1976-2014

Note: Annual frequency average of structural residuals implied by the SVAR model (1).

Focusing on the most recent years, from 2002 to mid-2008, the large increase in the real oil price was driven by a series of positive aggregate demand shocks associated with shifts in global real economic activity (Graph (b)). Interestingly, during the same period we find that oil supply shocks played a negligible role in oil price fluctuations (Graph (a)). From Graph (b), we observe that, at the end of 2008, the plunge in the real price of oil reflected the falls of aggregate demand and oil market-specific demand, respectively.

The last episode that we analyse concerns the surge in the oil price that occurred from 2011 to mid-2014. As we can see from Graph (c), during this period, there is evidence of a series of positive oil market-specific demand shocks. Indeed, serious concerns about political instability in the Middle East have emerged with protests taking place in Tunisia and Egypt. Some signs of civil unrest have also appeared in Lebanon, Algeria and Yemen. All these events have created concerns about future oil shortages in the Middle East. As Barrell et al. (2011b) have argued, the repeated oil market-specific demand shocks which occurred in this period can also be explained by the sharp rise in investors demand as the financial crisis unfolded, with investors pulling out of complex financial assets in search of a safer haven.

Figure 1.4 shows the impulse response analysis of global oil production, global real economic activity and the real price of oil to one standard deviation structural shocks. In particular, we normalize the signs of the shocks in order to induce an increase in the oil price.

In terms of results, Graph (a) shows that an unanticipated oil supply disruption implies an immediate strong reduction of global oil production. After one year we observe a partial recovery of global oil production. This result can be explained as follows. In the presence of a negative oil production shock in one region, producer countries of other regions in the world increase their production. From Graph (b), we see that an unanticipated oil supply disruption does not significantly affect global real economy activity. Interestingly, an unanticipated oil supply disruption causes a small and partially significant increase in the real price from fourth to seventh month (Graph (c)).

From Graph (d), we note that an unexpected increase in aggregate demand implies an expansion of global oil production that becomes significant three months after the shock occurs. Graph (e) shows that the unexpected increase in global real economic activity is very strong in terms of magnitude and highly significant. Similarly, the unexpected increase in global real economic activity causes a sharp, very persistent and statistically significant increase in the real oil price (Graph (f)).

Graph (g) indicates that an unanticipated expansion of oil market-specific demand does not influence global oil production. From Graph (h), we see that an unanticipated expansion of oil market-specific demand causes a temporary increase of global real economic activity that is significant until the tenth month. Finally, we find that an unanticipated expansion of oil market-specific demand implies an immediate large increase in the real oil price (Graph (i)). This effect is very persistent and highly significant.

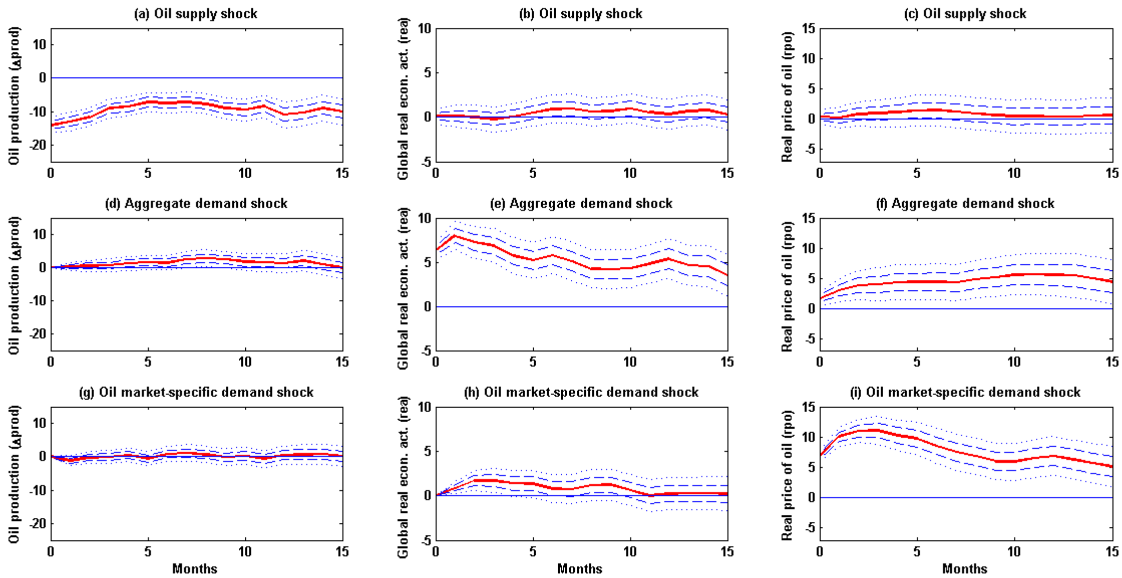


Figure 1.4: Impulse Response Analysis to One St. Dev. Shocks

Note: Solid red lines: point estimates; dash and dotted blue lines: one and two standard error bands, respectively.

In general, our results confirm the findings of Kilian (2009) and Alquist and Kilian (2010). In particular, the most important result emerging from our impulse response analysis is that shortfalls of oil supply have small and partially significant effects on oil price changes. This outcome can be explained as follows. Oil supply disruptions in one region are compensated by increases of endogenous oil supply from other regions of the world. Accordingly, the question that arises is: how can one explain the large increases in the real oil price following the major political events in the Middle East? Figure 1.4 shows that the answer coincides with the sharp increases of precautionary demand for oil. These changes in precautionary demand are caused by shifts in expectations of future oil supply. Such expectations respond on impact to exogenous political events in the Middle East and cause a large increase in the oil price.

The cumulative effects of oil demand and supply shocks on the real price of oil are shown in Figure 1.5. In general, our results suggest that oil supply shocks have played a small role in terms of determination of oil price. Aggregate demand shocks and oil market-specific shocks explain most of the variation in the oil price.

In what follows we describe in detail the most important episodes of oil price fluctuations. Graph (c) shows that the surge in the oil price in 1980 was caused by the increase in precautionary demand for oil. Indeed, the Iranian Revolution, the Iranian hostage crisis and the Soviet invasion of Afghanistan created concern about future supply of oil in the Middle East. Moreover, during the period 1980-1982, aggregate demand grew continuously implying the rise in the oil price (Graph (b)). Consequently, the increase in the oil price that occurred in late 1979 and continued until 1985 was mainly caused by demand shocks. Conversely, during this period, oil supply shocks do not influence substantially oil price variation.

From Graph (c), we observe that the fall in the real price of oil that occurred in 1986 is mainly associated with the fall in oil market-specific demand. The increase of Saudi Arabia oil production following the fall of OPEC cartel in the late 1985 does not seem to explain the drop in the oil price in in 1986 (Graph (a)).

In 1990-1991, we note a large increase in the oil market-specific demand that caused the sharp increase in the oil price (Graph (c)). Indeed, precautionary demand for oil increased in response to expected shortfalls in oil supply due to the

Kuwait Invasion. According to Graph (a), the latter episode also caused a physical disruption in oil supply. Again, oil market-specific demand shock was the main cause of the oil price surge of 1999-2000 (Graph (c)).

Turning to more recent episodes of oil price fluctuations, we find that the increase in the oil price during the period 2002-2008 coincided with a very large swing in global real economic activity (Graph (b)). Indeed, during this period there was sustained global demand pressure and the oil price increased more than other commodity prices. The latter effect occurred because the supply of crude oil supply stagnated between 2002-2008 (Graph (a)). At the end of 2008, the drop in oil price is associated with the fall in oil market-specific demand (Graph (c)).

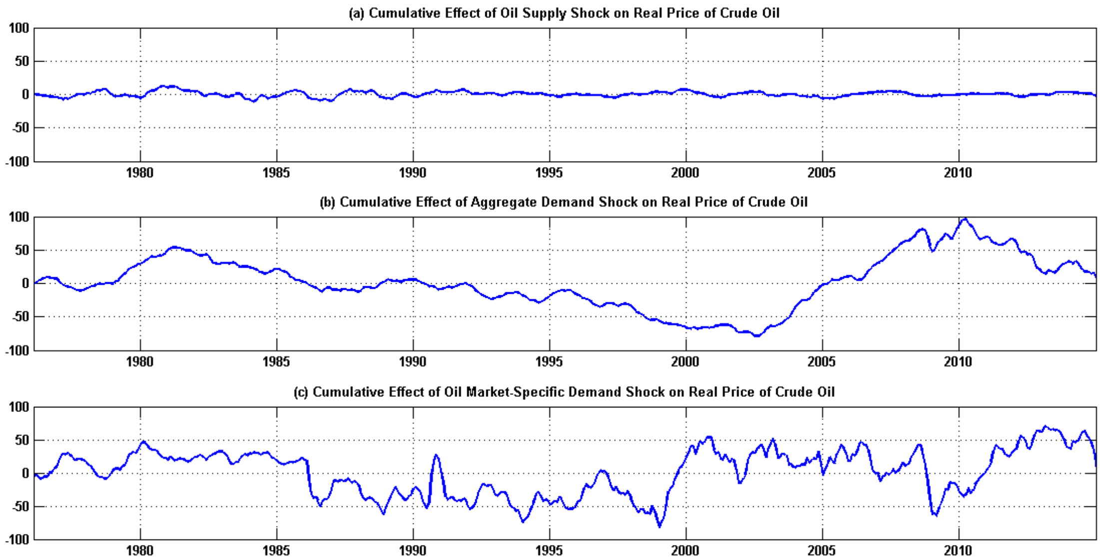


Figure 1.5: Historical Decomposition of Real Oil Price

Note: Estimation results obtained from the SVar model (1).

From Graph (c), we observe that between 2011 and mid-2014 there was a sustained increase in oil market-specific demand that pushed up the oil price. This rise of precautionary demand for oil was associated with social and political instability in the Middle East and North African regions. In particular, the unrest sweeping Tunisia in early 2011 rapidly spread over into many surrounding countries, including major oil producers, such as Algeria and, most significantly, Libya. Clearly, instability in the region automatically raised worries of supply disruptions and possible oil shortage. Moreover, between 2011 and mid-2014, the worsening of the financial crisis tended to increase precautionary demand for oil. In particular, Barrell et al. (2011b) highlighted that the rise in the precautionary demand for oil related to the sharp increase of investors demand for a safer haven than complex financial assets.

Finally, Graphs (b) and (c) show that the plunge in the oil price that started in mid-2014 seems to be associated with the decreases of both aggregate demand and oil market-specific demand.

In general, our analysis confirms the results of Barsky and Kilian (2002) and Kilian (2009) showing that most large and persistent fluctuations in the real price of oil since mid-1970s have been associated with the cumulative effects of oil demand rather than oil supply shocks. Thus, our results are in contrast with traditional studies (see for example Hamilton, 1983, 2003 and 2009) suggesting that all major fluctuations in the price of oil can be attributed to disruptions of oil supply triggered by political events occurred in the Middle East that are exogenous to the current or the past state of the economy.

The fact that flow supply disruptions have had small effects on the real oil price does not mean that political events in the Middle East do not matter. These events have affected the real oil price by shifting expectations about future shortages of oil supply relative to oil demand. As we explained above, in our model these expectations are captured by shocks to precautionary demand for oil. In this regard, our results have shown that oil market-specific demand shocks cause large fluctuations of real oil price even when oil supply is unchanged.

Finally, focusing on the most recent years our results indicate that aggregate demand shocks are mainly responsible for the "Great Surge" in the real price of oil between 2002 and mid-2008. Moreover, the increase in the real oil price between 2011 and mid-2014 is mostly explained by oil market-specific demand shocks associated with the social and political instability in the Middle East and North African regions together with an intensifying financial crisis. Interestingly, we find that the current oil price plunge that started in mid-2014 relates to a combined fall in aggregate demand and oil market-specific demand.

1.3.2 Consequences of Oil Shocks on the UK Economy: Estimates

In this section, using our regression model specified according to equations (1.3)-(1.6), we analyse the effects of the identified shocks on UK real GDP growth, CPI inflation, the nominal interest rate, and the real government deficit. Accordingly, Figures 1.6 and 1.7 show the impulse response functions of these UK macroeconomic aggregates to the three types of shocks defined earlier.

IRFs for the UK GDP Growth and CPI Inflation. We start by analysing the responses of domestic GDP growth and CPI inflation as shown in Figure 1.6. As we can see from Graph (a), the response of UK GDP growth to oil supply disruptions is negative throughout all quarters. However, the one-standard error confidence intervals indicate that the negative response is significant only for the first five quarters. Graph (c) indicates that, on impact, the response of UK GDP growth to aggregate demand expansions is positive but is not statistically significant. Seven quarters after the shock occurs, it turns to negative and it becomes significant from the second year onwards.

Graph (e) displays the response of UK GDP growth to oil market-specific demand shock. In particular, one-standard error confidence intervals indicate that the response of UK GDP growth to this shock is not statistically significant at all horizons. There is some evidence of a decline in UK GDP growth six quarters after the shock occurs.

From Graph (b), we note that negative oil supply shocks lead to increases in UK CPI inflation throughout all quarters. The response is statistically significant at all horizons. Graph (d) shows that the impact of increases in aggregate demand on the UK consumer price level is positive and statistically significant from the first year onwards. The maximum is reached three years after the shock occurs. Finally Graph (f) indicates that the impact of expansions of oil market-specific demand on UK inflation is more or less zero throughout all quarters.

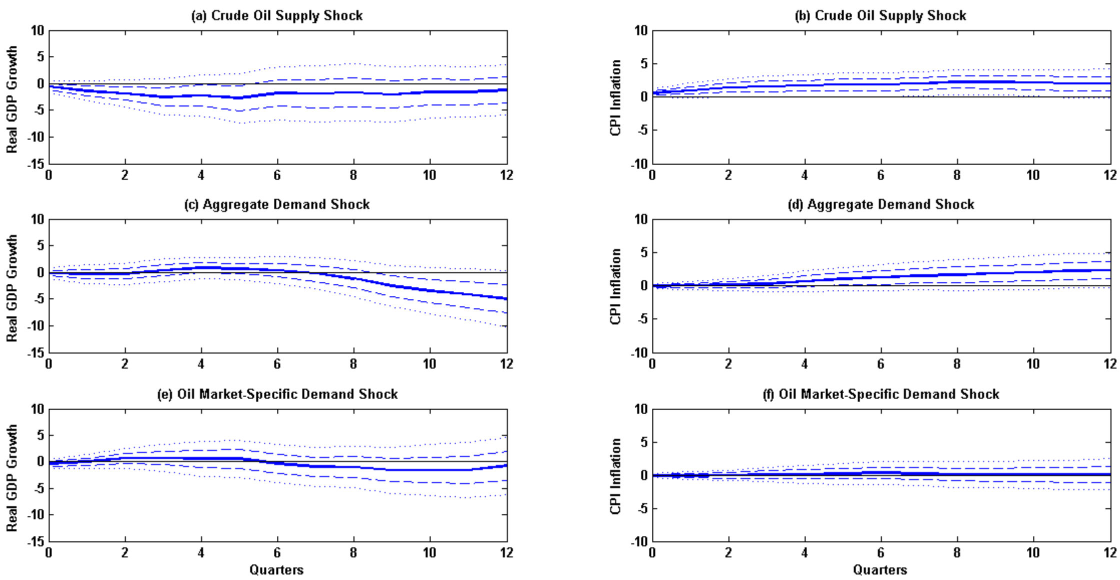


Figure 1.6: IRFs of the UK Real GDP Growth and CPI Inflation to Each Str. Shock

Note: Solid blue lines: point estimates; dash and dotted blue lines: one and two standard error bands, respectively.

In general, our results are in line with the findings of Millard and Shakir (2013) for the UK economy. In particular, oil supply disruptions induce an immediate fall in UK GDP growth and cause a sustained increase in UK inflation.

In line with the findings of Kilian (2009) for the US economy, we find that increases in aggregate demand initially have a negligible effect on UK output growth but in the long run they tend to depress it. This last result can be explained as follows. On impact, positive unexpected global economic shocks stimulate UK real output growth and offset the growth-retarding effects of a higher real price of oil. However, as this stimulus disappears over time, the response of UK GDP growth becomes negative. The most relevant example in this concern is the "Great Surge" in the real price of oil between 2002 and mid-2008. During this period, the UK economy did not experience any severe recession because the oil price surge was mainly driven by unexpectedly strong demand for oil from emerging Asia which offset the negative effects of higher oil prices and other imported commodities.

Similarly to the results of Peersman and Van Robays (2012), we find that positive precautionary demand shocks have a very small impact on UK GDP growth and have no significant effects on domestic inflation. These findings suggest that precautionary demand shocks have small and insignificant effects on domestic GDP growth and CPI inflation because the UK is an oil producer country. Therefore, the UK economy has been less affected by changes in inventory holdings compared to typical oil importing countries. In this regard, the UK had the possibility to increase its own oil production in order to self-insure against interruptions to foreign oil supply instead of drawing upon inventory holdings.

IRFs for the UK Nominal Interest Rate and Government Deficit. Figure 1.7 shows the impulse response functions for the UK nominal interest rate and the real government deficit to each of the three shocks defined above.

In Graph (a), we observe that the nominal interest rate progressively falls in response to oil supply disruptions. One-standard error confidence intervals indicate that the response of the UK nominal interest rate to this shock is statistically significant starting from the fourth quarter. Graph (c) shows that the increase in aggregate demand induces a positive nominal interest rate. The response is statistically significant from the third quarter onwards. Graph (e) indicates that positive oil specific-market demand shocks cause an increase in the nominal interest rate. The positive impact of oil specific-market demand shocks on the nominal interest rate is statistically significant from the second to the seventh quarter.

Graph (b) shows that in response to negative shocks of crude oil supply, the UK government deficit decreases. The one-standard error confidence intervals indicate that the negative response is significant for all the quarters considered. As we can observe from Graph (c), the response of UK government deficit to increases in aggregate demand is not statistically significant at all horizons. Similarly, Graph (e) shows that expansions of oil market-specific demand have more or less zero effect on the UK government deficit.

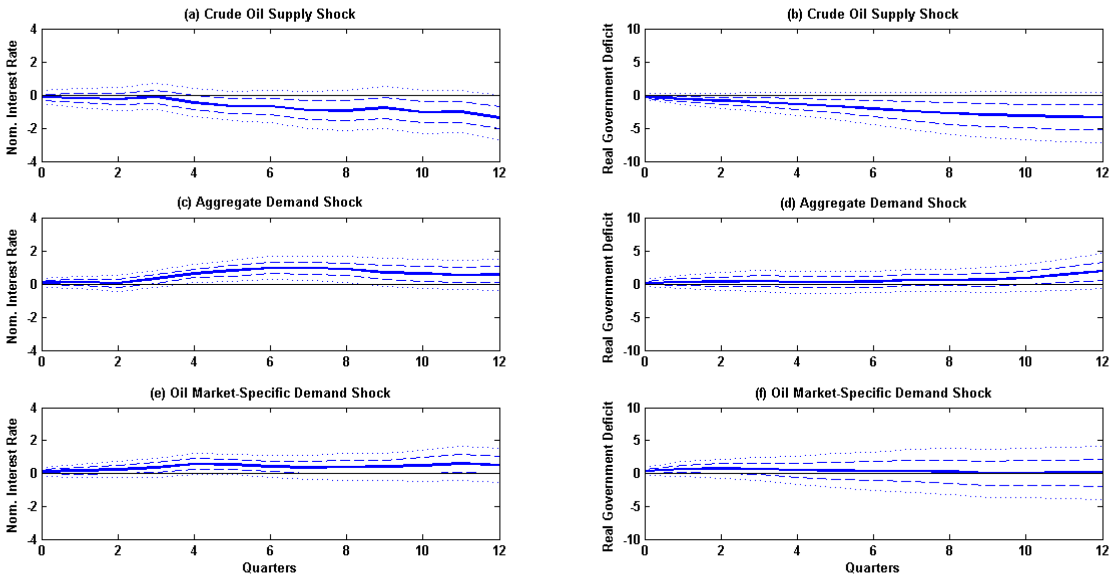


Figure 1.7: IRFs of the UK Nom. Int. Rate and Gov. Def. to Each Str. Shock

Note: Solid blue lines: point estimates; dash and dotted blue lines: one and two standard error bands, respectively.

In general, consistent with the results of Peersman and Van Robays (2012), Graphs (a), (c) and (e) show that the Bank of England responds differently to oil price fluctuations associated with unanticipated booms in oil demand with respect to oil price changes due to unexpected oil supply disruptions. Evidently, these different responses of the monetary authority relate to the corresponding effects of oil demand shocks and oil supply shocks on the UK economy.

For example, as we have shown in Figure 1.6, an unexpected demand boom driven by the global business cycle does not depress the UK economy in the short run. Conversely, an unanticipated oil supply disruption reduces immediately UK real output growth. This implies different reactions of UK monetary authority depending on the composition of the oil demand and oil supply shocks underlying the oil price shock.

In particular, Graphs (c) and (e) show that the nominal interest rate increases after both an aggregate demand shock and an oil market-specific demand shock. In this regard, the positive response to aggregate demand shocks is consistent with the Bank of England's decision to raise interest rates before the oil price shock of 1978-1980. Indeed, looking at the 3 Month Treasury Bills series, it is evident that the Bank of England had been raising interest rates steadily from mid-1977 to the end of 1980.

Figure 1.7 also shows that negative shocks to oil supply induce the Bank of England to decrease the nominal interest rate. This result is in line with the findings of Kilian and Lewis (2011) about the behaviour of the Federal Reserve in the case of negative oil supply shocks. In particular, the negative response of the nominal interest rate to unanticipated oil supply disruptions is consistent with the view that the Bank of England considers the resulting oil price increases as adverse demand shocks.

Although the results shown in Graphs (a), (c) and (e) on average correctly represent historical UK monetary policy, they cannot be interpreted as representative of actual monetary policy responses at any given point in time. Indeed, the well documented shifts in UK monetary policy between 1976 and 2014 imply that any VAR model that analyses the responses of the nominal interest rate to oil supply and demand shocks should allow for time-varying coefficients.

In this regard, an interesting example is provided by the paper of Millard and Shakir (2013). In particular, Millard and Shakir (2013) have employed an empirical framework with time-varying parameters in order to understand how the impact of oil price shocks on the UK economy may have developed over time. However, as argued by Kilian (2014), the idea of analysing the responses of nominal interest rate to oil demand and supply shocks within a time-varying parameter VAR is not practical for two reasons. Firstly, the methodology underlying our structural VAR requires long samples with sufficient variation in oil demand and oil supply shocks to ensure efficient estimation. Secondly, our identifying assumptions hold only using data at monthly frequency. However, it is well documented that time-varying parameter VARs are computationally infeasible when using monthly data.

This shortcoming does not apply to the recent generation of DSGE models which are able to disentangle the responses of monetary policy to oil demand and oil supply shocks. Indeed, recent advances in DSGE modelling of endogenous oil price shocks provide a useful solution in this direction. In particular, such DSGE models are able to distinguish between several causes of fluctuations in the global demand for industrial commodities and to estimate the impact of alternative policy choices. Therefore, one of the objectives of Chapter 2 and 3 is to develop a DSGE model in order to analyse the response of UK monetary policy to different types of oil price shocks.

Focusing on the responses of the UK government deficit, we find that negative shocks to world crude oil supply improve the UK public finances. In particular, the reduction of global crude oil supply induces an increase in the real oil price. Since the UK is an oil producer country this increase in oil price implies an improvement of government oil revenues. Consequently, UK government budget improves.

Our estimated result is consistent with previous UK literature (see, among the others, Powell and Horton, 1985; Hall et al., 1986; Young, 2000; OECD Economic Surveys, 2002; OBR, 2010; Barrel et al., 2011). In particular, all these studies have found that, after an increase in the oil price, the UK fiscal position is positively affected by the additional North Sea revenues stemming from the petroleum revenue tax and the VAT applied on oil products. In this regard, Young (2000) argued that in a scenario of high oil price, although the performance of UK economy deteriorates, the government represents one of the few winners in the short term.

As in the case of the nominal interest rate, we should be careful in the interpretation of these responses. Indeed, our structural VAR model is unable to take into account a large variety of sources of oil price shocks. More specifically, as we are going to show in Chapter 3, the particular implications of an oil price shock for the UK public finances differ depending on whether the shock is global or UK specific. Similarly, we will show that the effects implied by oil demand shocks are different from the ones generated by oil supply shocks.

1.4 Conclusions

In this paper, we have studied the causes and the consequences of oil price fluctuations on the UK economy for the sample period 1976:1-2014:12. As an empirical strategy, we adopted a two-stage method in order to estimate our model. In the first stage, we used the framework of Kilian (2009) to capture supply and demand conditions in the oil market using a SVAR framework. In particular, we identified shocks to the world oil price from three types of underlying source: oil supply shocks, aggregate demand shocks and oil market-specific demand shocks.

In the second stage, we assessed the impact of structural innovations estimated in the first stage on several UK macroeconomic aggregates such as, real GDP growth, CPI inflation, nominal interest rate and real government deficit.

Our empirical approach assumes that the real oil price is endogenous with respect to macroeconomic fundamentals. In order to estimate the causes of oil price changes we have used monthly data whereas, in order to assess the effects of different oil price fluctuations on the UK economy, we have constructed measures of the quarterly shocks by averaging the monthly structural innovations for each quarter.

Several important insights emerge from our analysis. Firstly, we find that, since the mid-1970s, shortfalls in oil supply have had small effects on oil price changes. Therefore, our results contrast with the view of traditional studies stating that major oil price changes are caused by disruptions in oil supply triggered by exogenous political events occurring in the Middle East.

We find that major fluctuations in the real oil price coincide with shifts in precautionary demand for oil. These changes in precautionary demand are mainly caused by shifts in expectations about future oil supply. Such expectations respond on impact to exogenous political events in the Middle East and cause large changes in the oil price.

For example, we find that the large increase in the real oil price, between 2011 and mid-2014, was mainly caused by oil market-specific demand shocks associated with the social and political instability in the Middle East and North African regions together with the financial crisis. Our results also indicate that the recent plunge in the oil price that started in mid-2014 was induced by decreases in both aggregate demand and oil market-specific demand.

Secondly, our IRFs show different responses of UK macroeconomic aggregates depending on the underlying shock affecting oil price. More specifically, UK GDP growth goes down immediately in response to negative oil supply shocks whereas increases in aggregate demand, initially, have small effects on domestic output growth but, in the long run, they tend to reduce it. In general, our estimated responses show that oil shocks cause a sustained increase in UK inflation.

Focusing on UK monetary policy, we find that the nominal interest rate increases after both aggregate demand shocks and oil market-specific demand shocks. The opposite occurs in the case of negative shocks to oil supply. Our estimated responses also indicate that the increase in the real oil price induces an improvement of UK public finances because of the rise in oil revenues. More specifically, in response to negative shocks of crude oil supply the UK government deficit diminishes.

Although the empirical approach presented in this paper provides a useful framework in order to understand the causes and the consequences of oil price shocks on the UK economy, it suffers from three main limitations. The first shortcoming concerns the effects of oil price fluctuations on the UK economy. In particular, our large sample includes structural shifts in several macroeconomic aggregates that affected the UK economy during this period. For example, it is well documented that UK monetary policy changed several times between 1976 and 2014. Therefore, our IRFs are not representative of actual policy responses at any given point in time. They represent only the average historical behaviour of UK macroeconomic aggregates during this period. Moreover, it is not possible to split the sample of our analysis since the methodology underlying our structural VAR requires long samples with sufficient variation in oil demand and oil supply shocks to ensure efficient estimation.

The second limitation of our structural VAR model is that it cannot differentiate between flow demand and supply shocks originating in different parts of the world. For example, it cannot identify whether a given oil price shock is caused by unexpected demand from China or by an exogenous supply disruption in the Middle East, as long as both shocks occur abroad. However, as agued by Kilian (2014), even controlling for the magnitude of the oil price shock on impact, the responses of the economy depend on the type of structural shock in the model and on where in the world this structural shock occurs.

The third shortcoming associated with the present structural VAR is that it is not able to differentiate between two distinct demand shocks. For example, it cannot differentiate whether a shock occurs to foreign productivity or to foreign monetary policy.

All three limitations do not apply to the recent generation of DSGE models which are able to distinguish between several causes of fluctuations in the global demand for industrial commodities and to estimate the impact of alternative policy choices. Therefore, in Chapter 2, we are going to analyse an open economy DSGE model for the UK economy in order to assess the effects of oil price fluctuations. Finally, in Chapter 3, we use an open economy DSGE model in order to evaluate the specific effects on UK fiscal sector and, in particular, the rate at which oil price changes work through the economy into UK public finances.

A Appendix: Chapter 1

A.1 Data

$\Delta prod_t$: as we described in the main body of the paper, this is the percentage change of global crude oil production. This series is obtained by the log differences of world crude oil production in millions per barrels pumped per day (averaged by month). The source is the US Department of Energy.

rea_t : as we described in the main body of the paper, this is the index of global real economic activity. The source of this series is Kilian website: http://www-personal.umich.edu/~lkilian/reaupdate.txt.

Kilian (2009) provides a clear explanation in order to obtain rea_t. In particular, the data series to construct this index are taken from representative single-voyage freight rates available in the monthly report on "Shipping Statistics and Economics" published by Drewry Shipping Consultants Ltd. These data series relate to various bulk dry cargoes consisting of grain, oilseeds, coal, iron ore, fertilizer and scrap metal. In order to eliminate the fixed effects for different routes, commodities and ship sizes, Kilian adopts two steps. Firstly, he computes the period-to-period growth rates for each series. Secondly, he takes the equal-weighted average of these growth rates and cumulates the average growth rate. The final series is deflated by the US CPI and linearly detrended. The base month is January 1986. Kilian also provides evidence that this index based on industrial commodity markets well represents the level of global real economic activity.

rpo_t : as we described in the main body of the paper, this is the real price of oil and it is expressed in log terms. This series is obtained from the refiner acquisition cost of imported crude oil. The source is US Department of Energy. The nominal series of oil price is deflated by the US CPI. The source is the US Bureau of Economic Analysis.

Δy_t : it is the growth rate of UK real GDP. This series is obtained by the log differences of real UK GDP: "gross domestic product, chained volume measures, seasonally adjusted (£m)". The source is Office for National Statistics (code ABMI in Quarterly National Accounts).

π_t : it is the UK CPI inflation. This series is obtained by the log differences of UK consumption expenditure deflator: "final consumption expenditure by household and NPISH deflator, seasonally adjusted (base period: 2011)". The source is Office for National Statistics (code YBFS in Quarterly National Accounts).

Δr_t : it is the UK short-term nominal interest rate. This series is the 3 month treasury bills: "quarterly average rate of discount, 3 month treasury bills (Sterling)". The source is Bank of England (code IUQAAJNB in Statistical Interactive Database).

d_t : it is the UK real government deficit. This series is obtained by the "central government net cash requirement, current price, not seasonally adjusted, (£m)". The source is Office for National Statistics (code RUUW in Quarterly National Accounts). The original series is seasonally adjusted and deflated by the final consumption expenditure by household and NPISH deflator.

Chapter 2: Oil Price Shocks and the UK Economy, 1990-2005

2.1 Introduction

This paper aims to assess the effects of movements in oil prices on the UK economy. In particular, our objective is to analyse an open economy Dynamic Stochastic General Equilibrium (DSGE) model for the United Kingdom in order to evaluate the economic repercussions of oil price fluctuations.

Media, policymakers and economists have been interested in oil prices changes since the 1970's. Indeed, large fluctuations in oil prices have significant economic effects. In this regard, most of the exisisting literature has focused on the US economy (see, for example, Kim and Loungani, 1992; Rotemberg and Woodford, 1996; Finn, 2000; Backus and Crucini, 2000; Barsky and Kilian, 2002 and 2004; Leduc and Sill, 2004; Carlstrom and Fuerst, 2006; Nakov and Pescatori, 2007; Dhawan and Jeske, 2007; Kilian, 2008a and 2009; Arora and Gomis-Porqueras, 2011; Antonakakis et al., 2014).

On the other hand, only few studies have analysed the UK macroeconomy and oil shocks. Thus, for instance, the paper by Harrison et al. (2011) investigates the effects of permanent energy price shocks for economies with declining stocks of natural resources, such as the United Kingdom. Millard (2011) considers a macroeconomic model which studies the effects of many temporary shocks, including but not limited to energy prices, on inflation as well as how monetary policy can respond to such shocks. Both these papers implicitly assume that the real oil price is exogenous with respect to macroeconomic fundamentals. However, this assumption has been proved to be incorrect (Kilian 2008a, 2008b and 2009).

Therefore, recent literature on DSGE models has largely investigated endogenous oil price shocks. A careful analysis in this direction is offered by the papers of Bodenstein et al. (2008), and Nakov and Nuño (2011). In particular, these two papers develop DSGE models with the endogenous real price of oil and monetary policy but without a global economic framework.

Another strand of literature has considered DSGE models with endogenous oil prices but it has ignored the many sources of possible shocks that affect oil price fluctuations (see, for example, Nakov and Pescatori 2010a and 2010b).

In contrast to the above literature, in the present chapter we develop a DSGE model for the UK economy considering the endogenous determination of the oil price and adopting a world economy model in a new Keynesian framework. In addition, our model presents a rich stochastic structure accounting for a broad range of shocks that potentially influence the real oil price. In this regard, we consider several causes for oil price changes. For example, oil price fluctuations can derive from an increased global demand as well as from oil supply disruptions. Similarly, we consider the fact that a country reacts differently to oil price movements that originate domestically rather than abroad. Moreover, our model evaluates the monetary policy responses following these oil price fluctuations. Therefore, our study offers a useful tool for UK monetary policy makers in responding to oil price shocks.

The theoretical framework of the present chapter is in line with the empirical model analysed in Chapter 1. Firstly, as in the previous chapter, we assume that the real oil price is endogenous with respect to global macroeconomic conditions. Secondly, we focus on the demand side of the oil market. In this regard, recent economic literature has stressed the importance of oil demand shocks in order to explain oil price fluctuations (see, for example, Kilian, 2009 and 2014; Baumeister and Peersman, 2013).

In the present paper we assume that there are two countries (UK and rest of the world) that differ in population sizes, oil intensities, oil endowments, non-oil trade flows and oil trade flows. In each country, we adopt a particular specification of the production function considering oil as an imported commodity. In addition, we assume that oil enters in the production function of consumption goods. This allows us to consider the effects of oil shocks on household demand. Accordingly, our approach is in line with the studies of Dhawan and Jeske (2008), Hamilton (2009), Edelstein and Kilian (2009) and Bodenstein et al. (2011). Indeed, all these papers have shown that the increases in oil price are expected to reduce households' discretionary income, as consumers have less money to spend after paying their energy bills.

In order to estimate our model, we use observed data series for the UK economy and the rest of the world over the sample period 1990-2005. The observed variables for the foreign bloc are constructed using the Loretan (2005) technique of trade weights and aggregating data of the main UK trading partners. Our sample choice is motivated by the fact that, in this period, the UK economy is a net oil exporter. Moreover, our sample period covers the "Non-Inflationary, Consistently Expansionary" (NICE) decade, as identified by King (2003), during which there were no major changes to the macroeconomic policy environment.

Our results contribute to previous literature by showing that there are different implications of oil price shocks on the UK economy depending on the specific source the shock. More specifically, we find that foreign oil intensity shock is the main cause of UK oil price variation. In this regard, oil intensity is defined as the measure of oil efficiency in a given economy. In particular, oil efficiency is related to the amount of oil required to provide products and services. Thus, for instance, oil efficiency depends on the methods of transportation and the conservation efforts. Accordingly, in a given economy, the increase in oil intensity induces an improvement in its oil efficiency. As we will describe below, we model oil intensity as an exogenous shock that affects the functions of production goods and consumption goods. Therefore, a positive oil intensity shock induces a fall in the oil demanded by the firms that produce both production goods and consumption goods.

We also find that that foreign technology shock and foreign oil supply shock explain significantly the UK oil price volatility. Moreover, our estimated results show a strong persistence of oil shocks.

As concerns the effects on the domestic economy, our IRFs are in line with the estimated responses of Millard (2011) for the UK economy.[11] In particular, we find that the lower oil price pushes down the costs of firms using oil as production input. Accordingly, firms increase their profits and employment rises stimulating real GDP. In addition, the fall in the oil price induces a drop in retail prices. Consequently, real incomes increase boosting consumer spending. Given the inflation target, the UK nominal interest rate decreases.

Our estimated results also indicate high values for Calvo (1983) prices and wages resetting parameters, whereas we find low degrees of price and wage indexations. In general, we observe that the reaction of wage inflation in response to oil shocks is close to zero. This finding refutes the predictions of Anderton and Barrell (1995) and Barrell et al. (2011a).

In contrast to previous literature (see, for example, Hall et al., 1986 and Young, 2000) that predicted a depreciation of the Pound in the presence of a fall in the oil price, our results show something different.[12] In response to a positive foreign oil supply shock British Sterling depreciates, whereas an increase in the foreign oil intensity implies an appreciation of UK currency. Moreover, we find that a negative shock to foreign technology implies a depreciation of UK currency. In general, positive shocks to foreign oil supply and oil intensity imply a deterioration of the UK trade balance since the UK is an oil exporter country.

Finally, our historical decomposition analysis complements the existing literature by showing that sharp increases in the oil price are associated with large reductions in the UK GDP and spikes in domestic inflation. More specifically, the large increases in oil price during 1990:Q3-1992:Q3 and 1999:Q1-1999:Q3 contributed considerably to the relative UK GDP recessions. Moreover, the surge

[11]In particular, Millard (2011) does not consider the different sources of oil price fluctuations assuming the real oil price as exogenous. Moreover, his analysis focuses on increases in real oil price.

[12]In particular, Young (2000) finds that the UK currency appreciates in response to the raise of oil price. Indeed, this author analyses the economic effects of the oil price increases on the UK economy. On the other hand, as we will show in Section 4, our impulse response analysis focuses on the case of oil price decreases.

of oil price in the second half of 1990 caused a large increase in UK inflation.

The remainder of this paper is organized as follows. Section 2 outlines the DSGE model on which our analysis is based. In Section 3, we illustrate the estimation strategy and results of our DSGE model. Section 4 presents the impulse response analysis of the estimated model. Section 5 shows the evolution of the exogenous shocks over time and decomposes recent movements in output and inflation among them. The concluding remarks are found in Section 6.

2.2 Model

In this section, we present a Dynamic Stochastic General Equilibrium (DSGE) model which has two main features: firstly, the endogenous determination of real oil price and, secondly, a global economic framework. Backus and Crucini (2000) were the first to develop a DSGE model with the endogenous real price of oil. In two recent papers Bodenstein and Guerrieri (2011) and Bodenstein et al. (2012) extended this approach by considering a world economy in a new Keynesian framework such as in the models of Christiano et al. (2005) and Smets and Wouters (2003, 2007).

Our main interest lies in analysing the response of the UK economy to changes in oil prices. Thus, we consider a world economy model with two symmetric blocs: the UK economy and the rest of the world. Specifically, we take into account differences of the two blocs related to population sizes, oil intensities, oil endowments, non-oil trade flows and oil trade flows. We also assume that asset markets are complete at the country level, but incomplete internationally.

In each country, a representative household has a utility function that includes two arguments, consumption and labour. This representative household consumes both oil and non-oil goods and has monopoly power over wages that implies sticky nominal wages à la Calvo (1983). The representative household rents capital services to intermediate production firms and decides how much capital to accumulate given certain capital adjustment costs.

Each country produces a single final production good and a continuum of intermediate production goods. The intermediate production firms produce under monopolistic competition and uses capital services, labour and oil as input factors. We assume that these intermediate production firms set prices according to the Calvo model (1983).

As an additional assumption concerning nominal rigidities, we allow for partial indexation of both wages and prices to past inflation rates. In this regard, previous studies on the UK economy (see, for example, Anderton and Barrell, 1995; Barrell et al. 2011a) have stressed the importance of the behaviour of wage and price setters in order to understand the impact of oil price shocks. However, these papers were not able to convincingly quantify these effects. Conversely, our model allows us to directly assess the importance of price and wage indexations in the presence of oil price shocks.

In each country, final consumption goods are produced by firms that combine non-oil consumption goods and oil goods. In this regard, we assume that oil intensity shocks directly affect the production of these goods. Accordingly, this specification is able to capture the demand side channel for oil price variation. We know that this aspect is potentially important from the study of Kilian (2008b).

Moreover, we assume that both oil and non-oil goods are traded across the two countries.

Finally, our model includes a rich stochastic structure that allows us to distinguish between the different sources of oil price fluctuations. In particular, we are able to differentiate between flow demand and supply shocks with different geographic origins and recognize the difference between a flow demand shock driven, for example, by foreign productivity shocks, foreign oil intensity shocks or foreign monetary policy shocks.

Since the model is symmetric we will describe in detail only the model for the domestic country.

2.2.1 The Representative Household

The representative household maximizes its intertemporal utility function:

$$E_t \sum_{j=0}^{\infty} \beta_1^j U_t \tag{2.1}$$

where E_t is the expectation operator at time t and β_1^j is the discount factor. We assume that the utility function is separable in consumption and labour:

$$U_t = \left[\frac{1}{1-\sigma_1} \left(Z_{1,t}^c C_{1,t+j} - \kappa_1 C_{1,t+j-1} \right)^{1-\sigma_1} + \frac{1}{1-\chi_1} \left(1 - L_{1,t+j} \right)^{1-\chi_1} \right] \tag{2.2}$$

where $C_{1,t}$, the representative household consumption, is influenced by the presence of external habit, κ_1, related to aggregate past consumption. The parameter σ_1 is the coefficient of relative risk aversion of the representative household or the inverse of the intertemporal elasticity of substitution. The variable $L_{1,t}$ represents hours worked, while χ_1 is the inverse of the elasticity of work effort with respect to the real wage (or Frisch elasticity). As we can note, equation (2.2) also contains a preference shock to consumption denoted by $Z_{1,t}^c$.

The representative household maximizes its intertemporal utility function subject to the following time t budget constraint:

$$\begin{aligned} & P_{1,t}^c C_{1,t} + P_{1,t}^i I_{1,t} + \frac{e_{1,t} P_{2,t}^b B_{1,t}}{\phi_{1,t}^b} + \int_S P_{1,t,t+1}^d D_{1,t,t+1}(h) - D_{1,t-1,t} \\ = \; & W_{1,t} L_{1,t} + R_{1,t}^k K_{1,t-1} + \Gamma_{1,t} + P_{1,t}^o Y_{1,t}^o + e_{1,t} B_{1,t-1} \end{aligned} \tag{2.3}$$

Financial wealth of the representative household derives from the purchase of state-contingent domestic bonds, $D_{1,t,t+1}$, and a non-state contingent foreign bond $B_{1,t}$. At time t, the price of domestic bonds is denoted by $P_{1,t}^d$, while $P_{2,t}^b$ is the foreign currency price of the non-state contingent foreign bond. $e_{1,t}$ represents the nominal exchange rate expressed in units of the domestic currency per unit of foreign currency. As in the paper of Bodenstein and Guerrieri (2011), we assume that the representative household faces an intermediation cost to purchase the foreign bond, $\phi^b_{1,t}$ in order to ensure that net foreign assets are stationary. The idea is simple: the representative household will earn lower returns from holding foreign bonds when it is a net lender. Conversely, the representative household will earn higher returns from holding foreign bonds when it is a net debtor.

The representative household current income consists of four components: labour income, $W_{1,t}L_{1,t}$, capital income, $R^k_{1,t}K_{1,t-1}$, an aliquot share, $\Gamma_{1,t}$, coming from firm and union profits, and a share of the country's (unrefined) oil endowment, $P^o_{1,t}Y^o_{1,t}$. The representative household uses both its current income and financial wealth in order to buy consumption, $C_{1,t}$, and investment, $I_{1,t}$, goods that are purchased at the prices $P^c_{1,t}$ and $P^i_{1,t}$, respectively.

We assume that the representative household owns the capital stock that it rents out to the firms of intermediate production goods at a rental rate of $R^k_{1,t}$. The law of capital motion corresponds to:

$$K_{1,t} = (1-\delta_1) K_{1,t-1} + \left(1 - S\left(\frac{I_{1,t}}{I_{1,t-1}}\right)^2\right) Z^i_{1,t} I_{1,t} \tag{2.4}$$

where $K_{1,t}$ is the capital stock, δ_1 is the depreciation rate, and the adjustment cost function $S(\cdot)$ is a positive function of changes in investment. In steady state, with a constant level of investment, we assume that $S(\cdot)$ is equal to zero. Moreover, its first derivative around equilibrium equals to zero too. In the equation (2.4), $Z^i_{1,t}$ represents a disturbance to the investment specific technology process and is assumed to follow a first order autoregressive process.

Given prices, wages, union transfer and oil endowment, the representative household chooses consumption, labour supply, investment, end of period capital stock and holdings of domestic and foreign bonds in order to maximize its intertemporal objective function (2.2) subject to the intertemporal budget constraint (2.3) and the capital accumulation equation (2.4).

Labour Supply. Following Smets and Wouters (2007), we consider a representative household that supplies its labour service to a labour union. This union differentiates the labour service and resells it to intermediate labour bundlers. We assume that the union has monopoly power and sets the wage according to the Calvo model (1983). Finally, firms of intermediate production goods purchase a labour bundle from intermediate labour bundlers.

Assuming a continuum of households indexed by h, where $h \in [0,1]$, the labour bundle demanded by firms is determined as follows:

$$L_{1,t}(h) = \left(\frac{W_{1,t}(h)}{W_{1,t}} \right)^{-\frac{1+\theta^w_{1,t}}{\theta^w_{1,t}}} L^d_{1,t} \tag{2.5}$$

where $L_{1,t}(h)$ is the labour service that labour bundlers purchase from union at wage $W_{1,t}(h)$. Then, labour bundlers combine the labour service in order to obtain $L^d_{1,t}$, and resell it to intermediate production firms at wage $W_{1,t}$. We assume that the labour bundle demanded by firms, $L^d_{1,t}$, and the aggregate nominal wage paid by firms, $W_{1,t}$, are determined by Dixit-Stiglitz aggregator functions:

$$L^d_{1,t} = \left[\int_0^1 L_{1,t}(h)^{\frac{1}{1+\theta^w_{1,t}}} \, dh \right]^{1+\theta^w_{1,t}} \tag{2.6}$$

$$W_{1,t} = \left[\int_0^1 W_{1,t}(h)^{-\frac{1}{\theta^w_{1,t}}} \, dh \right]^{-\theta^w_{1,t}} \tag{2.7}$$

where $\theta^w_{1,t}$ is an exogenous first order autoregressive process with an i.i.d. normal error term reflecting wage mark-up shocks.

We denote the nominal wage desired by the representative household by $W^f_{1,t+j}$, which corresponds to the marginal rate of substitution between leisure and consumption. As we described above, the union has monopoly power so that it can set the wage subject to the labour demanded by firms. Thus, the union takes into account $W^f_{1,t+j}$ during the negotiations with labour bundlers and gives to the representative household the mark-up above the nominal wage desired.

We assume that the union can adjust wages subject to nominal rigidities à la Calvo. Thus, the probability that the union can change the nominal wage in period t is constant and equal to $1 - \xi_1^w$. If the union receives a positive signal in a given period it can set up a new nominal wage. Conversely, if the union cannot change the wage in a given period, it keeps the wage as a geometric average of nominal wage inflation in the last period $(\omega_{1,t-1})$ and the inflation rate in steady state (π_1^{SS}). Thus, the maximization problem of the union h can be expressed as:

$$\max_{\{W_{1,t}(h)\}} E_t \sum_{j=0}^{\infty} (\xi_1^w)^j \psi_{1,t,t+j} \begin{bmatrix} \omega_{1,t,,j}^l W_{1,t}(h) L_{1,t+j}(h) \\ -W_{1,t+j}^f L_{1,t+j}(h) \end{bmatrix} \tag{2.8}$$

$$s.t \ : \ L_{1,t}(h) = \left(\frac{W_{1,t}(h)}{W_{1,t}} \right)^{-\frac{1+\theta_{1,t}^w}{\theta_{1,t}^w}} L_{1,t}^d \tag{2.9}$$

$$and \ : \ \omega_{1,t,,j}^l = \prod_{s=1}^{j} \left\{ (\omega_{1,t-1+s})^{\iota_1^w} \left(\pi_1^{SS}\right)^{1-\iota_1^w} \right\} \tag{2.10}$$

where ι_1^w indicates the degree of wage indexation.

2.2.2 Firms

Production Goods. Each country produces a single final production good and a continuum of intermediate production goods indexed by i, where $i \in [0,1]$. In order to produce a final production good a continuum of representative bundlers combine a variety of intermediate production goods. The final production good sector is perfectly competitive. There is monopolistic competition in the markets for intermediate production goods: each intermediate production good is produced by a single firm.

Final Production Good Sector. The final production good, $Y^d_{1,t}$, is produced according to the following technology:

$$Y^d_{1,t} = \left[\int_0^1 Y_{1,t}\left(i\right)^{\frac{1}{1+\theta^p_{1,t}}} di \right]^{1+\theta^p_{1,t}} \tag{2.11}$$

where $Y_{1,t}\left(i\right)$ is the quantity of intermediate production good of type i that is used to produce the final production good at time t. $\theta^p_{1,t}$ is a AR(1) stochastic process that determines the time varying mark-up in the goods market. We consider shocks to this parameter as "cost-push" shocks to the inflation equation.

Each intermediate firm i faces the following demand function:

$$Y_{1,t}\left(i\right) = \left(\frac{P_{1,t}\left(i\right)}{P^d_{1,t}}\right)^{-\frac{1+\theta^p_{1,t}}{\theta^p_{1,t}}} Y^d_{1,t} \tag{2.12}$$

where $P_{1,t}\left(i\right)$ is the price of the intermediate production good j and $P^d_{1,t}$ is the price of the final production good. As we mentioned above, the final production good sector is perfectly competitive. Thus, $P^d_{1,t}$ can be expressed as:

$$P^d_{1,t} = \left[\int_0^1 \left(P^d_{1,t}\left(i\right)\right)^{-\frac{1}{\theta^p_{1,t}}} di \right]^{-\theta^p_{1,t}} \tag{2.13}$$

and we can define the nominal exchange rate as:

$$e_{1,t} = \frac{P^d_{1,t}}{P^m_{2,t}} \tag{2.14}$$

where $P^m_{2,t}$ is the price of imported goods for the foreign country.

Intermediate Production Good Sector. Each intermediate production good i is produced using three input factors: capital, labour, and oil. Following Bodenstein and Guerrieri (2011) and Bodenstein et al. (2012), we assume a nested constant elasticity of substitution production function.

As well explained by Kilian (2008b), this specification has one main advantage: imported oil enters as an input factor of the production function of domestic gross output but does not enter in the production function of domestic value added. Since gross output is separable in value added and imported energy, holding capital and labour fixed, this implies that oil price shocks do not move value added. Thus, by definition, oil price shocks cannot be interpreted as productivity shocks for real GDP.[13]

Thus, we can write the cost minimization problem of the firm i as:

$$\min_{\left\{K_{1,t-1}(i),L_{1,t}(i),O^y_{1,t}(i),V_{1,t}(i)\right\}} \begin{pmatrix} R^k_{1,t}K_{1,t-1}(i)+ \\ W_{1,t}L_{1,t}(i)+ \\ P^o_{1,t}O^y_{1,t}(i) \end{pmatrix} \tag{2.15}$$

$$s.t \quad : \quad Y_{1,t}(i) = \begin{pmatrix} \left(\omega_1^{vy}\right)^{\frac{\rho_1^o}{1+\rho_1^o}} \left(V_{1,t}(i)\right)^{\frac{1}{1+\rho_1^o}} + \\ \left(\omega_1^{oy}\right)^{\frac{\rho_1^o}{1+\rho_1^o}} \left(Z^o_{1,t}O^y_{1,t}(i)\right)^{\frac{1}{1+\rho_1^o}} \end{pmatrix}^{1+\rho_1^o} \tag{2.16}$$

$$and \quad : \quad V_{1,t}(i) = \begin{pmatrix} \left(\omega_1^{k}\right)^{\frac{\rho_1^v}{1+\rho_1^v}} \left(K_{1,t-1}(i)\right)^{\frac{1}{1+\rho_1^v}} + \\ \left(\omega_1^{l}\right)^{\frac{\rho_1^v}{1+\rho_1^v}} \left(Z_{1,t}L_{1,t}(i)\right)^{\frac{1}{1+\rho_1^v}} \end{pmatrix}^{1+\rho_1^v} \tag{2.17}$$

where $K_{1,t}(i)$ and $L_{1,t}(i)$ are capital and labour services that are used to produce the value added input $V_{1,t}(i)$. In turn, oil input $O^y_{1,t}(i)$ is combined with gross value added input in order to produce the intermediate production good $Y_{1,t}(i)$.

We denote the respective weights of capital and labour in the value added production function by ω_1^k and ω_1^l, while ρ_1^v represents the elasticity of substitution between capital and labour.

Moreover, $Z_{1,t}$ is a productivity shock assumed to follow a second order

[13] See Kilian (2008b) for a more detailed explanation of the supply transmission channel of oil price shocks.

autoregressive process with i.i.d. zero mean normally distributed error. As we will describe in the results section, this shock plays a very important role for UK oil price fluctuations.

We consider oil intensity as factor augmenting technology. Thus, the term $Z^o_{1,t}$ represents an AR (2) stochastic process that influences the oil intensity in production. As we will show in Sections 3 and 4, this shock explains most of the UK oil price volatility and, in turn, significantly affects the behaviour of the domestic economy.

The parameters ω_1^{oy} and ω_1^{vy} determine the importance of oil and value added inputs in the output of the firm i. Finally, ρ_1^o indicates the price elasticity of demand for oil.

As in Calvo (1983), firms i are allowed to change their price with constant probability $1-\xi_1^p$. Following Smets and Wouters (2003, 2007), firms that cannot change their prices keep their prices as a geometric average of inflation in the last period ($\pi^d_{1,t-1}$) and the inflation rate in steady state (π_1^{SS}). Thus, the maximization problem of the firm i can be expressed as:

$$\max_{\left\{P^d_{1,t}(i)\right\}} E_t \sum_{j=0}^{\infty} \left(\xi_1^p\right)^j \psi_{1,t,t+j} \begin{bmatrix} \pi^d_{1,t,,j} P^d_{1,t}\left(i\right) Y_{1,t+j}\left(i\right) \\ -MC_{1,t+j} Y_{1,t+j}\left(i\right) \end{bmatrix} \tag{2.18}$$

$$s.t \quad : \quad Y_{1,t}\left(i\right) = \left(\frac{P_{1,t}\left(i\right)}{P^d_{1,t}}\right)^{-\frac{1+\theta_1^p}{\theta_1^p}} Y^d_{1,t} \tag{2.19}$$

$$and \quad : \quad \pi^d_{1,t,,j} = \prod_{s=1}^{j} \left\{ \left(\pi^d_{1,t-1+s}\right)^{\iota_1^p} \left(\pi_1^{SS}\right)^{1-\iota_1^p} \right\} \tag{2.20}$$

where ι_1^p indicates the degree of price indexation. $MC_{1,t}$ denotes firm i marginal cost at time t that is different from familiar formulation of Smets and Wouters (2003, 2007). Indeed, in this model the marginal cost depends on oil as an additional factor input.

Consumption Goods. Final consumption goods, $C_{1,t}$, are produced by firms that operate in a perfect competitive environment. These firms aggregate domestic, $C^d_{1,t}$, and foreign, $M^c_{1,t}$, intermediate consumption goods in order to produce a non-oil consumption good, $C^{ne}_{1,t}$. In turn, the final consumption good is produced by combining non-oil and oil, $O^c_{1,t}$, consumption goods. Finally, $C_{1,t}$ is sold to the representative household. We can express the minimization problem of the representative firm producing $C_{1,t}$ as follows:

$$\min_{\left\{C^d_{1,t},M^c_{1,t},C^{ne}_{1,t},O^c_{1,t}\right\}} P^d_{1,t}C^d_{1,t} + P^m_{1,t}M^c_{1,t} + P^o_{1,t}O^c_{1,t} \tag{2.21}$$

$$s.t \quad : \quad C_{1,t} = \left((\omega^{cc}_1)^{\frac{\rho^o_1}{1+\rho^o_1}} \left(C^{ne}_{1,t}\right)^{\frac{1}{1+\rho^o_1}} + (\omega^{oc}_1)^{\frac{\rho^o_1}{1+\rho^o_1}} \left(Z^o_{1,t}O^c_{1,t}\right)^{\frac{1}{1+\rho^o_1}} \right)^{1+\rho^o_1} \tag{2.22}$$

$$and \quad : \quad C^{ne}_{1,t} = \left((\omega^{c}_1)^{\frac{\rho^c_1}{1+\rho^c_1}} \left(C^{d}_{1,t}\right)^{\frac{1}{1+\rho^c_1}} + (\omega^{mc}_1)^{\frac{\rho^c_1}{1+\rho^c_1}} \left(Z^m_{1,t}M^c_{1,t}\right)^{\frac{1}{1+\rho^c_1}} \right)^{1+\rho^c_1} \tag{2.23}$$

where the same shock $Z^o_{1,t}$ that affects oil intensity in production goods also affects the oil intensity in consumption goods. ω^{cc}_1 and ω^{oc}_1 indicate the weights of non-oil and oil in the production of consumption goods, while ρ^o_1 is the same price elasticity of oil demand that we observed in the function of production goods.

As we can note, this specification allows us to consider oil not only as intermediate input of production goods but also an input of consumption goods. This is a very important point because, under standard assumptions, the cost share of oil in production goods is known to be very small so that traditional models are not able to explain large effects on GDP due to oil shocks. Conversely, in our model the oil intensity shock directly affects the production of consumption goods, implying a change of the representative household demand for these goods. As Kilian (2008b) rightly noted, this is a very important transmission channel of oil shocks.

In the production of non-oil consumption goods, ω^c_1 and ω^{mc}_1 determine the weights of domestic and imported goods respectively. The elasticity of substitution between domestic and foreign intermediate goods is denoted by ρ^c_1. In addition, the term $Z^m_{1,t}$ captures an import preference shock and can be expressed as an AR(2) exogenous process.

Finally, we consider the price of consumption goods, $P^c_{1,t}$, as the Lagrange multiplier of equation (2.22) in the problem of cost minimization faced by firms producing final consumption goods. We define non-oil consumption goods, $C^{ne}_{1,t}$, to comprise the core price level $P^{ne}_{1,t}$ of the economy.

Investment Goods. Firms that produce investment goods, $I_{1,t}$, work in a competitive market. Contrary to firms producing consumption goods, those producing investment goods do not need oil as an input factor. Investment goods are produced combining domestic and foreign investment goods and are sold to the representative household. The problem of cost minimization of a representative investment firm can be expressed as:

$$\min_{\{I^d_{1,t}, M^i_{1,t}\}} P^d_{1,t} I^d_{1,t} + P^m_{1,t} M^i_{1,t} \tag{2.24}$$

$$s.t \quad : \quad I_{1,t} = \left(\left(\omega^i_1\right)^{\frac{\rho^c_1}{1+\rho^c_1}} \left(I^d_{1,t}\right)^{\frac{1}{1+\rho^c_1}} + \left(\omega^{mi}_1\right)^{\frac{\rho^c_1}{1+\rho^c_1}} \left(Z^m_{1,t} M^i_{1,t}\right)^{\frac{1}{1+\rho^c_1}} \right)^{1+\rho^c_1} \tag{2.25}$$

where ω^i_1 and ω^{mi}_1 are the weights of domestic and foreign goods in the production of the final investment good. We denote the exogenous AR(2) shock influencing preferences of investment imports by $Z^m_{1,t}$. As in the production of consumption goods, ρ^c_1 represents the elasticity of substitution between domestic and foreign intermediate goods. Finally, we assume that the price of investment goods, $P^i_{1,t}$, coincides with the Lagrange multiplier associated with the problem of cost minimization faced by investment firms.

2.2.3 The Oil Sector

As we discussed above, the main objective of this paper is to assess the effects of oil price changes on the UK economy. Thus, it is crucial to carefully describe the dynamics of the oil market. In particular, we assume that the two blocs of the model (UK and rest of the world) are endowed with a non-storable supply of oil each period. As for non-oil goods, oil is traded across the two blocs. In addition, consistently with the empirical evidence (Kilian, 2008b and 2009), we focus on the oil demand side. Thus, we assume that the 2 blocs are not able to take any decision concerning endogenous oil production. In particular, domestic ($Y_{1,t}^{o}$) and foreign ($Y_{2,t}^{o}$) oil supplies follow two exogenous AR(2) processes respectively. As we will note in Sections 3 and 4, the foreign oil supply shock significantly affects the UK oil price variation and, in turn, it largely influences the responses of domestic macroeconomic variables.

With foreign and domestic oil productions determined exogenously, the real price of oil, $P_{1,t}^{o}$, adjusts endogenously to clear the oil market. Thus, the oil market clearing condition can be expressed as:

$$\begin{aligned} Y_{1,t}^{o}+\frac{\zeta_2}{\zeta_1}Y_{2,t}^{o} &= O_{1,t}+\frac{\zeta_2}{\zeta_1}O_{2,t} \qquad (2.26)\\ where &: O_{1,t}=O_{1,t}^{y}+O_{1,t}^{c} \qquad (2.27)\end{aligned}$$

where $O_{1,t}$ is the domestic oil demand of both firms and the representative household. ζ_1 and ζ_2 represent the relative population sizes of the two blocs. Finally, since we consider all the variables in per capita terms, we scale the foreign variables by size of the home country, $\frac{1}{\zeta_1}$.

2.2.4 Monetary Policy

The Central Bank sets the nominal interest rate according to the following monetary policy reaction function:

$$\begin{aligned} i_{1,t} &= \bar{\imath}_1 + \gamma_1^i \left(i_{1,t-1} - \bar{\imath}_1 \right) + \\ & \left(1 - \gamma_1^i \right) \left[\left(\pi_{1,t}^{core} - \bar{\pi}_1^{core} \right) + \gamma_1^\pi \left(\pi_{1,t}^{core} - \bar{\pi}_1^{core} - \bar{\pi}_{1,t}^{core} \right) + \gamma_1^y y_{1,t}^{gap} \right] \end{aligned} \tag{2.28}$$

This is a modified version of the Taylor (1993) rule in which the Central Bank responds to changes of past nominal interest rate, core inflation and output gap (defined as the difference between actual and potential output). We denote the steady state values for the nominal interest rate and core inflation by $\bar{\imath}_1$ and $\bar{\pi}_1^{core}$, respectively. The parameter γ_1^i allows for interest rate smoothing, whereas γ_1^y and γ_1^π indicate the reaction of interest rate on output gap and core inflation, respectively.

Moreover, we define the core inflation as the logarithmic percentage change in the price of non-oil goods:

$$\pi_{1,t}^{core} = \log \left(\frac{P_{1,t}^{ne}}{P_{1,t-1}^{ne}} \right) \tag{2.29}$$

Finally, we assume that $\bar{\pi}_{1,t}^{core}$ reflects a time varying inflation target and can be expressed as a AR(1) process.

2.2.5 Equilibrium of the Non-Oil Goods Market

The final non-oil good market for the domestic economy is in equilibrium if the production of firms equals demand by the representative household for consumption and investment and imports of the foreign country:

$$Y_{1,t}^d = C_{1,t}^d + I_{1,t}^d + \frac{\zeta_2}{\zeta_1} M_{2,t} \tag{2.30}$$

$$where \; : \; M_{2,t} = M_{2,t}^c + M_{2,t}^i \tag{2.31}$$

where $M_{2,t}$ denotes net imports of the foreign country. Again, since we consider variables in per capita terms we scale foreign imports by the population scaling factor $\frac{1}{\zeta_1}$.

The law of motion of the non-state contingent foreign bond is given by:

$$\begin{aligned} \frac{e_{1,t}P^b_{2,t}B_{1,t}}{\phi^b_{1,t}} &= e_{1,t}B_{1,t-1} + \frac{\zeta_2}{\zeta_1}e_{1,t}P^m_{2,t}\left(M^c_{2,t} + M^i_{2,t}\right) \\ &\quad -P^m_{1,t}\left(M^c_{1,t} + M^i_{1,t}\right) + P^o_{1,t}\left(Y^o_{1,t} - O_{1,t}\right) \end{aligned} \tag{2.32}$$

indicating that the evolution of the domestic holding of foreign bonds relates to the domestic non-oil trade balance.

Finally, the market clearing condition for the non state-contingent bond states that in equilibrium $B_{1,t} + B_{2,t} = 0$.

2.2.6 Shock Processes

Table 2.1 shows all the exogenous shocks driving the economy. Our choice of the stochastic processes is in line with previous papers modelling both the closed economy (Smets and Wouters, 2003; 2007) and the open economy and the oil sector (Bodenstein and Guerrieri, 2011; Bodenstein et al., 2012). However, in our model we do not consider the exogenous shock to government spending.

Differently from Bodenstein and Guerrieri (2011), in the case of UK economy we do not consider the interpretation of a government spending shock that captures all the movements in GDP that are not explained by the other exogenous shocks to be pertinent. Accordingly, we believe that the UK fiscal sector should be modelled carefully considering UK oil revenues and their relationship with UK public finances. Therefore, as we have a different goal in this paper, we prefer to exclude the government sector and leave this topic for a detailed analysis in Chapter 3.

As we can see from Table 2.1 we assume AR(2) processes for productivity, oil supply, oil intensity and import preferences shocks of both domestic and foreign countries. Our decision is motivated by the fact that AR(1) estimates for some of these shocks were non-stationary. In addition, whilst we consider different standard deviation sizes of our stochastic shocks, we assume the same persistence parameters for home and foreign shocks affecting productivity, oil intensity, consumption and import preferences.[14]

Shocks	**Stochastic Process**
Home Prod.	$\ln(Z_{1,t}) = \left(1+\rho_{1,1}^{z}-\rho_{2,1}^{z}\right)\ln(Z_{1,t-1}) - \rho_{1,1}^{z}\ln(Z_{1,t-2}) + \varepsilon_{1,t}^{z}$
Foreign Prod.	$\ln(Z_{2,t}) = \left(1+\rho_{1,2}^{z}-\rho_{2,2}^{z}\right)\ln(Z_{2,t-1}) - \rho_{1,2}^{z}\ln(Z_{2,t-2}) + \varepsilon_{2,t}^{z}$
Home Oil Sup.	$\ln\left(Y_{1,t}^{o}\right) = \left(1+\rho_{1,1}^{yo}-\rho_{2,1}^{yo}\right)\ln\left(Y_{1,t-1}^{o}\right) - \rho_{1,1}^{yo}\ln\left(Y_{1,t-2}^{o}\right) + \varepsilon_{1,t}^{yo}$
Foreign Oil Sup.	$\ln\left(Y_{2,t}^{o}\right) = \left(1+\rho_{1,2}^{yo}-\rho_{2,2}^{yo}\right)\ln\left(Y_{2,t-1}^{o}\right) - \rho_{1,2}^{yo}\ln\left(Y_{2,t-2}^{o}\right) + \varepsilon_{2,t}^{yo}$
Home Oil Int.	$\ln\left(Z_{1,t}^{o}\right) = \left(1+\rho_{1,1}^{zo}-\rho_{2,1}^{zo}\right)\ln\left(Z_{1,t-1}^{o}\right) - \rho_{1,1}^{zo}\ln\left(Z_{1,t-2}^{o}\right) + \varepsilon_{1,t}^{zo}$
Foreign Oil Int.	$\ln\left(Z_{2,t}^{o}\right) = \left(1+\rho_{1,2}^{zo}-\rho_{2,2}^{zo}\right)\ln\left(Z_{2,t-1}^{o}\right) - \rho_{1,2}^{zo}\ln\left(Z_{2,t-2}^{o}\right) + \varepsilon_{2,t}^{zo}$
Home Cons.	$\ln\left(Z_{1,t}^{c}\right) = \rho_{1,1}^{zc}\ln\left(Z_{1,t-1}^{c}\right) + \varepsilon_{1,t}^{c}$
Foreign Cons.	$\ln\left(Z_{2,t}^{c}\right) = \rho_{1,2}^{zc}\ln\left(Z_{2,t-1}^{c}\right) + \varepsilon_{2,t}^{c}$
Home Imp. Pref.	$\ln\left(Z_{1,t}^{m}\right) = \left(1+\rho_{1,1}^{zm}-\rho_{2,1}^{zm}\right)\ln\left(Z_{1,t-1}^{m}\right) - \rho_{1,1}^{zm}\ln\left(Z_{1,t-2}^{m}\right) + \varepsilon_{1,t}^{zm}$
Foreign Imp. Pref.	$\ln\left(Z_{2,t}^{m}\right) = \left(1+\rho_{1,2}^{zm}-\rho_{2,2}^{zm}\right)\ln\left(Z_{2,t-1}^{m}\right) - \rho_{1,2}^{zm}\ln\left(Z_{2,t-2}^{m}\right) + \varepsilon_{2,t}^{zm}$
Home Inv.	$\ln\left(Z_{1,t}^{i}\right) = \rho_{1,1}^{zi}\ln\left(Z_{1,t-1}^{i}\right) + \varepsilon_{1,t}^{i}$
Home Price Mar.	$\hat{\theta}_{1,t}^{p} = \rho_{1,1}^{p}\hat{\theta}_{1,t-1}^{p} + \varepsilon_{1,t}^{p}$
Home Wage Mar.	$\hat{\theta}_{1,t}^{w} = \rho_{1,1}^{w}\hat{\theta}_{1,t-1}^{w} + \varepsilon_{1,t}^{w}$
Home Infl. Target	$\bar{\pi}_{1,t}^{core} = \rho_{1,1}^{\pi}\bar{\pi}_{1,t-1}^{core} + \varepsilon_{1,t}^{\pi}$

Table 2.1: Exogenous Shocks

2.3 Estimation

In order to estimate the model, we log-linearize the equations described previously around their non-stochastic steady states.[15] As estimation technique, we use the Bayesian approach on data for the sample period 1990:Q1-2005:Q4. In what

[14] This assumption allows us to reduce the number of parameters that we are going to estimate. As it is well known, in order to have accurate results, the Bayesian approach requires that the number of estimated parameters is not too large.

[15] In Appendix B, we show the model equilibrium conditions and their log-linearized expressions in detail.

follows, we initially briefly discuss the estimation methodology (Section 3.1). Then we describe the data used in order to estimate the model (Section 3.2) and we present the parameters of the model (Section 3.3). We move on to discuss the estimation results (Section 3.4) and finally we compare the business cycle moments implied by our estimated model with those obtained from actual data (Section 3.5).

2.3.1 Estimation Methodology

Our theoretical model is estimated with the Bayesian approach. The attractions of this approach are by now well known in the economic literature. When successful, it provides a full characterisation of the data generating process and allows for proper specification testing. In particular, this approach allows us to formalise the use of prior information coming either from micro-econometric studies or previous macro-econometric studies and thereby makes an explicit link with the previous calibration-based literature. It also, as a consequence, reveals the underlying shocks (as indicated by the model). Thus, in order to estimate the parameters of the DSGE model presented in Section 2 we proceed with the following steps. First, we estimate the mode of the posterior distribution by maximising the log posterior function, which combines the prior information on the parameters with the likelihood of the data. In a second step, the Metropolis-Hastings algorithm is used to get a complete picture of the posterior distribution and to evaluate the marginal likelihood of the model.[16]

2.3.2 Data

As Millard and Shakir (2013) argued, the choice of the sample period is particularly important when we analyse the impact of oil shocks on the UK economy. Indeed, the United Kingdom has transitioned from net oil importer in the 1970's to net exporter in the 1980's and 1990's and returned oil importer again in the mid-2000's. Accordingly, we estimate the UK economy in the time period it was an oil

[16] All the estimations are done with Dynare (http://www.cpremap.cnrs.fr/dynare).

exporter.

Since there are fourteen exogenous shocks in the model, fourteen data series are used in the estimation. In particular, we use data on UK and foreign GDP, UK and foreign oil production, the real price of oil, the UK broad effective exchange rate, UK private consumption expenditure, UK total gross fixed capital formation, UK oil imports, UK non-oil goods imports, UK non-oil goods exports, UK core inflation, UK wage inflation and the UK nominal interest rate.[17]

The series of real UK GDP is taken from ONS and expressed in logarithmic terms. We consider foreign GDP as the log of aggregated foreign GDPs. In particular, this series corresponds to GDP data from the OECD source for the 10 most important trading partners of the United Kingdom.[18] These countries account for about the 73% of UK imports and exports.

UK crude oil production is taken from the Monthly Energy Review of the EIA and expressed in logarithmic terms. We compute the log of foreign crude oil production as the world production net of UK production taken from the Monthly Energy Review of the EIA. The series of oil price is taken from EIA and corresponds to the Europe Brent spot oil price. We convert this series into Sterling, we deflate it by using the UK GDP deflator and, finally, we express it in log terms. The UK broad effective exchange rate corresponds to the log of the quarterly average broad effective exchange rate as provided by the Bank of England.

The UK consumption expenditure and UK total gross fixed capital formation are taken from ONS and expressed as relative shares of UK GDP. We define UK oil imports as petroleum imports taken from International Energy Statistics of EIA expressed as a share of UK GDP using the series of oil price described above. We construct the series of UK non-oil goods imports as the difference between the UK total imports (taken from ONS) and UK oil imports as defined above. We express this series as a share of UK GDP. In a similar way, we define the UK share

[17] See Appendix B for a detailed description of data construction and sources for the observed variables of the model.

[18] These countries are: the Euro Area, the United States, Japan, Norway, Switzerland, Sweden, Canada, Denmark, Australia and India.

of non-oil goods exports on GDP as the difference between the UK total exports (obtained from ONS) and UK oil exports. Instead of deflating these variables by their own relative deflators, we consider them as share of GDP because our model has multiple relative prices that are oil and import prices.

We measure the UK core inflation as the log change in the consumer price index of all items excluding food and energy goods. We take this series from the FRED (Federal Reserve Bank of St. Louis) database and we seasonally adjust it. The UK wage inflation series is the log change in total compensation of employees taken from ONS. Finally, we measure the UK nominal interest rate as the 3 month Treasury Bills rate taken from the Bank of England.

2.3.3 Model Parameters

We decide to split the parameters of the model into three groups. In the first group we follow previous literature on DSGE models. The second group of parameters determines the steady state of the model and, hence, average ratios. These parameters are set so as to be consistent with observed data of both domestic and foreign blocs for the sample period 1990-2005. The third group includes endogenous parameters for the home country and is estimated with the Bayesian technique.

Fixed Parameters. We assume that these parameters have the same values for domestic and foreign blocs, holding them as fixed when we estimate the model (Table 2.2). In particular, we fix the discount factor in order to have a steady state real interest rate of 4% per year. As is common in the literature, we assume a capital depreciation rate of 0.025. Moreover, we fix the intertemporal elasticity of substitution equal to 1. We choose a value of 0.33 for L_1^{SS}. The latter parameter determines the ratio between hours worked and leisure in steady state. Moreover, we assume that the elasticity of substitution between capital and labour corresponds to 0.8. This value is slightly higher than the one found by micro level estimates of the UK economy (see Barnes et al., 2008). We follow Bodenstein et al. (2011) and assume a value of 0.0001 for the parameter capturing the curvature of the bond intermediation cost.

Parameter	Value	Description	Motivation
β_1	0.99	Discount Factor	Assumption
δ_1	0.025	Depreciation Rate	Assumption
σ_1	1	IES	Assumption
L_1^{SS}	0.33	Labour Steady State	Assumption
ϕ_b	0.0001	Bond Intermediation Cost	Bodenstein et al. (2011)
ρ_1^v	-5	Determines K-L Elas. Sub.	$\frac{1+\rho_1^v}{\rho_1^v} = 0.8$

Table 2.2: First Group of Parameter Values

Calibrated Parameters According to Observed Data. The UK parameters are constructed taking data from the ONS Quarterly National Accounts, the ONS Input - Output Analysis database and EIA International Energy Statistics. As concerning the foreign bloc, we use the Loretan (2005) technique of trade weights and we aggregate data from the main trading partners of UK. The observed data of UK trading partners are taken from the OECD Quarterly National Accounts, IMF International Financial Statistics, the NIPA Input - Output database, the Eurostat Input - Output database and EIA International Energy Statistics.[19] Once these parameters are computed we hold them as fixed in order to estimate the model[20] (Table 2.3).

We start by describing data concerning the UK bloc. In the period 1997-2005, the share of oil on gross output accounts for the 3.98%. Between 1992 and 2004, 78% of total oil demand comes from the production sector. For the period 1990-2005, EIA statistics indicate that the UK is a net oil exporter. Indeed, the average UK oil exports and oil imports are, respectively, 2.01 and 1.32 millions of barrels

[19] See Appendix B for a detailed description of the data used to construct the steady state parameters for the UK and foreign bloc.

[20] See Appendix B for the full derivation of composite parameters.

per day. In terms of GDP shares, UK oil exports and imports correspond to 1.16% and 0.79%, respectively. In addition, during this period in the United Kingdom crude oil production is 1.22 times higher than oil consumption.

Moreover, according to ONS data private investment, government spending and non-oil imports as shares of GDP are, respectively, 15%, 24% and 26% in the period 1990-2005. In this period, the UK total imports are divided into 77% of consumption goods and 23% of services.

Combining these statistics we are able to compute the steady state parameters of the home bloc. In particular, we find that the parameter capturing the weight of capital in the value added production function (ω_1^k) is 0.43. The parameter determining the importance of oil in production (ω_1^{oy}) corresponds to 0.03, while the weight of oil in consumption (ω_1^{oc}) is equal to 0.01. The parameter measuring the weight of consumption goods in total imports (ω_1^{mc}) is 0.32, while the one capturing the weight of services in total imports (ω_1^{mi}) corresponds to 0.38.

Now we move on to focus on the foreign bloc. These parameters are particularly important for two reasons. Firstly, in contrast to previous studies on the UK economy, we obtain their values aggregating data series for a large set of foreign countries. Secondly, they determine the structure and the weight of the foreign bloc with respect to the UK economy. Therefore, the effects of oil shocks on the UK economy crucially depend on these parameters.

Due to data limitations, we are not able to consider oil shares in every single country for the main UK trading partners. Thus, we decide to construct a proxy of this parameter. Since UK imports/exports with the Euro Area and US account for around 58% of the UK total trade, we take a weighted average of EU (2000-2008) and US (1990-2005) oil shares on their respective GDPs. Accordingly, we obtain that the overall oil share of the foreign economy is equal to 3.31%.

Using the procedure just described, we compute the quantity of oil demanded by the foreign production sector as a weighted average of the Euro Area (2000-2005) and the US (1998-2005) data. Accordingly, the oil demanded by the foreign production sector corresponds to 76% of total foreign oil demand.

Parameter Description	Home Country	Foreign Country
Capital Weight in Value Added	$\omega_1^k = 0.43$	$\omega_2^k = 0.56$
Weight of Oil in Production	$\omega_1^{oy} = 0.03$	$\omega_2^{oy} = 0.03$
Weight of Oil in Consumption	$\omega_1^{oc} = 0.01$	$\omega_2^{oc} = 0.01$
Weight of Cons. in Tot. Imp.	$\omega_1^{mc} = 0.32$	$\omega_2^{mc} = 0.48$
Weight of Services in Tot. Imp.	$\omega_1^{mi} = 0.38$	$\omega_2^{mi} = 0.39$
Share of Oil Production	$\frac{\left(Y_1^o\right)^{SS}}{\left(Y_1^o\right)^{SS}+\left(Y_2^o\right)^{SS}} = 0.06$	$\frac{\left(Y_2^o\right)^{SS}}{\left(Y_1^o\right)^{SS}+\left(Y_2^o\right)^{SS}} = 0.94$
Share of Oil Consumption	$\frac{(O_1)^{SS}}{(O_1)^{SS}+(O_2)^{SS}} = 0.03$	$\frac{(O_2)^{SS}}{(O_1)^{SS}+(O_2)^{SS}} = 0.97$
Population Size	$\zeta_1 = 0.02$	$\zeta_1 = 0.98$

Table 2.3: Second Group of Parameter Values

In order to obtain the value of foreign oil demand satisfied by foreign oil production, we apply the Loretan (2005) technique[21] of trade weights to the 13 most important UK trading partners. Thus, for the period 1990-2005, we find that the ratio between foreign oil production and consumption is equal to 0.66.

In regards to the foreign ratios of private investment and government spending on GDP, we compute these shares for the 13 most important UK trading partners (1990-2005). Thus, applying the Loretan (2005) technique of trade weights once again, we find that foreign investment and government spending shares on GDP are equal to 19.9% and 19.5%, respectively. During the same period, foreign total imports are divided into 79% for consumption goods and 21% for services.

From this set of statistics we compute the steady state values for the foreign bloc. Specifically, we obtain that the parameter indicating the weight of capital in the value added production function (ω_2^k) is equal to 0.56. The parameter capturing the weight of oil in production (ω_2^{oy}) equals 0.03, while the weight of

[21] For a detailed description of the Loretan (2005) technique and the procedure used to construct these series see Appendix B.

oil in consumption (ω_2^{oc}) corresponds to 0.01. The parameter determining the importance of consumption goods in total imports (ω_2^{mc}) is 0.48, while the one capturing the weight of services in total imports (ω_2^{mi}) is equal to 0.39.

Table 2.3 also shows the steady state parameters concerning the relative shares of oil production and consumption for both home and foreign blocs. As we mentioned in the description of our theoretical model, these shares are particularly important in order to analyse the dynamics of the oil sector. Thus, the share of oil produced by the United Kingdom on world oil production corresponds to 6%, while the ratio of oil consumed by the UK on world oil consumption is equal to 3%. Finally, from Table 2.3 we observe that the share of the UK population on world population corresponds to 2%.

Priors of the Estimated Parameters using Bayesian Techniques. We show our assumed priors for the endogenous parameters of the home country in Table 2.4, whereas the assumed priors for the exogenous shocks are presented in Tables 2.5 and 2.6.

Par.	**Description**	**Distrib.**	**Mean**	**St. Dev.**
κ_1	Degree of Habit Persistence in Cons.	Beta	0.70	0.05
ψ_1	Investment Adjustment Cost	Gamma	4.00	1.50
χ_1	Labour Supply Elasticity $\left(\frac{1}{2\chi}\right)$	Gamma	25.00	0.75
ξ_1^w	Calvo Wages Probability	Beta	0.60	0.20
ξ_1^p	Calvo Prices Probability	Beta	0.60	0.20
ι_1^w	Degree of Wage Indexation	Beta	0.20	0.08
ι_1^p	Degree of Price Indexation	Beta	0.20	0.08
γ_1^π	Taylor Rule Coefficient on Inflation	Gamma	0.90	0.05
γ_1^y	Taylor Rule Coefficient on Output	Gamma	1.20	0.20
γ_1^i	Degree of Int. Rate Smoothing in T.R.	Beta	0.50	0.20
$\frac{1+\rho_1^o}{\rho_1^o}$	Price Elasticity of Oil Demand	Gamma	0.10	0.05
$\frac{1+\rho_1^c}{\rho_1^c}$	Sub. El. between Dom. and For. Goods	Gamma	2.00	0.10

Table 2.4: Priors for the Third Group of Endogenous Parameters

Generally, we chose our priors following the papers of Del Negro and Schorfheide (2008) and Millard (2011). More specifically, our priors for habit in consumption (κ_1) and investment adjustment costs (ψ_1) are the same as Del Negro and Schorfheide (2008). The prior for the parameter determining labour supply elasticity (χ_1) is in line with Bodenstein et al. (2012).

As regards nominal rigidities, we assume Calvo probabilities (for both wages, ξ_1^w, and prices, ξ_1^p) and indexation parameters (for both wages, ι_1^w, and prices, ι_1^p) that are similar to those of Del Negro and Schorfheide (2008).

Autocorrelation Coefficients	**Distribution**	**Mean**	**St. Dev.**
UK Productivity: $\rho_{1,1}^z$	Beta	0.300	0.005
UK Productivity: $\rho_{2,1}^z$	Beta	0.0045	0.0040
UK Oil Supply: $\rho_{1,1}^{yo}$	Beta	0.500	0.050
UK Oil Supply: $\rho_{2,1}^{yo}$	Beta	0.0045	0.0040
Foreign Oil Supply: $\rho_{1,2}^{yo}$	Beta	0.700	0.050
Foreign Oil Supply: $\rho_{2,2}^{yo}$	Beta	0.0045	0.0040
UK Oil Intensity: $\rho_{1,1}^{zo}$	Beta	0.500	0.050
UK Oil Intensity: $\rho_{2,1}^{zo}$	Beta	0.0045	0.0020
UK Consumption: $\rho_{1,1}^{zc}$	Beta	0.70	0.20
UK Investment: $\rho_{1,1}^{zc}$	Beta	0.70	0.20
UK Import Preferences: $\rho_{1,1}^{zm}$	Beta	0.100	0.005
UK Import Preferences: $\rho_{2,1}^{zm}$	Beta	0.0045	0.0040
UK Price Mark-up: $\rho_{1,1}^{p}$	Beta	0.70	0.20
UK Wage Mark-up: $\rho_{1,1}^{w}$	Beta	0.70	0.20
UK Inflation Target: $\rho_{1,1}^{\pi}$	Beta	0.70	0.20

Table 2.5: Priors of Shock Processes: Persistence Parameters

Moreover, our priors for the coefficients of the monetary policy rule are set up such that the nominal interest rate strongly responds to changes in output gap (γ_1^y) and inflation (γ_1^π). As is standard in the literature, the policy rate smoothing parameter (γ_1^i) is beta distributed with a mean equal to 0.50 and standard deviation equal to 0.20.

In the last two rows of Table 2.4, we focus on the choice of the priors for the price elasticity of oil demand ($\frac{1+\rho_1^o}{\rho_1^o}$) and the elasticity of substitution between domestic and foreign non-oil goods ($\frac{1+\rho_1^c}{\rho_1^c}$). As concerns the first parameter, we chose a prior mean value that is slightly lower than the one assumed by several empirical studies on the US economy.[22] As regards the prior of the elasticity of substitution between domestic and foreign non-oil goods, its mean value is in line with typical estimates of UK aggregate data.[23]

Shock Standard Errors	**Distribution**	**Mean**	**St. Dev.**
UK Productivity: σ_1^z	Inv-Gamma	0.01	Inf
Foreign Productivity: σ_2^z	Inv-Gamma	0.01	Inf
UK Oil Supply: σ_1^{yo}	Inv-Gamma	0.01	Inf
Foreign Oil Supply: σ_2^{yo}	Inv-Gamma	0.01	Inf
UK Oil Intensity: σ_1^{zo}	Inv-Gamma	0.01	Inf
Foreign Oil Intensity: σ_2^{zo}	Inv-Gamma	0.01	Inf
UK Consumption: σ_1^{zc}	Inv-Gamma	0.01	Inf
Foreign Consumption: σ_2^{zc}	Inv-Gamma	0.01	Inf
UK Import Preferences: σ_1^{zm}	Inv-Gamma	0.01	Inf
Foreign Import Preferences: σ_2^{zm}	Inv-Gamma	0.01	Inf
UK Investment: σ_1^{zi}	Inv-Gamma	0.01	Inf
UK Price Mark-up: σ_1^p	Inv-Gamma	0.01	Inf
UK Wage Mark-up: σ_1^w	Inv-Gamma	0.01	Inf
UK Inflation Target: σ_1^π	Inv-Gamma	0.01	Inf

Table 2.6: Priors of Shock Processes: Standard Errors

In general, we use beta distributions for the persistence parameters of the several shocks (Table 2.5).

As regards AR(1) processes, we chose prior mean values of 0.70 and prior standard deviations of 0.20. In regards to AR(2) processes, we assume prior values implying that the productivity shock is more persistent than the import preferences

[22] See for example the papers of Bodenstein and Guerrieri (2011) and Bodenstein et al. (2012).
[23] See for example Hooper et al. (2000).

shock. In terms of oil intensity shock we assume that $\rho^{zo}_{1,1}$ has a prior mean and a standard deviation equal to 0.50 and 0.05, respectively, whereas $\rho^{zo}_{1,2}$ has a prior mean and a standard deviation equal to 0.0045 and 0.0020, respectively. We also assume distinct prior values for UK and foreign oil supply shocks. In particular, our prior values imply that the foreign oil supply shock is more persistent than the domestic oil supply shock.

Finally, we use inverse gamma distributions for standard errors of exogenous shocks with means equal to 0.01 and infinite degrees of freedom (Table 2.6). We chose these extremely loose priors as we have few strong priors and we wish to be guided more strongly by the data.

2.3.4 Estimation Results

As is standard in the literature, before proceeding with the estimation procedure we detrend our observed data.[24] As we explained above, we estimate the mode of the posterior distribution by maximising the log posterior function, which combines the priors with the likelihood function given by the data. Finally, we use the Metropolis-Hastings algorithm to obtain the full posterior distribution. Our sample includes 250,000 draws and we drop the first 100,000 of them. Our acceptation rate corresponds to 27%. In order to test the stability of the sample, we use the Brooks and Gelman (1998) diagnostic, which compares within and between moments of multiple chains. Table 2.7 shows the posterior modes and means for the endogenous parameters with a 90% confidence interval.[25]

In terms of estimation results, the posterior mean of consumption habit (κ_1) is well identified and corresponds to 0.90. This value is slightly higher than previous estimates on UK data.[26]

[24] To do so we use the HP filter with a smoothing parameter equal to 1,600. Alternatively, we estimated our model demeaning the series of UK core inflation, wage inflation and detrending the remaining series. Comparing the estimated results of these two different specifications we

Par.	Description	Post. Mode	Post. Mean	Conf. Inter.	
κ_1	Cons. Habit	0.90	0.90	0.87	0.93
ψ_1	Inv. Adj. Cost	6.86	6.83	4.58	9.18
χ_1	Lab. Supply El. $\left(\frac{1}{2\chi}\right)$	24.89	25.10	23.88	26.34
ξ_1^w	Calvo Wages Prob.	0.91	0.99	0.98	0.99
ξ_1^p	Calvo Prices Prob.	0.86	0.86	0.81	0.90
ι_1^w	Degree of Wage Ind.	0.64	0.09	0.03	0.15
ι_1^p	Degree of Price Ind.	0.13	0.19	0.06	0.30
γ_1^π	T. R. Coef. on Inflation	0.88	0.59	0.45	0.72
γ_1^y	T. R. Coef. on Output	1.82	1.70	1.39	1.99
γ_1^i	Int. Rate Smoothing Par.	0.66	0.59	0.45	0.72
$\frac{1+\rho_1^o}{\rho_1^o}$	Oil Elasticity	0.03	0.05	0.01	0.09
$\frac{1+\rho_1^c}{\rho_1^c}$	Trade Elasticity	2.56	2.54	2.42	2.68

Table 2.7: Estimation Results of Endogenous Parameters

The estimated parameter of the investment adjustment cost (ψ_1) is well identified and is higher than its prior mean. Our estimated value is much smaller than the one found by DiCecio and Nelson (2007).[27] The posterior mean estimate of the parameter determining the elasticity of labour supply (χ_1) is much higher than values found by Harrison and Oomen (2010) and Millard (2011). This large difference is due to our theoretical framework that includes additional channels affecting real wages with respect to the standard small economy models (such those in the papers of Harrison and Oomen, 2010, and Millard, 2011).

In terms of nominal rigidities, the posterior mean estimate of the Calvo wage setting probability (ξ_1^w) is higher than our prior assumption. Our results show that the probability of optimally resetting nominal wages is around 0.01, meaning that

did not find any particular difference in the posterior estimates.

[25]In Appendix B we show all the prior and posterior density functions for the estimated parameters.

[26]The estimated values found by Di Cecio and Nelson (2007), Harrison and Oomen (2010) and Millard (2011) range between 0.42 and 0.78.

[27]DiCecio and Nelson (2007) argue that their "... estimates imply large investment adjustment costs, mainly driven by the matching of the smoother investment responses after the initial period". In addition, they state that: "the model does not match the apparent initial spike in investment observed in the data".

nominal wages are very sticky.[28] As we can note from Table 2.7, the estimated mean of the Calvo price setting probability (ξ_1^p) is higher than its prior. This implies that our Calvo readjustment probability is around 0.14. This compares to the estimate of 0.10 for the probability of changing price in the non-energy sector found by Millard (2011). Moreover, our posterior mean estimates show that the indexation of wages to past inflation (ι_1^w) is lower than the indexation of price to past inflation (ι_1^p). This result is broadly consistent with the findings of Millard (2011).[29]

Our estimates of the monetary policy reaction function show that the response to the output gap (γ_1^y) is higher than the response to core inflation (γ_1^π). In particular, the mean estimate of the long run response to output gap (γ_1^y) is well identified and is higher than its prior mean. On the contrary, the long run response to core inflation (γ_1^π) is not well identified. Interestingly, the mean estimate of the interest rate smoothing parameter (γ_1^i) is well identified and shows that the nominal interest rate is highly autocorrelated.

As we can see from Table 2.7, the posterior mean estimate of the price elasticity of oil demand corresponds to 0.05. This parameter is well identified and its posterior mean estimate is in line with values of oil price elasticities found by Dahl (1993) and Cooper (2003).[30]

Moreover, we estimate the posterior mean of the elasticity between domestic and foreign non-oil goods is equal to 2.5. Our estimated result is higher than the export price elasticity estimated by Hooper et al. (2000) for the UK economy.[31]

Turning to the shocks, Tables 2.8 and 2.9 show the estimated posterior modes

[28] In general, our estimated value of ξ_1^w is higher than values found by previous studies on the UK economy (see for example Harrison and Oomen, 2010).

[29] Millard (2011) finds that: "wage changes are hardly indexed to lagged wage inflation, as might be expected given the lack of formal indexation of wage bargains in the United Kingdom".

[30] Dahl (1993) provides a survey of oil demand elasticities for developing countries. He finds that the short-run price elasticity of demand for crude oil is 0.07. Cooper (2003) estimates the short-run price elasticity for crude oil demand of UK economy. He finds that it is equal to 0.068. However, both these studies do not distinguish between oil demand and oil supply shocks.

[31] Hooper et al. (2000) estimated trade price elasticities for G-7 countries. They reported a long run elasticity of 1.6 for the United Kingdom.

and means of all the exogenous processes, together with a 90% confidence interval.

Autocorr. Coefficients	**Post. Mode**	**Post. Mean**	**Conf. Inter.**	
UK Productivity: $\rho^{z}_{1,1}$	0.2997	0.2996	0.2912	0.3078
UK Productivity: $\rho^{z}_{2,1}$	0.0114	0.0182	0.0046	0.0319
UK Oil Supply: $\rho^{yo}_{1,1}$	0.4255	0.4300	0.3526	0.5038
UK Oil Supply: $\rho^{yo}_{2,1}$	0.0004	0.0071	0.0001	0.0176
Foreign Oil Supply: $\rho^{yo}_{1,2}$	0.6283	0.6356	0.5465	0.7229
Foreign Oil Supply: $\rho^{yo}_{2,2}$	0.0008	0.0055	0.0001	0.0117
UK Oil Intensity: $\rho^{zo}_{1,1}$	0.4078	0.4026	0.3285	0.4755
UK Oil Intensity: $\rho^{zo}_{2,1}$	0.0034	0.0044	0.0012	0.0074
UK Consumption: $\rho^{zc}_{1,1}$	0.4362	0.4653	0.2799	0.6503
UK Investment: $\rho^{zi}_{1,1}$	0.2351	0.2672	0.1260	0.4129
UK Import Preferences: $\rho^{zm}_{1,1}$	0.1012	0.1014	0.0932	0.1098
UK Import Preferences: $\rho^{zm}_{2,1}$	0.0005	0.0026	0.0001	0.0054
UK Price Mark-up: $\rho^{p}_{1,1}$	0.3133	0.2422	0.0548	0.4144
UK Wage Mark-up: $\rho^{w}_{1,1}$	0.8789	0.7058	0.4156	0.9984
UK Inflation Target: $\rho^{\pi}_{1,1}$	0.9955	0.9954	0.9898	0.9999

Table 2.8: Estimation Results of Shock Processes: Persistence Parameters

In general, data appear to be very informative on most of the stochastic processes for the exogenous disturbances. As concerns AR(1) processes, estimated posterior means suggest that the inflation target ($\rho^{\pi}_{1,1}$) shock appears to be the most persistent followed by wage mark-up ($\rho^{w}_{1,1}$), consumption ($\rho^{zc}_{1,1}$), investment ($\rho^{zi}_{1,1}$) and price mark-up ($\rho^{p}_{1,1}$) shocks. Considering the posterior mean estimates of AR(2) non-oil processes, the productivity shock (whose coefficients are $\rho^{z}_{1,1}$ and $\rho^{z}_{2,1}$) is more persistent than the import preference shock (whose coefficients are $\rho^{zm}_{1,1}$ and $\rho^{zm}_{2,1}$).

Focusing on the UK oil sector, our results suggest that the persistence of the foreign oil production shock (whose coefficients are $\rho^{yo}_{1,2}$ and $\rho^{yo}_{2,2}$) is higher than the UK oil production shock (whose coefficients are $\rho^{yo}_{1,1}$ and $\rho^{yo}_{2,1}$). Concerning the oil intensity shock, the posterior mean estimate of $\rho^{zo}_{1,2}$ is well identified and corresponds to 0.40, whereas $\rho^{zo}_{2,2}$ is not well identified and corresponds 0.0044.

As we can observe from Table 2.9, posterior mean estimates indicate that UK price markup shock (σ_1^p) appears to be the most volatile. Moreover, the posterior mean estimate of UK productivity shock (σ_1^z) corresponds to 0.018. Considering the posterior mean estimates of oil shocks volatilities, the standard error of UK oil intensity (σ_1^{zo}) is the highest, followed by UK oil production (σ_1^{yo}), foreign oil intensity (σ_2^{zo}), and foreign oil production (σ_2^{yo}), respectively.

Shock Standard Error	**Post. Mode**	**Post. Mean**	**Conf. Inter.**	
UK Productivity: σ_1^z	0.0170	0.0179	0.0143	0.0213
Foreign Productivity: σ_2^z	0.0632	0.0660	0.0546	0.0770
UK Oil Supply: σ_1^{yo}	0.0896	0.0902	0.0765	0.1033
Foreign Oil Supply: σ_2^{yo}	0.0120	0.0123	0.0104	0.0143
UK Oil Intensity: σ_1^{zo}	0.1359	0.1418	0.1188	0.1647
Foreign Oil Intensity: σ_2^{zo}	0.0761	0.0772	0.0656	0.0889
UK Consumption: σ_1^{zc}	0.0119	0.0126	0.0101	0.0151
Foreign Consumption: σ_2^{zc}	0.0933	0.0974	0.0827	0.1115
UK Import Preferences: σ_1^{zm}	0.0227	0.0233	0.0197	0.0269
Foreign Import Preferences: σ_2^{zm}	0.0521	0.0530	0.0453	0.0611
UK Investment: σ_1^{zi}	0.3495	0.3454	0.2158	0.4670
UK Price Mark-up: σ_1^p	1.1641	1.4703	0.6594	2.3154
UK Wage Mark-up: σ_1^w	0.0046	0.0076	0.0026	0.0128
UK Inflation Target: σ_1^π	0.0043	0.0065	0.0037	0.0092

Table 2.9: Estimation Results of Shock Processes: Standard Errors

Variance Decomposition Analysis. Table 2.10 shows the importance of each shock in terms of the variance of several endogenous variables. In particular, the variance decomposition analysis is based on the simulation of the estimated model (10,000 iterations).[32] More specifically, our strategy consists of two steps. As first step we run the model estimation and we obtain that the parameters and the variance matrix of the shocks are set to the mode for the maximum likelihood

[32] Our simulation results are detrended using the HP filter with a smoothing parameter equal to 1,600.

estimation or posterior mode computation. As second step, we simulate the model so that our simulation of the estimated model is based on the posterior modes of the model.[33]

	Oil Price (real)	UK GDP (real)	UK Cons. (GDP share)	UK Inv. (GDP share)	For. GDP (real)	UK Head. Infl.	UK Ov. Bal. (GDP share)	UK Ex. Rate (real)
H. Prod.	0	59	12	4	1	4	4	0
F. Prod.	5	2	0	3	72	8	4	1
H. Cons.	0	1	17	1	1	2	7	0
F. Cons.	3	4	35	14	17	7	62	1
H. Imp.	0	0	0	0	0	7	1	10
F. Imp.	0	7	2	1	2	13	3	85
H. Oil Sup.	0	8	2	0	0	0	3	0
F. Oil Sup.	1	0	0	0	0	0	0	0
H. Oil Int.	0	10	10	1	0	7	7	1
F. Oil Int.	90	4	14	32	5	8	3	2
H. Inv.	0	4	6	45	1	2	7	0
H. W. Mar.	0	0	0	0	0	0	0	0
H. P. Mar.	0	1	0	0	0	28	0	0
H. M. Pol.	0	0	0.	0	0	14	0	0

Table 2.10: Variance Decompositions (Percentage) - All Shocks

In general, domestic shocks do not contribute to the variation of oil price. On the contrary, the foreign oil intensity shock explains most of the variance of oil price (90%). As we can observe from the first column of Table 2.10, foreign productivity, foreign consumption preferences and foreign oil supply also contribute to the variation of oil price.

[33] In general it is preferable to follow this approach because the exact distributions of the posteriors are not known. Consequently, in the presence of irregular posteriors the mode is preferred to the mean as a measure of the central tendency of the distribution.

Interestingly, oil shocks influence several other UK observed variables. In particular, the sum of (domestic and foreign) oil shocks significantly contribute to variations of UK GDP, consumption, investment and headline inflation equal. The domestic productivity shock is the most important in explaining UK output, accounting for 59% of GDP variation. Moreover, the foreign consumption shock contributes substantially to the variation of UK consumption (35%) whereas domestic investment shock explains most of the variance of UK investment (45%).

Turning to nominal variables, 41% of the variation of UK headline inflation is explained by the combination of price mark-up and inflation target shocks, with the combination of domestic and foreign preferences shocks accounting for the 20%. The 62% of variation of total trade balance is explained by foreign consumption preferences shock. The bulk of the variation of the UK broad effective exchange rate is explained by the foreign import preferences shock that accounts for 85%.

2.3.5 Business Cycle Moments

In order to evaluate the predictions of our estimated model we compare its statistical moments with similar moments that summarise the actual experience of the UK economy.

The business cycle statistics implied by our model are computed with same procedure used to obtain the variance decomposition analysis.

Tables 2.11 and 2.12 report summary statistics on HP cyclical components (smoothing parameter equal to 1600) of key variables implied by our model and actual data.

As we can see from Table 2.11, our model is able to reproduce the volatility of most of the variables that we observe from actual data.

More specifically, the real oil price is much more volatile than UK GDP. We also observe higher volatility of domestic and foreign oil productions, real effective exchange rate and nominal interest rate with respect to GDP.

Variable	Model	Data
UK GDP	1.00	1.00
UK Oil Production	6.50	7.58
Foreign Oil Production	1.17	1.74
UK Oil Imports (GDP Share)	0.53	0.16
Real Oil Price	21.88	20.95
UK Non-Oil Goods Imports (GDP Share)	0.63	0.93
UK Goods Exports (GDP Share)	0.73	0.78
UK Real Exchange Rate (qr.)	4.70	4.39
UK Consumption (GDP share)	0.82	0.48
UK Investment (GDP share)	0.64	0.64
UK Headline Inflation	0.39	0.56
UK 3 Months Treasury Bills (qr.)	1.63	1.22
UK Wage Inflation	0.26	0.07

Table 2.11: Observed Data and Model Implications - Relative St. Deviations to GDP

On the contrary, private consumption and gross fixed capital formation display almost half of the volatility of GDP. Considering wage inflation, we observe that it is much less volatile than gross domestic product.

Table 2.12 shows the coefficients of autocorrelation for the same variables described above. As we can observe from this table, the persistence generated by the model is as high as in the observed data. In particular, the first order correlation for most of the macroeconomic aggregates is on the order of 0.9. Interestingly, in line with observed data, headline inflation displays a low persistence.

Variable	**Model**	**Data**
UK GDP	0.82	0.96
UK Oil Production	0.86	0.85
Foreign Oil Production	0.91	0.93
UK Oil Imports (GDP Share)	0.88	0.81
Real Oil Price	0.96	0.84
UK Non-Oil Goods Imports (GDP Share)	0.84	0.90
UK Goods Exports (GDP Share)	0.89	0.94
UK Real Exchange Rate (qr.)	0.77	0.96
UK Consumption (GDP share)	0.89	0.92
UK Investment (GDP share)	0.88	0.89
UK Headline Inflation	0.30	0.53
UK 3 Months Treasury Bills (qr.)	0.73	0.97
UK Wage Inflation	0.90	0.57

Table 2.12: Observed Data and Model Implications - Autocorrelations

2.4 Impulse Response Functions

In this section, we show the results of impulse response functions (IRFs) for the estimated model considering some of the exogenous shocks driving the economy. In particular, we focus on the two shocks in the oil sector that most affect oil price variation, i.e. the foreign oil intensity shock and foreign oil supply shock. Moreover, we consider the foreign technology shock that accounts for 5% oil price change according to our variance decomposition analysis. In each figure we show the IRFs following a temporary one-standard deviation change in the exogenous shock. The signs of the shocks are chosen in order to induce a decrease in the price of oil.[34]

[34] In Appendix B, we show the impulse responses for the standard domestic technology shock. We believe that this case is not particularly relevant for the purposes of the present analysis. Indeed, it is evident that general transmission mechanisms on the several variables are dominated by the direct effects of this shock rather than oil market considerations.

2.4.1 Oil Shocks

We start by describing the IRFs for oil shocks. As we explained above, oil price fluctuations can derive from changes in oil intensity as well as oil supply. Similarly, we consider the fact that the UK reacts differently to oil price movements that originate domestically rather than abroad. According to our variance decomposition (Table 2.10), foreign oil shocks explain most of the oil price volatility. In particular, the foreign intensity shock has a much higher contribution than foreign oil supply shock in terms of UK oil price variation.

Foreign Oil Intensity. Figure 2.1 shows the effects of a shock that increases foreign oil intensity ($Z^o_{2,t}$). As we explained above, oil intensity can be defined as the measure of the energy efficiency of a nation's economy. In turn, energy efficiency can be seen as the goal to reduce the amount of energy required to provide products and services. Thus, energy efficiency is related to better methods of transportation, better use of building materials (for example: insulation), better capacities of mass transit, energy rationing and conservation efforts. As a consequence, shifts in oil efficiency include changes to both consumption behaviours and production processes. Accordingly, in a given country, a positive oil intensity shock implies an improvement in its oil efficiency and a reduction of its oil demand.

As we can note from Graph (a), the persistence of this shock is very high and resembles a unit root process. Accordingly, most of the variables react almost permanently in response to the foreign oil intensity shock.

In particular, after a positive shock to oil intensity occurred abroad foreign oil demand reduces and, in turn, the real price of oil in UK currency decreases (Graph (a)). As we can see from Graph (b), the reduction of domestic oil price implies an increase of UK oil demand.

In line with the results of Bodenstein et al. (2012) for the US economy, we find that the increase of oil used in production has effects on output and domestic absorption (defined as the sum of domestic consumption and domestic investment) similar to a persistent improvement in productivity, (Graphs (c) and (i), respectively).[35]

However, on impact, actual output responds negatively to the shock (Graph (c)). This result can be explained in two ways. Firstly, the presence of real rigidities does not allow output and domestic absorption to adjust immediately after the shock. Secondly, nominal rigidities prevent realized output from improving immediately.

Evidently, monetary policy also influences the response of actual output. Indeed, the decrease of nominal interest (Graph (h)) contributes to improve realized output. As a consequence, realized output expands more than potential output over time. From Graph (j), we note that hours worked mirror the behaviour of domestic output.

In contrast to the papers of Harrison et al. (2011) and Millard (2011), our model explicitly considers the trade channel between the UK and the rest of the world. In this regard, Graph (k) shows that the UK total balance worsens in response to a positive shock in foreign oil intensity. This reduction is due to the decrease of oil exports (Graph (k)) since the UK is a net oil exporter country. From Graph (k) we note that non-oil trade balance does not change substantially in response to the shock.

We define the real exchange rate as the price of the foreign consumption basket over the price of the domestic consumption basket in a common currency. Therefore, the downward movement shown in Graph (l) means the appreciation of UK Sterling Pound. Indeed, the positive effect on the foreign economy induced by an improvement of foreign oil intensity implies that the price of consumption goods in the foreign country falls more substantially than the price of consumption goods in the UK.[36] This result contrasts with the qualitative predictions of previous

[35]Note that Bodenstein et al. (2012) assume a negative shock to foreign oil intensity which induces persistent falls in both output and domestic absorption.

[36]In this regard, our model assumes that the oil intensity shock enters directly in the production function of the final consumption goods (see equation B24 in Appendix B).

studies on the UK economy such as Hall et al. (1986) and Young(2000).

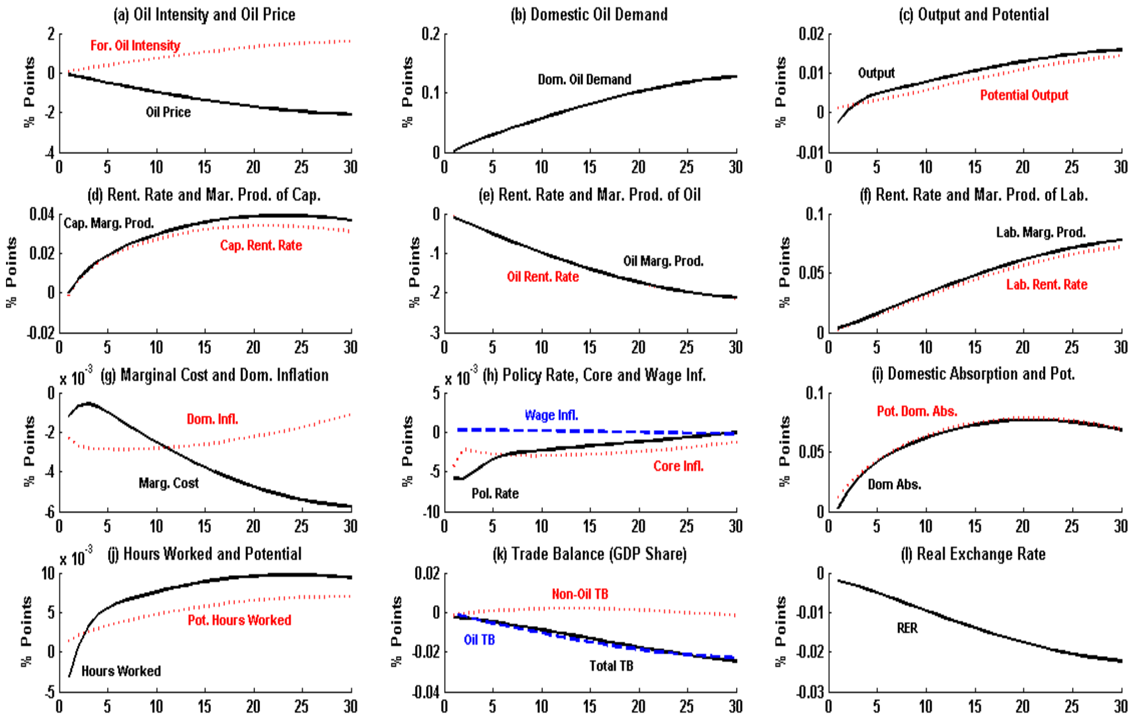


Figure 2.1: IRFs, Positive Foreign Oil Intensity Shock

Now we come to focus on the inflation dynamics. Graph (g) displays the IRFs for domestic goods inflation and marginal cost. Considering domestic goods inflation, the standard New-Keynesian Phillips curve provides a useful tool to understand the transmission mechanisms of oil price movements. For simplicity, we set up the parameter governing lagged indexation, ι_1^p, equal to zero and we abstract from the mark-up. Thus, we can express domestic inflation, $\hat{\pi}_{1,t}^d$, as:

$$\hat{\pi}_{1,t}^d = \sum_{s=0}^{\infty} \beta_1^s \frac{\left(1 - \beta_1 \xi_1^p\right)\left(1 - \xi_1^p\right)}{\xi_1^p} E_t m\hat{c}_{1,t+1} \tag{2.33}$$

In words, the first order approximation of current inflation can be thought of as the discounted sum of current and expected marginal cost of production. In our case the marginal cost depends on oil as an additional factor input and can be expressed as:

$$\begin{aligned} \hat{mc}_{1,t} &= \omega_1^{oy}\left(\left[\frac{\hat{P}^o}{\hat{P}^d}\right]_{1,t} - m\hat{p}o_{1,t}\right) + \omega_1^{vy}\phi_1^k\left(\hat{r}_{1,t}^k - m\hat{p}k_{1,t}\right) \\ &\quad + \omega_1^{vy}\left(1-\phi_1^k\right)\left(\hat{w}_{1,t} - m\hat{p}l_{1,t}\right) \end{aligned} \tag{2.34}$$

where $m\hat{p}o_{1,t}$, $m\hat{p}k_{1,t}$, and $m\hat{p}l_{1,t}$ are the marginal products of oil, capital and labour respectively. Thus, domestic inflation depends on these gaps between the rental rates and the marginal products of each input. When nominal rigidities are absent, these gaps are zero and real marginal cost is constant. On the contrary, with nominal rigidities these gaps can be large.

The positive foreign oil intensity shock induces an increase of oil input and causes a decrease of its marginal product (Graph (e)). The real rental rate of oil decreases as well. From Graph (e) we note that the gap between the rental rate and marginal product of oil does not contribute substantially to the decrease in the marginal cost. Since firms expand their demands for cheaper oil, they decrease the relative demands for other factor inputs. As we can note from Graph (f) there is a persistent negative gap between real wage and labour marginal product. Similarly, we note a significant negative difference between capital rental rate and capital marginal product (Graph (d)). These two persistent negative gaps are the key contributors to the decrease of marginal cost and, in turn, domestic inflation (Graph (g)).

Interestingly, contrary to the results of Anderton and Barrell (1995) and Barrell et al. (2011a), we find that the response of UK wage inflation to the fall in the oil price is close to zero for the entire period considered (Graph (h)).[37]

Finally, in line with the findings of Millard (2011), Graph (h) shows that UK core inflation decreases inducing the UK Central Bank to loosen its monetary

[37] In particular, Anderton and Barrell (1995) and Barrell et al. (2011a) found that an increase in the oil price induces a rise in wage inflation.

policy.[38]

Foreign Oil Supply Shock. Figure 2.2 displays the responses of the UK economy to a positive oil supply shock occurring abroad ($Y^o_{2,t}$). In general, the effects of this shock are similar to those for foreign oil intensity shock. The only difference between these two shocks is in terms of the magnitude of the effects. Indeed, our estimated results (Table 2.9) indicate that the foreign oil intensity shock has higher volatility than the foreign oil supply shock. Thus, the final effects of the foreign oil supply shock are smaller than those following the foreign oil intensity shock.

As we can note from Graph (a), the foreign oil supply shock is very similar to a stationary process and the return to the steady state happens beyond the horizons shown in the figure. In particular, the resulting persistent decrease of oil price (Graph (a)) leads to an increase in domestic oil demand (Graph (b)).

The responses of output (Graph (c)) and domestic absorption (Graph (h)) are similar to those occurring after a positive productivity shock. This result confirms the findings of Bodenstein et al. (2011) for the US economy.[39]

In particular, Graph (c) shows that the initial increase in actual output is lower than potential output. This effect is caused by the presence of both real and nominal rigidities. However, in the long run, loose monetary policy induces a more rapid expansion of actual output compared with potential. Moreover, the responses of hours worked mimic those of domestic output (Graph (j)).

Focusing on trade, we observe that the UK oil balance worsens inducing a fall in domestic total balance (Graph (k)). Moreover, Graph (k) shows that the UK non-oil trade balance remains close to zero for all the horizons considered. This result is line with the finding of the previous section and extends the previous literature (see, for example, Harrison et al., 2011; Millard, 2011) by showing that

[38] More specifically, Millard (2011) finds that a positive world oil price shock induces a rise in the nominal interest rate.

[39] In particular, Bodenstein et al. (2011) find that a negative shock foreign oil supply reduces both US output and domestic absorption.

a fall in the oil price adversely affects the UK trade sector because the UK is a net oil exporter country.

From Graph (l), we observe that UK real effective exchange rate has a U-shaped response to the shock. In particular, it appreciates from quarter four to quarter six. However, from the seventh quarter onwards British Sterling Pound depreciates vis-à-vis with foreign currency. Differently from the foreign oil intensity shock, a positive shock to foreign oil supply implies that the fall in the price of domestic consumption goods is larger than the one in foreign consumption goods. As a consequence, the UK currency depreciates. This result is line with the standard predictions of previous studies on the UK economy (such as Powell and Horton, 1985; Hall et al., 1986 and Young, 2000) relying on the fact that the fall in oil price induces the depreciation of the currency in the net oil exporter country.

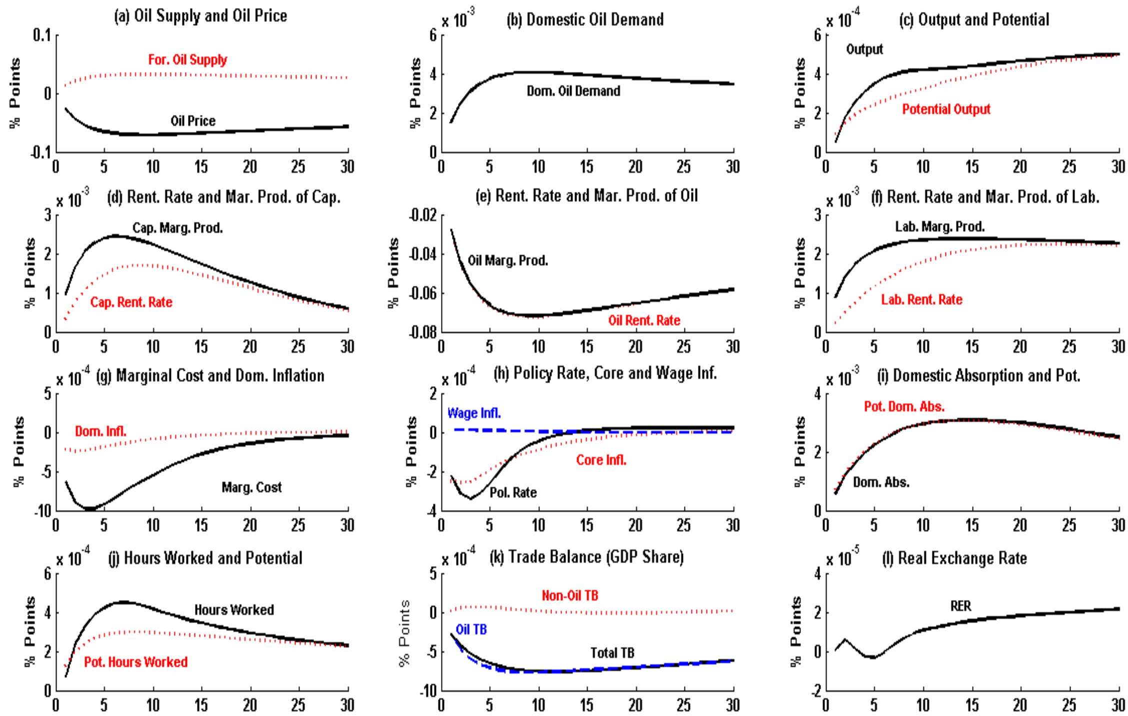


Figure 2.2: IRFs, Positive Foreign Oil Supply Shock

Considering inflation dynamics, Graph (g) shows the negative response of firms marginal cost that causes a fall in domestic goods inflation. As we described above, the drop in the domestic marginal cost depends on the negative gaps between the rental rates and the marginal products of each production factor (Graphs (d), (e) and (f)).

As we can observe from Graph (h), the decrease in UK core inflation is immediately followed by the reduction of the nominal interest rate. Accordingly, in line with the results of Millard (2011), we find the drop of the oil price in response to this shock induces the Bank of England to reduce its policy rate.

As for the case of the shock to foreign oil intensity, UK wage inflation does not react significantly (Graph (h)). Again, this response contrasts with the findings of existing papers analysing the UK economy (such as Anderton and Barrell, 1995; Barrell et al., 2011a).

2.4.2 Foreign Technology Shock

Our analysis of the model variance decomposition suggested that the foreign technology shock significantly affects the variation of the UK oil price (see Table 2.10). Hence, it is important to understand the behaviour of the main macroeconomic variables after this shock through our IRFs analysis. Thus, Figure 2.3 shows a negative shock to foreign technology ($Z_{2,t}$).

Contrary to the findings of Bodenstein et al. (2011), our results show that oil market transmission channels prevail on the standard effects of the foreign technology shock. In particular, the negative shock to foreign productivity causes the fall in foreign oil demand pushing down UK oil price (Graph (a)). As a consequence of less expensive oil, domestic households and firms increase their demand for this input (Graph (b)).

Since this shock is very persistent the effects on the several UK macroeconomic variables last for a long time period.

In line with the results of Bodenstein and Guerrieri (2011), we find that domestic output increases immediately in response to the shock and remains positive for all the quarters considered (Graph (c)).[40] In particular, potential output displays a stronger initial increase than actual output.

As in Bodenstein et al. (2011), we find that domestic absorption positively responds to the fall in foreign technology (Graph (i)).[41] Moreover, from Graph (j) we note that the response of actual and potential hours worked mirrors the patters of actual and potential outputs.

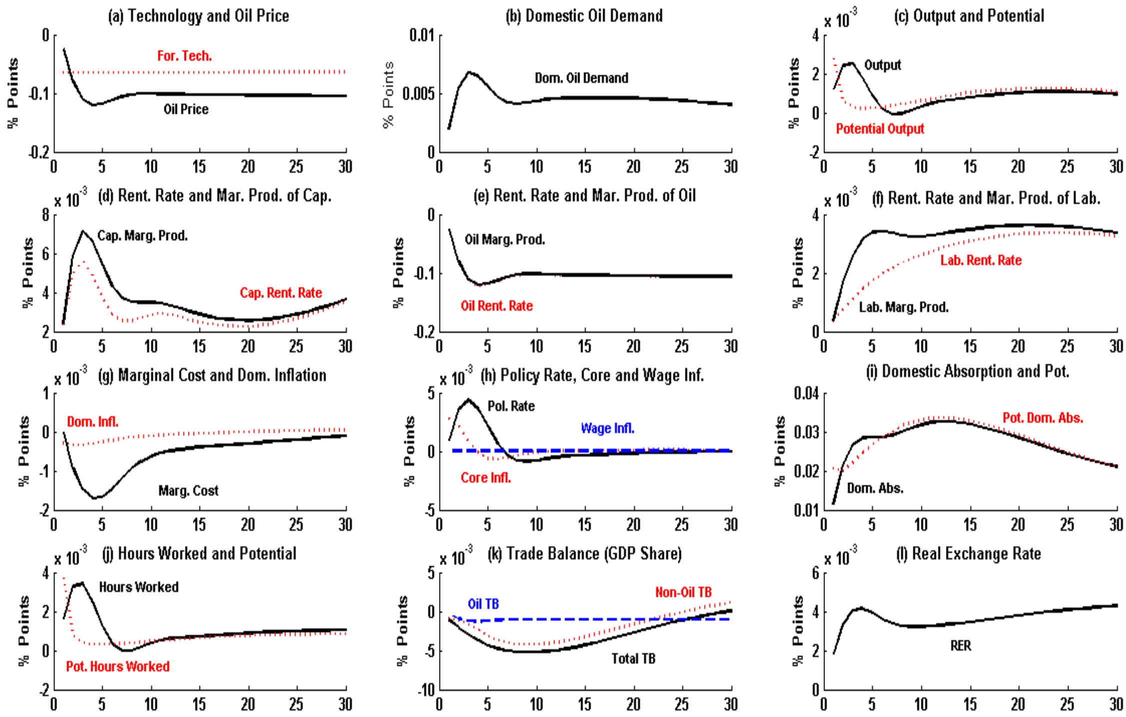


Figure 2.3: IRFs, Negative Foreign Technology Shock

Focusing on international relative prices (Graph (l)), we note that the UK real effective exchange rate depreciates. Indeed, in response to the negative

[40] Bodenstein and Guerrieri (2011) find a negative response of US GDP in response to a foreign technology shock that causes an increase in the oil price.

[41] According to Bodenstein et al. (2011) an increase in the oil price induces a fall in US domestic absorption.

productivity shock that occurred abroad the relative price of imported goods with respect to domestic goods increases. This result is broadly in line with the findings of Powell and Horton (1985), Hall et al. (1986) and Young (2000).

Although Sterling depreciates, we observe the deterioration of the domestic non-oil trade balance (Graph (k)). That can be explained by the strong consumption habits of domestic households. In particular, domestic households dislike changes in the composition of the consumption basket. Therefore, the increase in the price of imported goods does not affect substantially the demand for these goods. As a consequence, the value of imports increases more than the value of exports and we observe a deficit in the non-oil goods balance. Similarly, oil trade balance decreases because UK net oil exports reduce. The final effect is a large fall in the UK total trade balance (Graph (k)).

In general, these findings complement the existing literature by showing specific transmission channels of oil shocks that were missing in previous studies on the UK economy (see, for example, Harrison et al., 2011; Millard, 2011).

Turning to the inflation dynamics, we note a decrease of marginal cost and domestic goods inflation (Graph (g)). As explained above, domestic marginal cost depends on the gaps between rental rates and marginal products of each production input. As we can see from Graph (d) and (f), the largest negative gaps correspond to labour and capital inputs.

Interestingly, on the shock impact UK core inflation expands due to the spike in import prices (Graph (g)). However, after four quarters it turns to be negative. Although the immediate response of the nominal interest rate is positive, after six quarters it turns to be negative (Graph (h)).

Finally, contrary to the results of Anderton and Barrell (1995) and Barrell et al. (2011a), we note that the reaction of wage inflation is negligible compared to core inflation (Graph (h)).

2.5 Using the Model to Decompose Movements in Output and Inflation

The major motivation for estimating this model is to analyse the effects of movements in oil prices on the UK economy. In this section we will focus on the main drivers of domestic output and inflation during the sample period 1990-2005.

Given that estimation produces time series for the shocks, it possible to decompose movements in output and inflation into those fractions caused by each of the shocks.

Figure 2.4 and 2.5 show the estimated series for the exogenous shocks of the model.

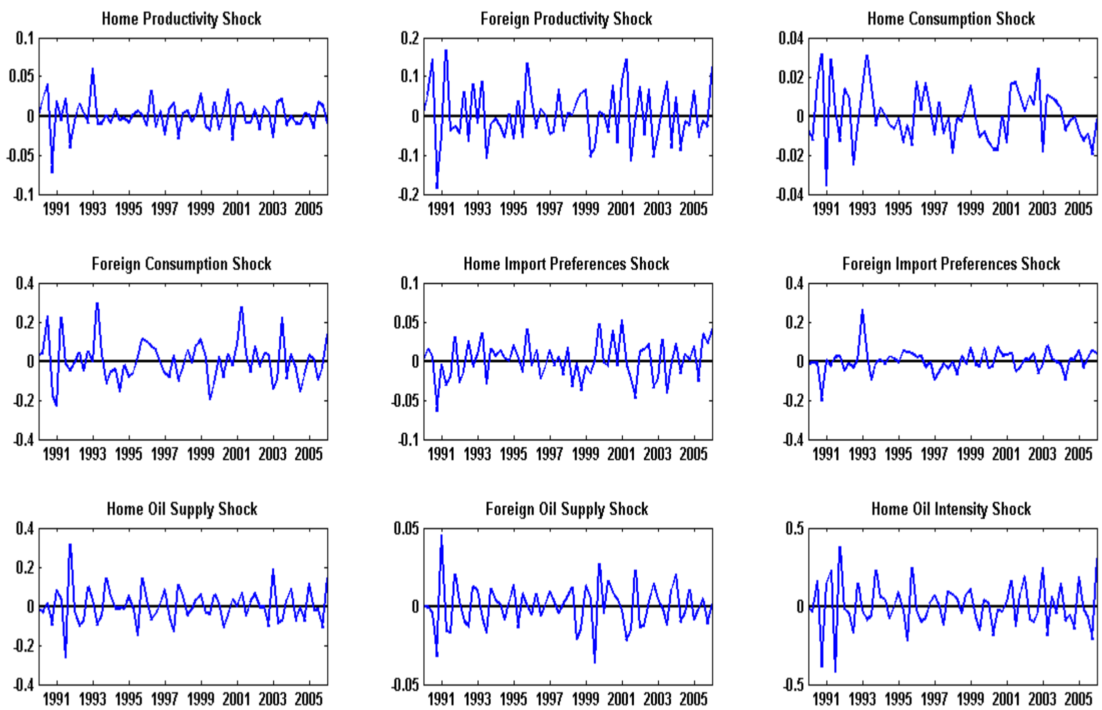


Figure 2.4: Exogenous Shocks (1)

As we can observe from these figures, home price mark-up, home investment, home oil intensity, foreign oil intensity, home oil supply and foreign consumption preferences show high volatilities over this period.

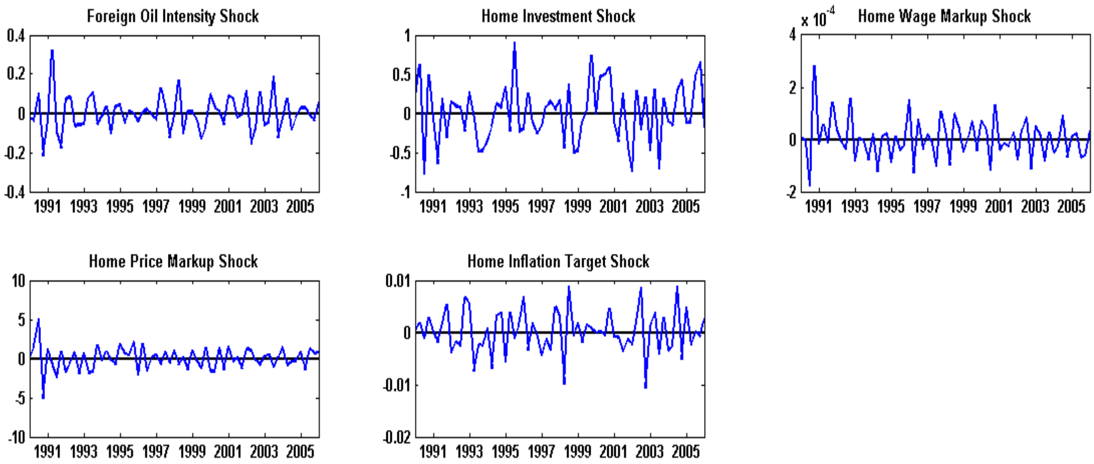


Figure 2.5: Exogenous Shocks (2)

To investigate further which shocks have been driving the UK economy over this sample period, Figure 2.6 shows the historical decomposition of UK GDP into the portions caused by each of the shocks. We can observe that major UK GDP expansions have occurred during the quarters 1990:Q1-1990:Q2 and 2000:Q1-2000:Q4 whereas most severe recessions happened during the quarters 1990:Q3-1992:Q3 and 1999:Q1-1999:Q3. In what follows we analyse in detail each of these episodes. In general, oil prices have considerable effects on GDP and inflation.

In particular, from Figure 2.6, we can see that during the period 1990:Q1-1990:Q2 the economy has been affected by a large positive shock to domestic productivity. As reported in the OECD Economic Surveys (1991), the UK economy started to expand in early 1987 and continued to grow until mid-1990.

According to the OECD Economic Surveys (1991), the UK GDP expansion was the result of structural reforms which raised productivity and also led to strong private sector confidence. In the same period, the UK economy experienced a strong expansion of its domestic demand occurred mainly because of the unprecedented upsurge in private investment due to the financial-market liberalisation which enabled households and companies to borrow much more freely than ever before.[42]

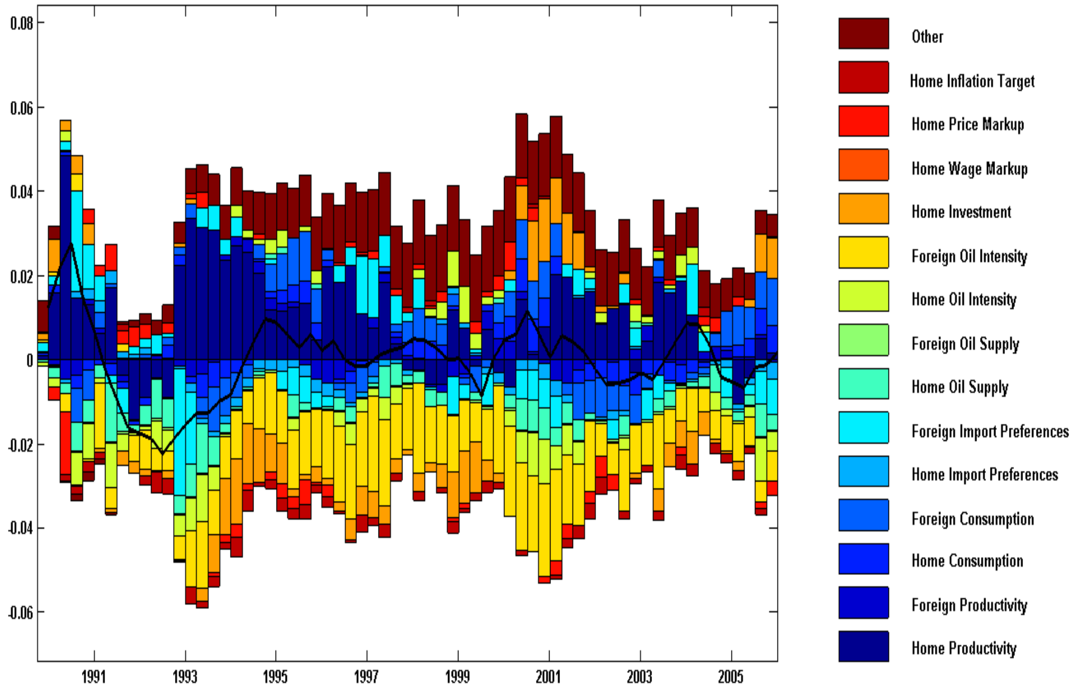


Figure 2.6: Shock Decomposition for UK GDP

Figure 2.6 also shows that during the period 2000:Q1-2000:Q4 two main positive shocks occurred to both domestic productivity and domestic investment. Firstly, the positive productivity shock reflected the outcomes deriving from structural reforms undertaken by UK government in order to enhance productivity so as to boost total labour supply. As observed by the OECD Economic Surveys (2000), during this period, the UK productivity benefited from positive effects of social sphere reforms aimed at lifting people out of poverty and alleviating exclusion. Secondly, the positive investment shock was associated with the boom

[42] For a careful description of the causes of this increase in the UK aggregate demand see the OECD Economic Surveys (1991).

of business investment registered in UK in that period. Indeed, the ratio between business investment and GDP achieved the highest level since at least the mid 1960's.

Interestingly, oil shocks were the major drivers of two recessions experienced by UK economy during this period. In particular, Figure 2.6 shows that during the period 1990:Q3-1992:Q3 the economy was affected by negative shocks to foreign oil supply, foreign oil intensity and foreign import preferences. As we have described in Chapter 1, during this period there was a large increase in oil-market specific demand that caused a sharp increase in oil price. Indeed, precautionary demand for oil increased in response to expected shortfalls in oil supply due to Iraq's invasion of Kuwait in August 1990. The latter episode also caused a small physical disruption in oil supply. In addition, the Gulf conflict increased private sector uncertainty inducing a drop in the UK trade sector.[43]

Moreover, from Figure 2.6, we can see that during the period 1999:Q1-1999:Q3 a large negative shock to foreign oil intensity caused the immediate increase in UK oil price implying a fall of domestic output. As we have shown in Chapter 1, even in this case the increase of precautionary demand for oil was the main cause of the oil price surge. Contemporaneously, UK economy experienced negative shocks to domestic investment and foreign consumption preferences. The former shock reflected the fall of investment in the manufacturing sector as reported by the OECD Economic Surveys (2000). The negative shock to foreign consumption preferences can be explained by the strong appreciation of the pound during that period.[44]

Turning to inflation, Figure 2.7 suggests that oil intensity and oil supply shocks were pushing up oil price in the second half of 1990 in correspondence with the Kuwait Invasion. As a consequence, headline inflation increased substantially in that period. Domestic and foreign and import preferences shocks also contributed

[43]See the OECD Economic Surveys (1991) for a more detailed explanation of the negative effects on UK trade sector caused by the Gulf war.

[44]See the OECD Economic Surveys (2000) for a detailed description of the pattern of the UK real effective exchange rate during this period.

to the rise of headline inflation.

On the contrary, the relatively low oil price in 1993 pushed down headline inflation. As we have shown in Chapter 1, during that period there were negative shocks to both aggregate and oil market-specific demands that caused a decrease in oil price. Consistently with this finding, our model shows that the negative foreign oil intensity shock was the main cause of the decrease in headline inflation.

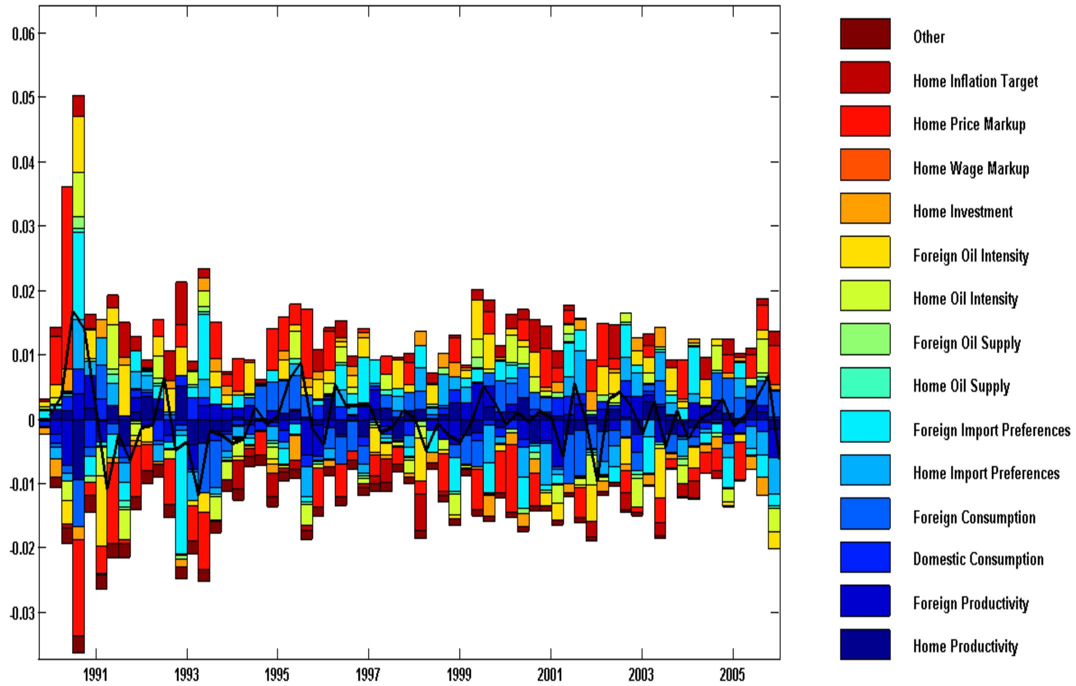


Figure 2.7: Shock Decomposition for UK Headline Inflation

2.6 Conclusion

Hitherto, economists have used global DSGE models to analyse largely the US and the EU economies. In this chapter, we construct a global model capturing the 73% of the UK's export markets. In this framework, we are able to model the endogenous formation of oil prices and analyse how vulnerable the UK economy has been to variations in the oil price.

In particular, we analyse a period in which the UK was a net oil exporter and where, otherwise, the domestic economic environment was relatively stable (no nominal regime changes). Our results indicate that movements of the UK oil price occur mainly for 2 reasons: firstly, changes in global oil demand (foreign oil intensity shock and foreign productivity shock); secondly, changes in global oil supply (foreign oil supply shock).

Moreover, our findings show that the main consequences of oil price decreases on the UK economy are the following. Negative oil price shocks push down the costs of firms using oil as production input. These shocks tend to increase profits, stimulating employment and thus real GDP. Moreover, negative oil price shocks translate to lower retail prices. This improves real incomes and therefore stimulates consumer spending. Our impulse response analysis also shows that UK Central Bank decreases its policy rate in response to the reduction of domestic inflation. We also find a negligible response of the wage inflation to oil price shocks.

In regards to the external sector, the UK total trade balance worsens after negative oil shocks since UK net oil exports reduce. Moreover, British Sterling appreciates against other currencies in the presence of a positive foreign oil intensity shock while the opposite occurs after a positive oil supply shock and a negative foreign technology shock.

These findings contrast with the existing analysis of the UK economy over this period. We would highlight, in particular, that the response of the UK exchange rate to oil price fluctuations depends on the specific source of the oil price shock. Moreover, contrary to the papers of Harrison et al. (2011) and Millard (2011), our model explicitly considers the trade channel between the UK and the rest of the world. Therefore, we find that the worsening of the UK trade balance in response to a drop in the oil price depends on the fact that the UK was a net oil exporter for the period considered.

Interestingly, our results differ from those found by Anderton and Barrell (1995) and Barrell et al. (2011a), showing that wage inflation is not significantly affected by oil price changes. Finally, the findings of our historical decomposition analysis complement existing literature by showing that episodes of sustained increase of oil price contributed to UK GDP recessions and caused spikes of domestic inflation.

The model presented in this paper provides a clear understanding of the impact of oil price movements and changes in the global oil market structure on the UK economy. However, our theoretical framework does not include the government sector. In particular, the latter is expected to play an important role in response to oil price changes especially in a oil producer country such as United Kingdom. Therefore, in the next chapter we extend the present theoretical framework modelling the UK fiscal sector in detail. Accordingly, our objective will concern the development of an open economy DSGE model in order to assess the fiscal policy responses to oil price fluctuations in the UK economy.

B Appendix: Chapter 2

B.1 Model Solution

This appendix shows the non-linearized and linearized versions of the key optimality and market clearing conditions used in our analysis of the model's equilibrium dynamics. Here, we focus on the endogenous variables of the model whereas the stochastic processes and the relative exogenous variables are reported in Table 2.1. We denote by small letters with hat, $\hat{x}_{i,t}$, the log-deviation of a given variable, $X_{1,t}$, from its steady state value, while $(X_1)^{SS}$ stands for its steady state value.

B.1.1 Country-Specific Relations

In what follows we derive the relations for the domestic country assuming that the same conditions apply to the foreign country because the model is symmetric.

Representative Household Maximization Problem. The representative household solves the following intertemporal problem:

$$E_t \left\{ \sum_{j=0}^{\infty} \beta_1^j \left[\begin{array}{c} \frac{1}{1-\sigma_1} \left(Z_{1,t}^c C_{1,t+j} - \kappa_1 C_{1,t+j-1} \right)^{1-\sigma_1} + \\ \frac{1}{1-\chi_1} \left(1 - L_{1,t+j} \right)^{1-\chi_1} \end{array} \right] \right\} \tag{B1}$$

subject to the budget constraint:

$$\begin{aligned} & P_{1,t}^c C_{1,t} + P_{1,t}^i I_{1,t} + \frac{e_{1,t} P_{2,t}^b B_{1,t}}{\phi_{1,t}^b} + \int_S P_{1,t,t+1}^d D_{1,t,t+1}(h) - D_{1,t-1,t} \\ = \; & W_{1,t} L_{1,t} + R_{1,t}^k K_{1,t-1} + \Gamma_{1,t} + P_{1,t}^o Y_{1,t}^o + e_{1,t} B_{1,t-1} \end{aligned} \tag{B2}$$

and the capital accumulation equation:

$$K_{1,t} = (1-\delta_1) K_{1,t-1} + \left(1 - S \left(\frac{I_{1,t}}{I_{1,t-1}} \right)^2 \right) Z_{1,t}^i I_{1,t} \tag{B3}$$

The first order condition for $C_{1,t}$ is:

$$\left(Z_{1,t}^{c}C_{1,t}-\kappa_{1}C_{1,t-1}\right)^{-1}Z_{1,t}^{c}=\lambda_{1,t}^{q}\frac{P_{1,t}^{c}}{P_{1,t}^{d}} \tag{B4}$$

where:

$$\lambda_{1,t}^{q}=\lambda_{1,t}^{c}P_{1,t}^{d}$$

and $\lambda_{1,t}^{c}$ is the Lagrange multiplier associated with the representative household budget constraint. The linearized equation is given by:

$$\frac{1}{1-\kappa_{1}}\left(\hat{c}_{1,t}+\hat{z}_{1,t}^{c}\right)=\frac{\kappa_{1}}{1-\kappa_{1}}\hat{c}_{1,t-1}+\hat{z}_{1,t}^{c}-\hat{\lambda}_{1,t}^{q}-\left[\frac{\hat{P}^{c}}{\hat{P}^{d}}\right]_{1,t} \tag{B5}$$

The first order condition for $L_{1,t}$ is:

$$(1-L_{1,t})^{-\chi_{1}}=\lambda_{1,t}^{q}w_{1,t}^{f}$$

where:

$$w_{1,t}^{f}=\frac{W_{1,t}^{f}}{P_{1,t}^{d}} \tag{B6}$$

that is $w_{1,t}^{f}$ is the desired real wage expressed in terms of $P_{1,t}^{d}$. The linearized equation is given by:

$$\hat{w}_{1,t}^{f}=\frac{(L_{1})^{SS}}{1-(L_{1})^{SS}}\chi_{1}\hat{l}_{1,t}-\hat{\lambda}_{1,t}^{q} \tag{B7}$$

Labour Supply Decision. If wages are flexible:

$$\hat{w}_{1,t}=\hat{w}_{1,t}^{f}+\frac{(\theta_{1}^{w})^{SS}}{1+(\theta_{1}^{w})^{SS}}\hat{\theta}_{1,t}^{w} \tag{B8}$$

If wages are sticky, the labour union solves the following maximization problem:

$$\max_{\{W_{1,t}(h)\}} E_t \sum_{j=0}^{\infty} \left(\xi_1^w\right)^j \psi_{1,t,t+j} \left[\begin{array}{c} \omega_{1,t,,j}^l W_{1,t}(h) L_{1,t+j}(h) - \\ W_{1,t+j}^f L_{1,t+j}(h) \end{array} \right] \tag{B9}$$

$$s.t \quad : \quad L_{1,t}(h) = \left(\frac{W_{1,t}(h)}{W_{1,t}}\right)^{-\frac{1+\theta_{1,t}^w}{\theta_{1,t}^w}} L_{1,t}^d \tag{B10}$$

$$and \quad : \quad \omega_{1,t,,j}^l = \prod_{s=1}^{j} \left\{ \left(\omega_{1,t-1+s}\right)^{\iota_1^w} \left(\pi_1^{SS}\right)^{1-\iota_1^w} \right\} \tag{B11}$$

the first order condition is given by:

$$E_t \sum_{j=0}^{\infty} \Xi_{1,t+j}^w \left[\begin{array}{c} \frac{W_{1,t}(h)}{W_{1,t}} \frac{1}{\theta_{1,t+j}^w} - \\ \frac{W_{1,t+j}^f}{P_{1,t+j}^d} \frac{P_{1,t+j}^d}{W_{1,t+j}} \left(\frac{W_{1,t}\omega_{1,t,j}^l}{W_{1,t+j}}\right)^{-1} \frac{1+\theta_{1,t+j}^w}{\theta_{1,t+j}^w} \end{array} \right] = 0 \tag{B12}$$

where:

$$\Xi_{1,t+j}^w = \left(\xi_1^w\right)^j \psi_{1,t,t+j} L_{1,t+j}(h)\, \omega_{1,t,j}^l$$

The linearized equation is given by:

$$\begin{aligned} & \frac{1}{\pi_1^{SS}} \left(\hat{\omega}_{1,t} - \iota_1^w \hat{\omega}_{1,t-1}\right) - \frac{\beta_1}{\pi_1^{SS}} \left(\hat{\omega}_{1,t+1} - \iota_1^w \hat{\omega}_{1,t}\right) \\ = \quad & \frac{\left(1-\xi_1^w \beta_1\right)\left(1-\xi_1^w\right)}{\xi_1^w} \left(\hat{w}_{1,t+j}^f - \hat{w}_{1,t+j} + \frac{\left(\theta_1^w\right)^{SS}}{1+\left(\theta_1^w\right)^{SS}} \hat{\theta}_{1,t}^w \right) \end{aligned} \tag{B13}$$

where:

$$\frac{1}{\pi_1^{SS}} \left(\hat{\omega}_{1,t} - \iota_1^w \hat{\omega}_{1,t-1}\right) = \hat{\omega}_{1,t} - \iota_1^w \hat{\omega}_{1,t-1}$$

The wage inflation is:

$$\omega_{1,t} = \log\left(\frac{W_{1,t}}{W_{1,t-1}}\right) \tag{B14}$$

the linearized equation is given by:

$$\hat{\omega}_{1,t} = \hat{w}_{1,t} - \hat{w}_{1,t-1} + \hat{\pi}_{1,t}^d \tag{B15}$$

Capital Accumulation. The representative household solves the following intertemporal problem:

$$E_t\left\{\sum_{j=0}^{\infty}\beta_1^j\left[\begin{array}{c}\frac{1}{1-\sigma_1}\left(Z_{1,t}^c C_{1,t+j}-\kappa_1 C_{1,t+j-1}\right)^{1-\sigma_1}+\\ \frac{1}{1-\chi_1}\left(1-L_{1,t+j}\right)^{1-\chi_1}\end{array}\right]\right\} \tag{B16}$$

subject to the budget constraint:

$$\begin{aligned} & P_{1,t}^c C_{1,t}+P_{1,t}^i I_{1,t}+\frac{e_{1,t}P_{2,t}^b B_{1,t}}{\phi_{1,t}^b}+ \\ & \int_S P_{1,t,t+1}^d D_{1,t,t+1}(h)-D_{1,t-1,t} \\ = \;& W_{1,t}L_{1,t}+R_{1,t}^k K_{1,t-1}+\Gamma_{1,t}+P_{1,t}^o Y_{1,t}^o+e_{1,t}B_{1,t-1} \end{aligned} \tag{B17}$$

and the capital accumulation equation:

$$K_{1,t}=\left(1-\delta_1\right)K_{1,t-1}+\left(1-S\left(\frac{I_{1,t}}{I_{1,t-1}}\right)^2\right)Z_{1,t}^i I_{1,t} \tag{B18}$$

The first order condition for $I_{1,t}$ is:

$$\begin{aligned} 0 \;=\; & 1-q_{1,t}Z_{1,t}^i\left[1-\frac{1}{2}\varphi_1^i\left(\frac{I_{1,t}}{I_{1,t-1}}-1\right)^2\right]+ \\ & q_{1,t}Z_{1,t}^i I_{1,t}\varphi_1^i\left(\frac{I_{1,t}}{I_{1,t-1}}-1\right)\frac{1}{I_{1,t-1}}- \\ & \beta_1\frac{P_{1,t+1}^i\lambda_{1,t+1}^c}{P_{1,t}^i\lambda_{1,t}^c}q_{1,t+1}Z_{1,t+1}^i I_{1,t+1}\varphi_1^i\left(\frac{I_{1,t+1}}{I_{1,t}}-1\right)\frac{I_{1,t+1}}{\left(I_{1,t}\right)^2} \end{aligned} \tag{B19}$$

where:

$$q_{1,t}=\frac{Q_{1,t}}{P_{1,t}^i\lambda_{1,t}^c}$$

and $Q_{1,t}$ is the Lagrange multiplier associated with the capital accumulation equation. The linearized equation is given by:

$$\hat{q}_{1,t}=\varphi_1^i\left(\hat{\imath}_{1,t}-\hat{\imath}_{1,t-1}\right)-\varphi_1^i\beta_1\left(\hat{\imath}_{1,t+1}-\hat{\imath}_{1,t}\right)-\hat{z}_{1,t}^i \tag{B20}$$

The first order condition for $K_{1,t}$ is:

$$
\begin{aligned}
q_{1,t} &= \beta_1 \frac{\lambda^q_{1,t+1}}{\lambda^q_{1,t}} \frac{P^d_{1,t}}{P^i_{1,t}} \frac{R^k_{1,t+1}}{P^d_{1,t+1}} \\
&\quad + \beta_1 (1-\delta_1)\, q_{1,t+1} \frac{P^i_{1,t+1}}{P^d_{1,t+1}} \frac{P^d_{1,t}}{P^i_{1,t}} \frac{\lambda^q_{1,t+1}}{\lambda^q_{1,t}}
\end{aligned} \tag{B21}
$$

The linearized equation is given by:

$$
\begin{aligned}
\hat{q}_{1,t} &= \hat{\lambda}^q_{1,t+1} - \hat{\lambda}^q_{1,t} + (1-(1-\delta_1)\beta_1) \left(\hat{r}^k_{1,t+1} - \left[\frac{\hat{P}^i}{\hat{P}^d} \right]_{1,t} \right) \\
&\quad + (1-\delta_1\beta_1) \left(\hat{q}_{1,t+1} \left[\frac{\hat{P}^i}{\hat{P}^d} \right]_{1,t+1} - \left[\frac{\hat{P}^i}{\hat{P}^d} \right]_{1,t} \right)
\end{aligned} \tag{B22}
$$

The linearized capital accumulation equation is:

$$
\hat{k}_{1,t} = (1-\delta_1)\, \hat{k}_{1,t-1} + \delta_1 \left(\hat{z}^i_{1,t} + \hat{\imath}_{1,t} \right) \tag{B23}
$$

Firms - Production of Consumption Goods. The consumption basket equation is:

$$
C_{1,t} = \left((\omega^{cc}_1)^{\frac{\rho^o_1}{1+\rho^o_1}} \left(C^{ne}_{1,t} \right)^{\frac{1}{1+\rho^o_1}} + (\omega^{oc}_1)^{\frac{\rho^o_1}{1+\rho^o_1}} \left(Z^o_{1,t} O^c_{1,t} \right)^{\frac{1}{1+\rho^o_1}} \right)^{1+\rho^o_1} \tag{B24}
$$

the linearized equation is given by:

$$
\hat{c}_{1,t} = \omega^{cc}_1 \hat{c}^{ne}_{1,t} + \omega^{oc}_1 \left(\hat{o}^c_{1,t} + \hat{z}^o_{1,t} \right) \tag{B25}
$$

The non-oil consumption aggregate equation is:

$$
C^{ne}_{1,t} = \left((\omega^c_1)^{\frac{\rho^c_1}{1+\rho^c_1}} \left(C^d_{1,t} \right)^{\frac{1}{1+\rho^c_1}} + (\omega^{mc}_1)^{\frac{\rho^c_1}{1+\rho^c_1}} \left(Z^m_{1,t} M^c_{1,t} \right)^{\frac{1}{1+\rho^c_1}} \right)^{1+\rho^c_1} \tag{B26}
$$

the linearized equation is given by:

$$\hat{c}_{1,t}^{ne} = \omega_1^c \hat{c}_{1,t}^d + \omega_1^{mc}\left(\hat{m}_{1,t}^c + \hat{z}_{1,t}^m\right) \tag{B27}$$

The first order condition for $C_{1,t}^d$ in the consumption basket equation is:

$$\frac{P_{1,t}^c}{P_{1,t}^d}\left(\omega_1^{cc}\frac{C_{1,t}}{C_{1,t}^{ne}}\right)^{\frac{\rho_1^o}{1+\rho_1^o}}\left(\omega_1^c\frac{C_{1,t}^{ne}}{C_{1,t}^d}\right)^{\frac{\rho_1^c}{1+\rho_1^c}} = 1 \tag{B28}$$

the linearized equation is given by:

$$\left[\frac{\hat{P}^c}{\hat{P}^d}\right]_{1,t} = -\frac{\rho_1^o}{1+\rho_1^o}\left(\hat{c}_{1,t} - \hat{c}_{1,t}^{ne}\right) - \frac{\rho_1^c}{1+\rho_1^c}\left(\hat{c}_{1,t}^{ne} - \hat{c}_{1,t}^d\right) \tag{B29}$$

The first order condition for $M_{1,t}^c$ in the consumption basket equation is:

$$\frac{P_{1,t}^m}{P_{1,t}^d} = \frac{P_{1,t}^c}{P_{1,t}^d}\left(\omega_1^{cc}\frac{C_{1,t}}{C_{1,t}^{ne}}\right)^{\frac{\rho_1^o}{1+\rho_1^o}}\left(\omega_1^c\frac{C_{1,t}^{ne}}{Z_{1,t}^m M_{1,t}^c}\right)^{\frac{\rho_1^c}{1+\rho_1^c}} Z_{1,t}^m \tag{B30}$$

the linearized equation is given by:

$$\begin{aligned}\left[\frac{\hat{P}^m}{\hat{P}^d}\right]_{1,t} &= \left[\frac{\hat{P}^c}{\hat{P}^d}\right]_{1,t} + \frac{\rho_1^o}{1+\rho_1^o}\left(\hat{c}_{1,t} - \hat{c}_{1,t}^{ne}\right) \\ &\quad + \frac{\rho_1^c}{1+\rho_1^c}\left(\hat{c}_{1,t}^{ne} - \hat{m}_{1,t}^c - \hat{z}_{1,t}^m\right) + \hat{z}_{1,t}^m\end{aligned} \tag{B31}$$

The first order condition for $O_{1,t}^c$ in the consumption basket equation is:

$$\frac{P_{1,t}^o}{P_{1,t}^d} = \frac{P_{1,t}^c}{P_{1,t}^d}\left(\omega_1^{cc}\frac{C_{1,t}}{Z_{1,t}^o O_{1,t}^c}\right)^{\frac{\rho_1^o}{1+\rho_1^o}} Z_{1,t}^o \tag{B32}$$

the linearized equation is given by:

$$\left[\frac{\hat{P}^o}{\hat{P}^d}\right]_{1,t} = \left[\frac{\hat{P}^c}{\hat{P}^d}\right]_{1,t} + \frac{\rho_1^o}{1+\rho_1^o}\left(\hat{c}_{1,t} - \hat{o}_{1,t}^c - \hat{z}_{1,t}^o\right) + \hat{z}_{1,t}^o \tag{B33}$$

Firms - Production of Investment Goods. The investment basket equation is:

$$I_{1,t} = \left(\left(\omega_1^i\right)^{\frac{\rho_1^c}{1+\rho_1^c}} \left(I_{1,t}^d\right)^{\frac{1}{1+\rho_1^c}} + \left(\omega_1^{mi}\right)^{\frac{\rho_1^c}{1+\rho_1^c}} \left(Z_{1,t}^m M_{1,t}^i\right)^{\frac{1}{1+\rho_1^c}} \right)^{1+\rho_1^c} \tag{B34}$$

the linearized equation is given by:

$$\hat{\imath}_{1,t} = \omega_1^i \hat{\imath}_{1,t}^d + \omega_1^{mi} \left(\hat{m}_{1,t}^i + \hat{z}_{1,t}^m\right) \tag{B35}$$

The first order condition for $I_{1,t}^d$ in the investment basket equation is:

$$\frac{P_{1,t}^i}{P_{1,t}^d} \left(\omega_1^i \frac{I_{1,t}}{I_{1,t}^d}\right)^{\frac{\rho_1^c}{1+\rho_1^c}} = 1 \tag{B36}$$

the linearized equation is given by:

$$\left[\frac{\hat{P}^i}{\hat{P}^d}\right]_{1,t} = -\frac{\rho_1^c}{1+\rho_1^c} \left(\hat{\imath}_{1,t} - \hat{\imath}_{1,t}^d\right) \tag{B37}$$

The first order condition for $M_{1,t}^i$ in the investment basket equation is:

$$\frac{P_{1,t}^m}{P_{1,t}^d} = \frac{P_{1,t}^i}{P_{1,t}^d} \left(\omega_1^{mi} \frac{I_{1,t}}{Z_{1,t}^m M_{1,t}^i}\right)^{\frac{\rho_1^c}{1+\rho_1^c}} Z_{1,t}^m \tag{B38}$$

the linearized equation is given by:

$$\left[\frac{\hat{P}^m}{\hat{P}^d}\right]_{1,t} = \left[\frac{\hat{P}^i}{\hat{P}^d}\right]_{1,t} + \frac{\rho_1^c}{1+\rho_1^c} \left(\hat{\imath}_{1,t} - \hat{m}_{1,t}^i - \hat{z}_{1,t}^m\right) + \hat{z}_{1,t}^m \tag{B39}$$

Firms - Production of Domestic Intermediate Goods. The value added aggregate production function is:

$$V_{1,t}(i) = \left(\left(\omega_1^k\right)^{\frac{\rho_1^v}{1+\rho_1^v}} \left(K_{1,t-1}\right)^{\frac{1}{1+\rho_1^v}} + \left(\omega_1^l\right)^{\frac{\rho_1^v}{1+\rho_1^v}} \left(Z_{1,t}L_{1,t}\right)^{\frac{1}{1+\rho_1^v}} \right)^{1+\rho_1^v} \tag{B40}$$

the linearized equation is given by:

$$\hat{v}_{1,t} = \phi_1^k \hat{k}_{1,t-1} + \phi_1^l \left(\hat{l}_{1,t} + \hat{z}_{1,t}\right) \tag{B41}$$

where:

$$\phi_1^k = \left(\omega_1^k\right)^{\frac{\rho_1^v}{1+\rho_1^v}} \left(\frac{(K_1)^{SS}}{(V_1)^{SS}} \right)^{\frac{1}{1+\rho_1^v}} \tag{B42}$$

$$\phi_1^l = \left(\omega_1^l\right)^{\frac{\rho_1^v}{1+\rho_1^v}} \left(\frac{(L_1)^{SS}}{(V_1)^{SS}} \right)^{\frac{1}{1+\rho_1^v}} \tag{B43}$$

and:

$$\phi_1^k + \phi_1^l = 1$$

The gross output aggregate production function is:

$$Y_{1,t} = \left(\left(\omega_1^{vy}\right)^{\frac{\rho_1^o}{1+\rho_1^o}} \left(V_{1,t}\right)^{\frac{1}{1+\rho_1^o}} + \left(\omega_1^{oy}\right)^{\frac{\rho_1^o}{1+\rho_1^o}} \left(Z_{1,t}^o O_{1,t}^y\right)^{\frac{1}{1+\rho_1^o}} \right)^{1+\rho_1^o} \tag{B44}$$

the linearized equation is given by:

$$\hat{y}_{1,t} = \omega_1^{vy} \hat{v}_{1,t} + \omega_1^{oy} \left(\hat{o}_{1,t}^y + \hat{z}_{1,t}^o\right) \tag{B45}$$

The first order condition for $K_{1,t-1}$ in the output aggregator:

$$\frac{R_{1,t}^k}{P_{1,t}^d} = \frac{MC_{1,t}}{P_{1,t}^d} \left(\omega_1^{vy} \frac{Y_{1,t}}{V_{1,t}} \right)^{\frac{\rho_1^o}{1+\rho_1^o}} \left(\omega_1^k \frac{V_{1,t}}{K_{1,t-1}} \right)^{\frac{\rho_1^v}{1+\rho_1^v}} \tag{B46}$$

the linearized equation is given by:

$$r^k_{1,t} = m\hat{c}_{1,t} + \frac{\rho^o_1}{1+\rho^o_1}\left(\hat{y}_{1,t} - \hat{v}_{1,t}\right) - \frac{\rho^v_1}{1+\rho^v_1}\left(\hat{v}_{1,t} - \hat{k}_{1,t-1}\right) \tag{B47}$$

The first order condition for $L_{1,t}$ in the output aggregator:

$$\frac{W_{1,t}}{P^d_{1,t}} = \frac{MC_{1,t}}{P^d_{1,t}}\left(\omega^{vy}_1\frac{Y_{1,t}}{V_{1,t}}\right)^{\frac{\rho^o_1}{1+\rho^o_1}}\left(\omega^l_1\frac{V_{1,t}}{Z_{1,t}L_{1,t}}\right)^{\frac{\rho^v_1}{1+\rho^v_1}} Z_{1,t} \tag{B48}$$

the linearized equation is given by:

$$\begin{aligned}\hat{w}_{1,t} &= m\hat{c}_{1,t} + \frac{\rho^o_1}{1+\rho^o_1}\left(\hat{y}_{1,t} - \hat{v}_{1,t}\right) + \\ &\quad \frac{\rho^v_1}{1+\rho^v_1}\left(\hat{v}_{1,t} - \hat{l}_{1,t} - \hat{z}_{1,t}\right) + \hat{z}_{1,t}\end{aligned} \tag{B49}$$

The first order condition for $O^y_{1,t}$ in the output aggregator:

$$\frac{P^o_{1,t}}{P^d_{1,t}} = \frac{MC_{1,t}}{P^d_{1,t}}\left(\omega^{oy}_1\frac{Y_{1,t}}{Z^o_{1,t}O^y_{1,t}}\right)^{\frac{\rho^o_1}{1+\rho^o_1}} Z^o_{1,t} \tag{B50}$$

the linearized equation is given by:

$$\left[\frac{\hat{P}^o}{\hat{P}^d}\right]_{1,t} = m\hat{c}_{1,t} + \frac{\rho^o_1}{1+\rho^o_1}\left(\hat{y}_{1,t} - \hat{o}^y_{1,t} - \hat{z}^o_{1,t}\right) + \hat{z}^o_{1,t} \tag{B51}$$

Evolution of the Marginal Cost. If prices are flexible:

$$\frac{MC_{1,t}}{P^d_{1,t}} = \frac{1}{1+\theta^p_{1,t}} \tag{B52}$$

the linearized equation is given by:

$$m\hat{c}_{1,t} = -\frac{1}{1+(\theta^p_1)^{SS}}\hat{\theta}^p_{1,t} \tag{B53}$$

If prices are sticky, the profit maximization problem of firms that are allowed to reoptimize their prices at time t can be expressed as:

$$\max_{\left\{P_{1,t}^{d}(i)\right\}} E_t \sum_{j=0}^{\infty} \left(\xi_1^p\right)^j \psi_{1,t,t+j} \left[\begin{array}{c} \pi_{1,t,,j}^{d} P_{1,t}^{d}\left(i\right) Y_{1,t+j}\left(i\right) - \\ MC_{1,t+j} Y_{1,t+j}\left(i\right) \end{array} \right] \tag{B54}$$

$$s.t \quad : \quad Y_{1,t}\left(i\right) = \left(\frac{P_{1,t}^{d}\left(i\right)}{P_{1,t}^{d}}\right)^{-\frac{1+\theta_1^p}{\theta_1^p}} Y_{1,t}^{d} \tag{B55}$$

$$and \quad : \quad \pi_{1,t,,j}^{d} = \prod_{s=1}^{j} \left\{ \left(\pi_{1,t-1+s}^{d}\right)^{\iota_1^p} \left(\pi_1^{SS}\right)^{1-\iota_1^p} \right\} \tag{B56}$$

the first order condition is given by:

$$E_t \sum_{j=0}^{\infty} \Xi_{1,t+j}^{p} \left[\begin{array}{c} \frac{P_{1,t}^{d}(i)}{P_{1,t}^{d}} \frac{1}{\theta_{1,t+j}^{p}} - \\ \frac{MC_{1,t+J}}{P_{1,t+J}^{d}} \left(\frac{P_{1,t}^{d}(i)\pi_{1,t,,j}^{d}}{P_{1,t+j}^{d}}\right) \frac{1+\theta_{1,t+j}^{p}}{\theta_{1,t+j}^{p}} \end{array} \right] = 0 \tag{B57}$$

where:

$$\Xi_{1,t+j}^{p} = \left(\xi_1^p \beta_1\right)^j \frac{\lambda_{1,t+j}^{c}}{\lambda_{1,t}^{c}} \left(\frac{P_{1,t}^{d}\pi_{1,t,,j}^{d}}{P_{1,t+j}^{d}}\right)^{-\frac{1}{\theta_{1,t+j}^{p}}} \left(\frac{P_{1,t}^{d}\left(i\right)}{P_{1,t}^{d}}\right)^{-\frac{1+\theta_{1,t+j}^{p}}{\theta_{1,t+j}^{p}}} Y_{1,t+j}^{d} \tag{B58}$$

The linearized equation is given by:

$$\begin{aligned} \frac{1}{\pi_1^{SS}} \left(\hat{\pi}_{1,t}^{d} - \iota_1^p \hat{\pi}_{1,t-1}^{d}\right) &= \frac{\beta_1}{\pi_1^{SS}} \left(\hat{\pi}_{1,t+1}^{d} - \iota_1^p \hat{\pi}_{1,t}^{d}\right) \\ &+ \frac{\left(1-\xi_1^p\beta_1\right)\left(1-\xi_1^p\right)}{\xi_1^p} \left(m\hat{c}_{1,t} + \frac{\left(\theta_1^p\right)^{SS}}{1+\left(\theta_1^p\right)^{SS}} \hat{\theta}_{1,t}^{p}\right) \end{aligned} \tag{B59}$$

where:

$$\frac{1}{\pi_1^{SS}} \left(\hat{\pi}_{1,t}^{d} - \iota_1^p \hat{\pi}_{1,t-1}^{d}\right) = \hat{\pi}_{1,t}^{d} - \iota_1^p \hat{\pi}_{1,t-1}^{d} \tag{B60}$$

Remaining Relations. The market clearing condition for the domestic non-oil goods market is:

$$Y_{1,t}^{d}=C_{1,t}^{d}+I_{1,t}^{d}+X_{1,t} \tag{B61}$$

the linearized equation is given by:

$$\hat{y}_{1,t}^{d}=\frac{\left(C_{1}^{d}\right)^{SS}}{\left(Y_{1}^{d}\right)^{SS}}\hat{c}_{1,t}^{d}+\frac{\left(I_{1}^{d}\right)^{SS}}{\left(Y_{1}^{d}\right)^{SS}}\hat{\imath}_{1,t}^{d}+\frac{\left(X_{1}\right)^{SS}}{\left(Y_{1}^{d}\right)^{SS}}\hat{x}_{1,t} \tag{B62}$$

The oil demand equation is:

$$O_{1,t}=O_{1,t}^{y}+O_{1,t}^{c} \tag{B63}$$

the linearized equation is given by:

$$\hat{o}_{1,t}=\frac{\left(O_{1}^{y}\right)^{SS}}{\left(O_{1}\right)^{SS}}\hat{o}_{1,t}^{y}+\frac{\left(O_{1}^{c}\right)^{SS}}{\left(O_{1}\right)^{SS}}\hat{o}_{1,t}^{c} \tag{B64}$$

The nominal interest rate is:

$$\frac{1}{R_{1,t}^{s}}=\beta_{1}\frac{\lambda_{1,t+1}^{q}}{\lambda_{1,t}^{q}}\frac{P_{1,t}^{d}}{P_{1,t+1}^{d}} \tag{B65}$$

The relative linearized equation is given by:

$$\hat{r}_{1,t}^{s}=-\left(\hat{\lambda}_{1,t+1}^{q}-\hat{\lambda}_{1,t}^{q}\right)+\hat{\pi}_{1,t+1}^{d} \tag{B66}$$

Thus the real interest rate is:

$$\hat{r}_{1,t}^{rs}=\hat{r}_{1,t}^{s}-\hat{\pi}_{1,t+1}^{d}=-\left(\hat{\lambda}_{1,t+1}^{q}-\hat{\lambda}_{1,t}^{q}\right) \tag{B67}$$

The Taylor rule is:

$$\begin{aligned} i_{1,t} &= \bar{\imath}_{1}+\gamma_{1}^{i}\left(i_{1,t-1}-\bar{\imath}_{1}\right)+ \\ &\quad \left(1-\gamma_{1}^{i}\right)\left[\left(\pi_{1,t}^{core}-\bar{\pi}_{1}^{core}\right)+\gamma_{1}^{\pi}\left(\pi_{1,t}^{core}-\bar{\pi}_{1}^{core}-\bar{\pi}_{1,t}^{core}\right)+\gamma_{1}^{y}y_{1,t}^{gap}\right] \end{aligned} \tag{B68}$$

where:

$$i_{1,t} = R^s_{1,t} - 1 \tag{B69}$$

the linearized equation is given by:

$$\hat{r}^s_{1,t} = \gamma^i_1 \hat{r}^s_{1,t-1} + \left(1 - \gamma^i_1\right) \left[\hat{\pi}^{core}_{1,t} + \gamma^\pi_1 \left(\hat{\pi}^{core}_{1,t} - \bar{\pi}^{core}_{1,t}\right) + \gamma^y_1 \hat{y}^{gap}_{1,t}\right] \tag{B70}$$

The core price level $P^{ne}_{1,t}$ is given by:

$$P^{ne}_{1,t} = P^c_{1,t} \left(\omega^{cc}_1 \frac{C_{1,t}}{C^{ne}_{1,t}}\right)^{\frac{\rho^o_1}{1+\rho^o_1}} \tag{B71}$$

the linearized expression is given by:

$$\begin{aligned} \left[\frac{\hat{P}^{ne}}{\hat{P}^d}\right]_{1,t} &= \left[\frac{\hat{P}^c}{\hat{P}^d}\right]_{1,t} + \frac{\rho^o_1}{1+\rho^o_1}\left(\hat{c}_{1,t} - \hat{c}^{ne}_{1,t}\right) \\ &= \frac{1}{\omega^{cc}_1}\left[\frac{\hat{P}^c}{\hat{P}^d}\right]_{1,t} - \frac{\omega^{oc}_1}{\omega^{cc}_1}\left(\left[\frac{\hat{P}^o}{\hat{P}^d}\right]_{1,t} - \hat{z}^o_{1,t}\right) \end{aligned} \tag{B72}$$

As we can note from expression (B72) the shock to oil intensity enters since it affects the headline price $\hat{P}^c_{1,t}$.

The inflation of domestic prices is given by:

$$\pi^d_{1,t} = \log\left(\frac{P^d_{1,t}}{P^d_{1,t-1}}\right) \tag{B73}$$

the linearized equation is given by:

$$\hat{\pi}^d_{1,t} = \hat{p}^d_{1,t} - \hat{p}^d_{1,t-1} \tag{B74}$$

The inflation of core prices is given by:

$$\pi^{core}_{1,t} = \log\left(\frac{P^{ne}_{1,t}}{P^{ne}_{1,t-1}}\right) \tag{B75}$$

the linearized equation is given by:

$$\hat{\pi}^{core}_{1,t} = \left[\frac{\hat{P}^{ne}}{\hat{P}^{d}}\right]_{1,t} - \left[\frac{\hat{P}^{ne}}{\hat{P}^{d}}\right]_{1,t-1} + \hat{\pi}^{d}_{1,t} \tag{B76}$$

The inflation of headline prices is given by:

$$\pi^{head}_{1,t} = \log\left(\frac{P^{c}_{1,t}}{P^{c}_{1,t-1}}\right) \tag{B77}$$

the linearized equation is given by:

$$\hat{\pi}^{head}_{1,t} = \left[\frac{\hat{P}^{c}}{\hat{P}^{d}}\right]_{1,t} - \left[\frac{\hat{P}^{c}}{\hat{P}^{d}}\right]_{1,t-1} + \hat{\pi}^{d}_{1,t} \tag{B78}$$

The equation for aggregate imports is given by:

$$M_{1,t} = \frac{P^{m}_{1,t}}{P^{d}_{1,t}} M^{c}_{1,t} + \frac{P^{m}_{1,t}}{P^{d}_{1,t}} M^{i}_{1,t} \tag{B79}$$

the linearized expression is given by:

$$\hat{m}_{1,t} = \frac{(M^{c}_{1})^{SS}}{(M_{1})^{SS}} \left(\left[\frac{\hat{P}^{m}}{\hat{P}^{d}}\right]_{1,t} + \hat{m}^{c}_{1,t}\right) + \frac{(M^{i}_{1})^{SS}}{(M_{1})^{SS}} \left(\left[\frac{\hat{P}^{m}}{\hat{P}^{d}}\right]_{1,t} + \hat{m}^{i}_{1,t}\right) \tag{B80}$$

because relative prices are assumed to be 1 in the steady state.

The equation for aggregate exports is given by:

$$X_{1,t} = \frac{\zeta_2}{\zeta_1}\left(M^{c}_{2,t} + M^{i}_{2,t}\right) \tag{B81}$$

because country 1 real per capita exports, $X_{1,t}$, and country 2 real per capita imports, $M_{2,t}$, are related by the relative population weight, $\frac{\zeta_2}{\zeta_1}$.

The linearized expression is given by:

$$\hat{x}_{1,t} = \frac{(M^{c}_{2})^{SS}}{(M^{c}_{2})^{SS} + (M^{i}_{2})^{SS}} \hat{m}^{c}_{2,t} + \frac{(M^{i}_{2})^{SS}}{(M^{c}_{2})^{SS} + (M^{i}_{2})^{SS}} \hat{m}^{i}_{2,t} \tag{B82}$$

The ratio between total trade balance and gross output is given by:

$$\frac{T^{bal}_{1,t}}{P^{d}_{1,t}Y^{d}_{1,t}} = \frac{X_{1,t} - M_{1,t} + \frac{P^{o}_{1,t}}{P^{d}_{1,t}}\left(Y^{o}_{1,t} - O_{1,t}\right)}{Y^{d}_{1,t}} \tag{B83}$$

the linearized equation is given by:

$$\begin{aligned} \hat{t}^{bal}_{1,t} \quad = \quad & \frac{(X_1)^{SS}}{\left(Y^d_1\right)^{SS}}\hat{x}_{1,t} - \frac{(M_1)^{SS}}{\left(Y^d_1\right)^{SS}}\hat{m}_{1,t} + \frac{(P^o_1)^{SS}\,(Y^o_1)^{SS}}{\left(P^d_1\right)^{SS}\left(Y^d_1\right)^{SS}}\hat{y}^{o}_{1,t} \\ & -\frac{(P^o_1)^{SS}\,(O_1)^{SS}}{\left(P^d_1\right)^{SS}\left(Y^d_1\right)^{SS}}\hat{o}_{1,t} - \frac{(P^o_1)^{SS}\left[(O_1)^{SS} - (Y^o_1)^{SS}\right]}{\left(P^d_1\right)^{SS}\left(Y^d_1\right)^{SS}}\left[\frac{\hat{P}^o}{\hat{P}^d}\right]_{1,t} \end{aligned} \tag{B84}$$

The ratio between non-oil goods trade balance and gross output is given by:

$$\frac{G^{bal}_{1,t}}{P^{d}_{1,t}Y^{d}_{1,t}} = \frac{X_{1,t} - M_{1,t}}{Y^{d}_{1,t}} \tag{B85}$$

the linearized equation is given by:

$$\hat{g}^{bal}_{1,t} = \frac{(X_1)^{SS}}{\left(Y^d_1\right)^{SS}}\hat{x}_{1,t} - \frac{(M_1)^{SS}}{\left(Y^d_1\right)^{SS}}\hat{m}_{1,t} + \left[\frac{(X_1)^{SS}}{\left(Y^d_1\right)^{SS}} - \frac{(M_1)^{SS}}{\left(Y^d_1\right)^{SS}}\right]\hat{y}^{d}_{1,t} \tag{B86}$$

B.1.2 Bilateral Relations

For country 1, the relative import prices can be expressed as follows:

$$\frac{P^{m}_{1,t}}{P^{d}_{1,t}} = \frac{e_{1,t}P^{c}_{2,t}}{P^{c}_{1,t}}\frac{P^{d}_{2,t}}{P^{c}_{2,t}}\frac{P^{c}_{1,t}}{P^{d}_{1,t}} \tag{B87}$$

where $e_{1,t}$ is the nominal exchange rate. Considering that the consumption real exchange rate is:

$$rer_{1,t} = \frac{e_{1,t}P^{c}_{2,t}}{P^{c}_{1,t}} \tag{B88}$$

the linearized expression for (B87) is given by:

$$\left[\frac{\hat{P}^m}{\hat{P}^d}\right]_{1,t} = r\hat{e}r_{1,t} - \left[\frac{\hat{P}^c}{\hat{P}^d}\right]_{2,t} + \left[\frac{\hat{P}^c}{\hat{P}^d}\right]_{1,t} \tag{B89}$$

For country 2, the linearized expression for the relative import prices is given by:

$$\left[\frac{\hat{P}^m}{\hat{P}^d}\right]_{2,t} = -r\hat{e}r_{1,t} + \left[\frac{\hat{P}^c}{\hat{P}^d}\right]_{2,t} - \left[\frac{\hat{P}^c}{\hat{P}^d}\right]_{1,t} \tag{B90}$$

The uncovered interest rate parity condition is:

$$\frac{\lambda^q_{2,t+1}}{\lambda^q_{2,t}} \frac{P^d_{2,t}}{P^c_{2,t}} \frac{P^c_{2,t+1}}{P^d_{2,t+1}} = \phi^b_{1,t} \frac{rer_{1,t+1}}{rer_{1,t}} \frac{\lambda^q_{1,t+1}}{\lambda^q_{1,t}} \frac{P^d_{1,t}}{P^c_{1,t}} \frac{P^c_{1,t+1}}{P^d_{1,t+1}} \tag{B91}$$

the linearized equation is given by:

$$\begin{aligned}\left(\hat{\lambda}^q_{2,t+1} - \hat{\lambda}^q_{2,t}\right) &= \left(\hat{\lambda}^q_{1,t+1} - \hat{\lambda}^q_{1,t}\right) + \phi^b_1 \hat{b}^f_{1,t} + r\hat{e}r_{1,t+1} - r\hat{e}r_{1,t} \\ &- \left[\frac{\hat{P}^c}{\hat{P}^d}\right]_{1,t} + \left[\frac{\hat{P}^c}{\hat{P}^d}\right]_{1,t+1} + \left[\frac{\hat{P}^c}{\hat{P}^d}\right]_{2,t} - \left[\frac{\hat{P}^c}{\hat{P}^d}\right]_{2,t+1}\end{aligned} \tag{B92}$$

The net foreign asset condition is:

$$\begin{aligned}\frac{e_{1,t}\left(P^b_{2,t}\right)^{-1} B_{1,t}}{\phi^b_{1,t}} &= e_{1,t}B_{1,t-1} + \frac{\zeta_2}{\zeta_1} e_{1,t} P^m_{2,t}\left(M^c_{2,t} + M^i_{2,t}\right) \\ &-P^m_{1,t}\left(M^c_{1,t} + M^i_{1,t}\right) + P^o_{1,t}\left(Y^o_{1,t} - O_{1,t}\right)\end{aligned} \tag{B93}$$

the linearized equation is given by:

$$\beta_1 \hat{b}_{1,t} = \hat{b}_{1,t-1} + \hat{t}^{bal}_{1,t} \tag{B94}$$

where:

$$\hat{b}_{1,t} = \frac{e_{1,t}B_{1,t}}{P^d_{1,t}Y^d_{1,t}} \tag{B95}$$

The oil market clearing condition is:

$$Y_{1,t}^{o}+\frac{\zeta_2}{\zeta_1}Y_{2,t}^{o}=O_{1,t}+\frac{\zeta_2}{\zeta_1}O_{2,t} \tag{B96}$$

the linearized equation is given by:

$$\begin{aligned} & \frac{\frac{\zeta_1}{\zeta_2}\left(Y_1^o\right)^{SS}}{\frac{\zeta_1}{\zeta_2}\left(Y_1^o\right)^{SS}+\left(Y_2^o\right)^{SS}}\hat{y}_{1,t}^{o}+\frac{\left(Y_2^o\right)^{SS}}{\frac{\zeta_1}{\zeta_2}\left(Y_1^o\right)^{SS}+\left(Y_2^o\right)^{SS}}\hat{y}_{2,t}^{o} \\ = \; & \frac{\frac{\zeta_1}{\zeta_2}\left(O_1\right)^{SS}}{\frac{\zeta_1}{\zeta_2}\left(O_1\right)^{SS}+\left(O_2\right)^{SS}}\hat{o}_{1,t}+\frac{\left(O_2\right)^{SS}}{\frac{\zeta_1}{\zeta_2}\left(O_1\right)^{SS}+\left(O_2\right)^{SS}}\hat{o}_{2,t} \end{aligned} \tag{B97}$$

The law of one price for oil is:

$$\frac{P_{1,t}^{o}}{P_{1,t}^{d}}=rer_{1,t}\frac{P_{1,t}^{c}}{P_{1,t}^{d}}\frac{P_{2,t}^{d}}{P_{2,t}^{c}}\frac{P_{2,t}^{o}}{P_{2,t}^{d}} \tag{B98}$$

the linearized equation is given by:

$$\left[\frac{\hat{P}^{o}}{\hat{P}^{d}}\right]_{1,t}=\hat{rer}_{1,t}+\left[\frac{\hat{P}^{c}}{\hat{P}^{d}}\right]_{1,t}-\left[\frac{\hat{P}^{c}}{\hat{P}^{d}}\right]_{2,t}+\left[\frac{\hat{P}^{o}}{\hat{P}^{d}}\right]_{2,t} \tag{B99}$$

B.1.3 Important Definitions

The definition of $GDP_{1,t}$ using Laspeyres index is:

$$GDP_{1,t}=GDP_{1,t-1}\frac{P_{1,t-1}^{d}Y_{1,t}-P_{1,t-1}^{o}O_{1,t}^{y}+P_{1,t-1}^{o}Y_{1,t}^{o}}{P_{1,t-1}^{d}Y_{1,t-1}-P_{1,t-1}^{o}O_{1,t-1}^{y}+P_{1,t-1}^{o}Y_{1,t-1}^{o}} \tag{B100}$$

the linearized equation is given by:

$$\begin{aligned}
& \left(1-\frac{\left(P_1^o\right)^{SS}\left(O_1^y\right)^{SS}}{\left(P_1^d\right)^{SS}\left(Y_1^d\right)^{SS}}+\frac{\left(P_1^o\right)^{SS}\left(Y_1^o\right)^{SS}}{\left(P_1^d\right)^{SS}\left(Y_1^d\right)^{SS}}\right) \\
& \left(g\hat{d}p_{1,t}-g\hat{d}p_{1,t-1}\right)-\left(\hat{y}_{1,t}-\hat{y}_{1,t-1}\right) \\
= \quad & -\left(\frac{\left(P_1^o\right)^{SS}\left(O_1^y\right)^{SS}}{\left(P_1^d\right)^{SS}\left(Y_1^d\right)^{SS}}\right)\left(\hat{o}_{1,t}^y-\hat{o}_{1,t-1}^y\right) \\
& +\left(\frac{\left(P_1^o\right)^{SS}\left(Y_1^o\right)^{SS}}{\left(P_1^d\right)^{SS}\left(Y_1^d\right)^{SS}}\right)\left(\hat{y}_{1,t}^o-\hat{y}_{1,t-1}^o\right)
\end{aligned} \tag{B101}$$

The ratio between nominal GDP and nominal gross output is:

$$\frac{NGDP_{1,t}}{P_{1,t}^d Y_{1,t}}=1-\frac{P_{1,t}^o O_{1,t}^y}{P_{1,t}^d Y_{1,t}}+\frac{P_{1,t}^o Y_{1,t}^o}{P_{1,t}^d Y_{1,t}} \tag{B102}$$

the linearized equation is given by:

$$\begin{aligned}
& \frac{\left(NGDP_1\right)^{SS}}{\left(P_1^d\right)^{SS}\left(Y_1^d\right)^{SS}}\left[\frac{NG\hat{D}P}{\hat{P}^d\hat{Y}}\right]_{1,t} \\
= \quad & \left(\frac{\left(P_1^o\right)^{SS}\left(O_1^y\right)^{SS}}{\left(P_1^d\right)^{SS}\left(Y_1^d\right)^{SS}}-\frac{\left(P_1^o\right)^{SS}\left(Y_1^o\right)^{SS}}{\left(P_1^d\right)^{SS}\left(Y_1^d\right)^{SS}}\right)\left(\hat{y}_{1,t}-\left[\frac{\hat{P}^o}{\hat{P}^d}\right]_{1,t}\right) \\
& -\frac{\left(P_1^o\right)^{SS}\left(O_1^y\right)^{SS}}{\left(P_1^d\right)^{SS}\left(Y_1^d\right)^{SS}}\hat{o}_{1,t}^y+\frac{\left(P_1^o\right)^{SS}\left(O_1^y\right)^{SS}}{\left(P_1^d\right)^{SS}\left(Y_1^d\right)^{SS}}\hat{y}_{1,t}^o
\end{aligned} \tag{B103}$$

The equation for the oil price deflated by the GDP deflator is:

$$\frac{P_{1,t}^o}{P_{1,t}^{GDP}}\frac{P_{1,t}^{GDP}}{P_{1,t-1}^o}=\frac{P_{1,t}^o}{P_{1,t}^d}\frac{P_{1,t-1}^d}{P_{1,t-1}^o}\frac{\frac{NGDP_{1,t-1}}{P_{1,t-1}^d Y_{1,t-1}}}{\frac{NGDP_{1,t}}{P_{1,t}^d Y_{1,t}}}\frac{GDP_{1,t}}{GDP_{1,t-1}}\frac{Y_{1,t-1}}{Y_{1,t}} \tag{B104}$$

the linearized equation is given by:

$$\log\left(\left[\frac{P^{o}_{1,t}}{P^{GDP}_{1,t}}\right]^{obs}\right)-\log\left(\left[\frac{P^{o}_{1,t-1}}{P^{GDP}_{1,t-1}}\right]^{obs}\right) \tag{B105}$$
$$= -\left(\left[\frac{NG\hat{D}P}{\hat{P}^{d}\hat{Y}}\right]_{1,t}-\left[\frac{NG\hat{D}P}{\hat{P}^{d}\hat{Y}}\right]_{1,t-1}\right)-\left(\hat{y}_{1,t}-\hat{y}_{1,t-1}\right)$$
$$+\left[\frac{\hat{P}^{o}}{\hat{P}^{d}}\right]_{1,t}-\left[\frac{\hat{P}^{o}}{\hat{P}^{d}}\right]_{1,t-1}+g\hat{d}p_{1,t}-g\hat{d}p_{1,t-1}$$

The ratio between the total trade balance and nominal GDP is:

$$\frac{T^{bal}_{1,t}}{NGDP_{1,t}}=\frac{T^{bal}_{1,t}}{P^{d}_{1,t}Y_{1,t}}\frac{P^{d}_{1,t}Y_{1,t}}{NGDP_{1,t}} \tag{B106}$$

the linearized equation is given by:

$$\left[\frac{\hat{T}^{bal}}{NG\hat{D}P}\right]_{1,t}=\frac{\left(P^{d}_{1}\right)^{SS}\left(Y^{d}_{1}\right)^{SS}}{\left(NGDP_{1}\right)^{SS}}\hat{t}^{bal}_{1,t} \tag{B107}$$

The ratio between the non-oil goods trade balance and nominal GDP is:

$$\frac{G^{bal}_{1,t}}{NGDP_{1,t}}=\frac{1}{\frac{NGDP_{1,t}}{P^{d}_{1,t}Y_{1,t}}}\left(\frac{X_{1,t}}{Y_{1,t}}-\frac{P^{d}_{1,t}}{P^{d}_{1,t}}\frac{M_{1,t}}{Y_{1,t}}\right) \tag{B108}$$

the linearized equation is given by:

$$\left[\frac{\hat{G}^{bal}}{NG\hat{D}P}\right]_{1,t} = -\frac{1}{\frac{\left(NGDP_{1}\right)^{SS}}{\left(P^{d}_{1}\right)^{SS}\left(Y_{1}\right)^{SS}}}\left(\frac{\left(X_{1}\right)^{SS}}{\left(Y^{d}_{1}\right)^{SS}}-\frac{\left(P^{d}_{1}\right)^{SS}\left(M_{1}\right)^{SS}}{\left(P^{d}_{1}\right)^{SS}\left(Y_{1}\right)^{SS}}\right) \tag{B109}$$
$$\left[\frac{NG\hat{D}P}{\hat{P}^{d}\hat{Y}}\right]_{1,t}+\frac{1}{\frac{\left(NGDP_{1}\right)^{SS}}{\left(P^{d}_{1}\right)^{SS}\left(Y_{1}\right)^{SS}}}\hat{g}^{bal}_{1,t}$$

B.1.4 Observation Equations

In what follows we denote by $X_{i,t}^{obs}$ the observed data series associated with a given linearized variable, $\hat{x}_{i,t}$. We start listing the observation equations for country 1.

The observation equation for GDP is:

$$\log\left(GDP_{1,t}^{obs}\right) - \log\left(GDP_{1,t-1}^{obs}\right) = g\hat{d}p_{1,t} - g\hat{d}p_{1,t-1} \tag{B110}$$

The observation equation for oil production is:

$$\log\left(Y_{1,t}^{o,obs}\right) - \log\left(Y_{1,t-1}^{o,obs}\right) = \hat{y}_{1,t}^{o} - \hat{y}_{1,t-1}^{o} \tag{B111}$$

The observation equation for oil imports as share of nominal GDP is:

$$\begin{aligned}\frac{OIL\ IMP_{1,t}^{obs}}{NGDP_{1,t}^{obs}} &= \frac{\left(P_1^d\right)^{SS}\left(Y_1^d\right)^{SS}}{\left(NGDP_1\right)^{SS}}\left(\frac{\left(O_1\right)^{SS}}{\left(Y_1^d\right)^{SS}} - \frac{\left(Y_1^o\right)^{SS}}{\left(Y_1^d\right)^{SS}}\right) \\ &\quad \left[-\left[\frac{NG\hat{D}P}{\hat{P}^d\hat{Y}}\right]_{1,t} + \left[\frac{\hat{P}^o}{\hat{P}^d}\right]_{1,t} - \hat{y}_{1,t}\right] \\ &\quad + \frac{\left(P_1^d\right)^{SS}\left(Y_1^d\right)^{SS}}{\left(NGDP_1\right)^{SS}}\left(\frac{\left(O_1\right)^{SS}}{\left(Y_1^d\right)^{SS}}\hat{o}_{1,t} - \frac{\left(Y_1^o\right)^{SS}}{\left(Y_1^d\right)^{SS}}\hat{y}_{1,t}^{o}\right)\end{aligned} \tag{B112}$$

The observation equation for the real oil price is:

$$\log\left(\left[\frac{P_{1,t}^o}{P_{1,t}^{GDP}}\right]^{obs}\right) - \log\left(\left[\frac{P_{1,t-1}^o}{P_{1,t-1}^{GDP}}\right]^{obs}\right) = \left[\frac{\hat{P}^o}{\hat{P}^{GDP}}\right]_{1,t} - \left[\frac{\hat{P}^o}{\hat{P}^{GDP}}\right]_{1,t-1} \tag{B113}$$

The observation equation for non-oil imports as share of nominal GDP is:

$$\begin{aligned}\frac{NONOIL\ IMP_{1,t}^{obs}}{NGDP_{1,t}^{obs}} &= \frac{\left(P_1^d\right)^{SS}\left(M_1\right)^{SS}}{\left(P_1^d\right)^{SS}\left(Y_1^d\right)^{SS}}\frac{\left(NGDP_1\right)^{SS}}{\left(P_1^d\right)^{SS}\left(Y_1^d\right)^{SS}} \\ &\quad \left(\hat{m}_{1,t} - \hat{y}_{1,t} - \left[\frac{NG\hat{D}P}{\hat{P}^d\hat{Y}}\right]_{1,t}\right)\end{aligned} \tag{B114}$$

The observation equation for non-oil exports as share of nominal GDP is:

$$\frac{NONOIL\ EXP^{obs}_{1,t}}{NGDP^{obs}_{1,t}} = \frac{\left(P^d_1\right)^{SS}(X_1)^{SS}}{\left(P^d_1\right)^{SS}\left(Y^d_1\right)^{SS}}\frac{(NGDP_1)^{SS}}{\left(P^d_1\right)^{SS}\left(Y^d_1\right)^{SS}} \left(\hat{x}_{1,t} - \hat{y}_{1,t} - \left[\frac{NG\hat{D}P}{\hat{P}^d\hat{Y}}\right]_{1,t}\right) \tag{B115}$$

The observation equation for the real exchange rate is:

$$rer^{obs}_{1,t} = r\hat{e}r_{1,t} \tag{B116}$$

The observation equation for consumption as share of nominal GDP is:

$$\frac{CONS^{obs}_{1,t}}{NGDP^{obs}_{1,t}} = \frac{\left(P^c_1\right)^{SS}(C_1)^{SS}}{\left(P^d_1\right)^{SS}\left(Y^d_1\right)^{SS}}\frac{(NGDP_1)^{SS}}{\left(P^d_1\right)^{SS}\left(Y^d_1\right)^{SS}} \left(\hat{c}_{1,t} + \left[\frac{\hat{P}^c}{\hat{P}^d}\right]_{1,t} - \hat{y}_{1,t} - \left[\frac{NG\hat{D}P}{\hat{P}^d\hat{Y}}\right]_{1,t}\right) \tag{B117}$$

The observation equation for total gross fixed capital formation as share of nominal GDP is:

$$\frac{INV^{obs}_{1,t}}{NGDP^{obs}_{1,t}} = \frac{\left(P^i_1\right)^{SS}(I_1)^{SS}}{\left(P^d_1\right)^{SS}\left(Y^d_1\right)^{SS}}\frac{(NGDP_1)^{SS}}{\left(P^d_1\right)^{SS}\left(Y^d_1\right)^{SS}} \left(\hat{\imath}_{1,t} + \left[\frac{\hat{P}^i}{\hat{P}^d}\right]_{1,t} - \hat{y}_{1,t} - \left[\frac{NG\hat{D}P}{\hat{P}^d\hat{Y}}\right]_{1,t}\right) \tag{B118}$$

The observation equation for core price inflation is:

$$\pi^{core,obs}_{1,t} = \hat{\pi}^{core}_{1,t} \tag{B119}$$

The observation equation for wage inflation is:

$$\omega^{obs}_{1,t} = \hat{\omega}_{1,t} \tag{B120}$$

The observation equation for nominal interest rate is:

$$r_{1,t}^{b,obs} = \hat{r}_{1,t}^{b} \tag{B121}$$

For country 2 the observation equations are the following.

The observation equation for GDP is:

$$\log\left(GDP_{2,t}^{obs}\right) - \log\left(GDP_{2,t-1}^{obs}\right) = g\hat{d}p_{2,t} - g\hat{d}p_{2,t-1} \tag{B122}$$

The observation equation for oil production is:

$$\log\left(Y_{2,t}^{o,obs}\right) - \log\left(Y_{2,t-1}^{o,obs}\right) = \hat{y}_{2,t}^{o} - \hat{y}_{2,t-1}^{o} \tag{B123}$$

B.1.5 Decomposition of the Marginal Costs

As we derived above, from the profit maximization problem of firms producing intermediate domestic goods we have that:

$$\phi_1^k = \left(\omega_1^k\right)^{\frac{\rho_1^v}{1+\rho_1^v}} \left(\frac{(K_1)^{SS}}{(V_1)^{SS}}\right)^{\frac{1}{1+\rho_1^v}} \tag{B124}$$

$$\phi_1^l = \left(\omega_1^l\right)^{\frac{\rho_1^v}{1+\rho_1^v}} \left(\frac{(L_1)^{SS}}{(V_1)^{SS}}\right)^{\frac{1}{1+\rho_1^v}} \tag{B125}$$

and:

$$\phi_1^k + \phi_1^l = 1$$

Thus, recasting (B124) and (B125), respectively:

$$\phi_1^k = \omega_1^k \left(\frac{sharek y_1}{\omega_1^k sharev y_1}\right)^{\frac{1}{1+\rho_1^v}} \tag{B126}$$

$$\phi_1^l = \omega_1^l \left(\frac{sharel y_1}{\omega_1^l sharev y_1}\right)^{\frac{1}{1+\rho_1^v}} \tag{B127}$$

and:

$$\phi_1^k + \phi_1^l = 1$$

The marginal products of oil, capital and labour are respectively:

$$m\hat{p}o_{1,t} = \frac{\rho_1^o}{1+\rho_1^o}\left(\hat{y}_{1,t} - \hat{o}_{1,t}^y - \hat{z}_{1,t}^o\right) + \hat{z}_{1,t}^o \tag{B128}$$

$$m\hat{p}k_{1,t} = \frac{\rho_1^o}{1+\rho_1^o}\left(\hat{y}_{1,t} - \hat{v}_{1,t}\right) + \frac{\rho_1^v}{1+\rho_1^v}\left(\hat{v}_{1,t} - \hat{k}_{1,t-1}\right) \tag{B129}$$

$$m\hat{p}l_{1,t} = \frac{\rho_1^o}{1+\rho_1^o}\left(\hat{y}_{1,t} - \hat{v}_{1,t}\right) + \frac{\rho_1^v}{1+\rho_1^v}\left(\hat{v}_{1,t} - \hat{l}_{1,t} - \hat{z}_{1,t}\right) + \hat{z}_{1,t} \tag{B130}$$

and from the first order conditions:

$$\left[\frac{\hat{P}^o}{\hat{P}^d}\right]_{1,t} = m\hat{c}_{1,t} + m\hat{p}o_{1,t} \tag{B131}$$

$$\hat{r}_{1,t}^k = m\hat{c}_{1,t} + m\hat{p}k_{1,t} \tag{B132}$$

$$\hat{w}_{1,t} = m\hat{c}_{1,t} + m\hat{p}l_{1,t} \tag{B133}$$

Multiplying equation (B131) by ω_1^{oy}, equation (B132) by $\omega_1^{vy}\phi_1^k$, and equation (B133) by $\omega_1^{vy}\left(1-\phi_1^k\right)$, and summing up these three equations we have that:

$$\begin{aligned} m\hat{c}_{1,t} = {} & \omega_1^{oy}\left(\left[\frac{\hat{P}^o}{\hat{P}^d}\right]_{1,t} - m\hat{p}o_{1,t}\right) \\ & +\omega_1^{vy}\phi_1^k\left(\hat{r}_{1,t}^k - m\hat{p}k_{1,t}\right) \\ & +\omega_1^{vy}\left(1-\phi_1^k\right)\left(\hat{w}_{1,t} - m\hat{p}l_{1,t}\right) \end{aligned} \tag{B134}$$

where:

$$\omega_1^{oy} + \omega_1^{vy}\phi_1^k + \omega_1^{vy}\left(1-\phi_1^k\right) = 1$$

B.1.6 Calibrated Parameters

As we explained in the main body of the paper, some of the parameter values are taken from observed data means. In what follows we describe the relative expressions associated with these values.

The share of nominal oil demand on nominal gross output is:

$$shareoy_1 = \frac{(P_1^o)^{SS}(O_1)^{SS}}{\left(P_1^d\right)^{SS}\left(Y_1^d\right)^{SS}} = \frac{(O_1)^{SS}}{\left(Y_1^d\right)^{SS}} \tag{B135}$$

because the real price of oil is assumed to be 1 in steady state.

The ratio between oil used in production and oil used in consumption is:

$$ratiooyoc_1 = \frac{(P_1^o)^{SS}(O_1^y)^{SS}}{\left(P_1^d\right)^{SS}(O_1^c)^{SS}} = \frac{(O_1^y)^{SS}}{(O_1^c)^{SS}} \tag{B136}$$

The share of investment on gross output is:

$$shareiy_1 = \frac{\left(I_1^d\right)^{SS}}{\left(Y_1^d\right)^{SS}} \tag{B137}$$

The share of government spending on gross output is:

$$sharegy_1 = \frac{\left(G_1^d\right)^{SS}}{\left(Y_1^d\right)^{SS}} \tag{B138}$$

The ratio between oil production and oil demand is:

$$ratioyoo_1 = \frac{(Y_1^o)^{SS}}{(O_1)^{SS}} \tag{B139}$$

The share of imports on gross output is:

$$sharemy_1 = \frac{(M_1)^{SS}}{\left(Y_1^d\right)^{SS}} \tag{B140}$$

The ratio between imports of investment goods and imports of consumption goods is:

$$ratioyoo_1 = \frac{(M_1^i)^{SS}}{(M_1^c)^{SS}} \tag{B141}$$

Finally, we assume that the weight of labour in the value added production function is:

$$\omega_1^l = 1 \tag{B142}$$

B.1.7 Composite Parameters

Given the parameter values taken from observed data means and the expressions listed above, we can derive the remaining parameters as follows.

The share of hours worked is:

$$labshare_1 = \frac{L_1^{SS}}{1 - L_1^{SS}} \tag{B143}$$

The weight of oil input in the overall output production function is:

$$\omega_1^{oy} = \frac{(O_1^y)^{SS}}{\left(Y_1^d\right)^{SS}} = shareoyy_1 \tag{B144}$$

The weight of value added input in the overall output production function is:

$$\omega_1^{vy} = 1 - \omega_1^{oy} = \frac{(V_1)^{SS}}{\left(Y_1^d\right)^{SS}} = sharevy_1 \tag{B145}$$

The real rental rate in steady state is:

$$\left(r_1^k\right)^{SS} = \frac{1}{\beta_1} - 1 + \delta_1 \tag{B146}$$

The share of capital on gross output is:

$$\frac{(K_1)^{SS}}{\left(Y_1^d\right)^{SS}} = \frac{1}{\delta_1} shareiy_1 = shareky_1 \tag{B147}$$

The weight of capital in the value added production function is:

$$\omega_1^k = \frac{1}{\delta_1}\left(\frac{1}{\beta_1} - 1 + \delta_1\right)^{\frac{1+\rho_1^v}{\rho_1^v}} \frac{shareiy_1}{sharevy_1} \tag{B148}$$

The share of labour on gross output is:

$$\frac{(L_1)^{SS}}{\left(Y_1^d\right)^{SS}} = sharevy_1 \left(1 - \omega_1^k \left(\left(r_1^k\right)^{SS}\right)^{-\frac{1}{\rho_1^v}}\right)^{1+\rho_1^v} = sharely_1 \tag{B149}$$

The share of nominal consumption on nominal gross output is:

$$\begin{aligned} \frac{(P_1^c)^{SS}(C_1)^{SS}}{\left(P_1^d\right)^{SS}\left(Y_1^d\right)^{SS}} &= 1 - \frac{\left(P_1^d\right)^{SS}(I_1)^{SS}}{\left(P_1^d\right)^{SS}\left(Y_1^d\right)^{SS}} - \frac{\left(P_1^d\right)^{SS}(G_1)^{SS}}{\left(P_1^d\right)^{SS}\left(Y_1^d\right)^{SS}} \\ &\quad + \frac{(P_1^o)^{SS}(Y_1^o)^{SS}}{\left(P_1^d\right)^{SS}\left(Y_1^d\right)^{SS}} - \frac{(P_1^o)^{SS}(O_1^y)^{SS}}{\left(P_1^d\right)^{SS}\left(Y_1^d\right)^{SS}} \\ &= sharecy_1 \end{aligned} \tag{B150}$$

that is:

$$sharecy_1 = 1 - shareiy_1 - sharegy_1 + shareyoy_1 - shareoyy_1 \tag{B151}$$

The weight of oil in the production of consumption goods is:

$$\omega_1^{oc} = \frac{(O_1^c)^{SS}}{(C_1)^{SS}} = shareocc_1 \tag{B152}$$

where:

$$shareocc_1 = \frac{shareoy_1 - shareoyy_1}{sharecy_1} \tag{B153}$$

The weight of non-oil in the production of consumption goods is:

$$\omega_1^{cc} = 1 - \omega_1^{oc} = \frac{(C_1^{ne})^{SS}}{(C_1)^{SS}} \tag{B154}$$

The weight of domestic goods in the production of consumption goods is:

$$\omega_1^c = 1 - \omega_1^{mc} = \frac{\left(C_1^d\right)^{SS}}{\left(C_1^{ne}\right)^{SS}} = sharecdcn_1 \tag{B155}$$

The weight of imported goods in the production of consumption goods is:

$$\omega_1^{mc} = \frac{\left(M_1^c\right)^{SS}}{\left(C_1^{ne}\right)^{SS}} = sharemccn_1 \tag{B156}$$

where:

$$sharemccn_1 = \frac{sharemy_1}{sharecy_1 \cdot sharecnc_1} \frac{1}{1 + ratiomimc_1} \tag{B157}$$

The weight of domestic goods in the production of investment goods is:

$$\omega_1^i = 1 - \omega_1^{mi} = \frac{\left(I_1^d\right)^{SS}}{\left(I_1\right)^{SS}} \tag{B158}$$

The weight of imported goods in the production of investment goods is:

$$\omega_1^{mi} = \frac{\left(M_1^i\right)^{SS}}{\left(I_1\right)^{SS}} = sharemii_1 \tag{B159}$$

where:

$$sharemii_1 = \frac{sharemy_1}{shareiy_1} \frac{ratiomimc_1}{1 + ratiomimc_1} \tag{B160}$$

The share of exports on gross output of country 1 is:

$$\begin{aligned} \frac{\left(P_1^d\right)^{SS}\left(X_1\right)^{SS}}{\left(P_1^d\right)^{SS}\left(Y_1^d\right)^{SS}} &= \frac{\left(P_1^d\right)^{SS}\left(M_1\right)^{SS}}{\left(P_1^d\right)^{SS}\left(Y_1^d\right)^{SS}} \\ &+ \frac{\left(P_1^o\right)^{SS}\left(O_1\right)^{SS}}{\left(P_1^d\right)^{SS}\left(Y_1^d\right)^{SS}} \\ &- \frac{\left(P_1^o\right)^{SS}\left(Y_1^o\right)^{SS}}{\left(P_1^d\right)^{SS}\left(Y_1^d\right)^{SS}} \\ &= sharexy_1 \end{aligned} \tag{B161}$$

or:

$$sharexy_1 = sharemy_1 + shareoy_1 - shareyoy_1 \tag{B162}$$

The share of exports on gross output of country 2 is:

$$\frac{(X_2)^{SS}}{\left(Y_2^d\right)^{SS}} = \frac{(M_2)^{SS}}{\left(Y_2^d\right)^{SS}} - \left(\frac{(O_1)^{SS}}{\left(Y_1^d\right)^{SS}} + \frac{(Y_1^o)^{SS}}{\left(Y_1^d\right)^{SS}}\right) \frac{\left(Y_1^d\right)^{SS}}{\left(Y_2^d\right)^{SS}} \frac{1}{\zeta_2} \tag{B163}$$

or:

$$sharexy_2 = sharemy_2 - (shareoy_1 - shareyoy_1) \frac{\left(Y_1^d\right)^{SS}}{\left(Y_2^d\right)^{SS}} \frac{1}{\zeta_2} \tag{B164}$$

The share of imports on gross output of country 2 is:

$$\begin{aligned} & \frac{\left(P_1^d\right)^{SS} (M_1)^{SS}}{\left(P_1^d\right)^{SS} \left(Y_1^d\right)^{SS}} + \frac{(P_1^o)^{SS} (O_1 - Y_1^o)^{SS}}{\left(P_1^d\right)^{SS} \left(Y_1^d\right)^{SS}} \\ = \; & \frac{(e_1)^{SS} \left(P_2^d\right)^{SS} (M_2)^{SS}}{\left(P_2^d\right)^{SS} \left(Y_2^d\right)^{SS}} \frac{\left(P_2^d\right)^{SS}}{\left(P_1^d\right)^{SS}} \frac{\left(Y_2^d\right)^{SS}}{\left(Y_1^d\right)^{SS}} \zeta_2 \\ = \; & sharemy_2 \end{aligned} \tag{B165}$$

or:

$$sharemy_2 = (sharemy_1 + (shareoy_1 - shareyoy_1)) \frac{\left(Y_1^d\right)^{SS}}{\left(Y_2^d\right)^{SS}} \frac{1}{\zeta_2} \tag{B166}$$

The ratio between nominal GDP and nominal gross output is:

$$\frac{(NGDP_1)^{SS}}{\left(P_1^d\right)^{SS} \left(Y_1^d\right)^{SS}} = 1 - \frac{(P_1^o)^{SS} (O_1^y)^{SS}}{\left(P_1^d\right)^{SS} \left(Y_1^d\right)^{SS}} + \frac{(P_1^o)^{SS} (Y_1^o)^{SS}}{\left(P_1^d\right)^{SS} \left(Y_1^d\right)^{SS}} \tag{B167}$$

or:

$$sharengdpny_1 = 1 - shareoyy_1 + shareyoy_1 \tag{B168}$$

The ratio between gross outputs of country 1 and 2 is:

$$\frac{\left(Y_1^d\right)^{SS}}{\left(Y_2^d\right)^{SS}} = \frac{sharely_2}{sharely_1} \frac{(L_1)^{SS}}{(L_2)^{SS}} \tag{B169}$$

The share in world oil production for country 2 is:

$$\begin{aligned} & \frac{\left(Y_2^o\right)^{SS}}{\frac{\zeta_1}{\zeta_2}\left(Y_1^o\right)^{SS}+\left(Y_2^o\right)^{SS}} \\ = & \frac{\frac{\left(Y_2^o\right)^{SS}}{\left(Y_2^d\right)^{SS}}}{\frac{\zeta_1}{\zeta_2}\frac{\left(Y_1^o\right)^{SS}}{\left(Y_1^d\right)^{SS}}\frac{\left(Y_1^d\right)^{SS}}{\left(Y_2^d\right)^{SS}}+\frac{\left(Y_2^o\right)^{SS}}{\left(Y_2^d\right)^{SS}}} \\ = & \; shareoprod_2 \end{aligned} \tag{B170}$$

or:

$$shareoprod_2 = \frac{shareyoy_2}{\frac{\zeta_1}{\zeta_2} shareyoy_1 \frac{\left(Y_1^d\right)^{SS}}{\left(Y_2^d\right)^{SS}} + shareyoy_2} \tag{B171}$$

The share in world oil consumption for country 2 is:

$$\begin{aligned} & \frac{\left(O_2\right)^{SS}}{\frac{\zeta_1}{\zeta_2}\left(O_1\right)^{SS}+\left(O_2\right)^{SS}} \\ = & \frac{\frac{\left(O_2\right)^{SS}}{\left(Y_2^d\right)^{SS}}}{\frac{\zeta_1}{\zeta_2}\frac{\left(O_1\right)^{SS}}{\left(Y_1^d\right)^{SS}}\frac{\left(Y_1^d\right)^{SS}}{\left(Y_2^d\right)^{SS}}+\frac{\left(O_2\right)^{SS}}{\left(Y_2^d\right)^{SS}}} \\ = & \; shareocons_2 \end{aligned} \tag{B172}$$

or:

$$shareocons_2 = \frac{shareoy_2}{\frac{\zeta_1}{\zeta_2} shareoy_1 \frac{\left(Y_1^d\right)^{SS}}{\left(Y_2^d\right)^{SS}} + shareoy_2} \tag{B173}$$

The overall oil production as share of gross output is:

$$\frac{\left(Y_1^o\right)^{SS}}{\left(Y_1^d\right)^{SS}} = \frac{\left(Y_1^o\right)^{SS}}{\left(O_1\right)^{SS}}\frac{\left(O_1\right)^{SS}}{\left(Y_1^d\right)^{SS}} = shareyoy_1 \tag{B174}$$

or:

$$shareyoy_1 = ratioyoo_1 \cdot shareoy_1 \tag{B175}$$

B.2 Observed Data Construction

As we described in the main body of the paper, we use quarterly data and the model is estimated for the sample period 1990:Q1-2005:Q4 with a pre-sample from 1988:Q1 to 1989:Q4. In this appendix we provide the several sources and construction methods of the observed series. Unless otherwise noted, all original series are seasonally adjusted.

UK GDP. The UK GDP is the log of real UK GDP (code ABMI in ONS Quarterly National Accounts).

Foreign GDP. The foreign GDP is the log of trade-weighted foreign GDP. The data series for real GDPs of the foreign countries are taken from the OECD - Quarterly National Accounts[45]. The countries are: the Euro area, the United States, Japan, Norway, Switzerland, Sweden, Canada, Denmark, Australia and India. These are the most important trading partners of the United Kingdom for the period considered. We follow the paper of Loretan (2005) in order to construct the relative imports/exports weights.

UK crude oil production. The UK crude oil production is the log of the UK crude oil production taken from US Energy Information Administration[46] - Monthly Energy Review - Table 11.1b.

Foreign crude oil production. The foreign crude oil production is the log of foreign crude oil production (calculated as world production net of UK production) taken from US Energy Information Administration[47] - Monthly Energy Review - Table 11.1b.

Real oil price. The real oil price is the log of the Europe Brent Spot Price FOB from the US Energy Information Administration[48] converted from US dollars to Sterling Pounds using the Quarterly Average Forward Exchange Rate, 3 month, US$ into Sterling (code XUQADS3 in Bank of England Statistical Interactive

[45] http://dx.doi.org/10.5257/oecd/na/2012-06.
[46] http://www.eia.gov/totalenergy/data/monthly/#petroleum.
[47] http://www.eia.gov/totalenergy/data/monthly/#petroleum.
[48] http://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=PET&s=RBRTE&f=M.

Database[49]) and deflated by the UK GDP deflator (code YBGB in ONS Quarterly National Accounts).

UK real effective exchange rate. The UK real effective exchange rate is the log of the Quarterly Average Broad Effective Exchange Rate Index, (code XUQABK82 in the Bank of England Statistical Interactive Database[50]).

UK private consumption expenditure. The UK private consumption expenditure is the Household Final Consumption Expenditure at market prices (code ABJQ in ONS Quarterly National Accounts) and it is expressed as share of UK GDP at Market Prices (code YBHA in ONS Quarterly National Accounts).

UK total gross fixed capital formation. The UK total gross fixed capital formation is the total gross fixed capital formation at market prices (code NPQS in ONS Quarterly National Accounts) and it is expressed as share of UK GDP at Market Prices (code YBHA in ONS Quarterly National Accounts).

UK oil imports. The UK oil imports are total oil gross imports (Petroleum - Imports) taken from the US Energy Information Administration[51] - International Energy Statistics, expressed as share of UK GDP using the Europe Brent Spot Price FOB (British Sterling per Barrel) and the UK GDP at Market Prices (code YBHA in ONS Quarterly National Accounts).

UK non-oil goods imports. The UK non-oil goods imports are the Goods Imports at market prices (code BOKH in ONS Quarterly National Accounts) minus the UK oil imports, expressed as share of UK GDP using the UK GDP at Market Prices (code YBHA in ONS Quarterly National Accounts).

UK non-oil goods exports. The UK non-oil goods exports are the Goods Exports at market prices (code BOKG in ONS Quarterly National Accounts) minus the UK oil exports, expressed as share of UK GDP using the UK GDP at

[49] http://www.bankofengland.co.uk/boeapps/iadb/index.asp?first=yes&SectionRequired=I&HideNums=-1&ExtraInfo=true&Travel=NIxIRx.

[50] http://www.bankofengland.co.uk/boeapps/iadb/index.asp?first=yes&SectionRequired=I&HideNums=-1&ExtraInfo=true&Travel=NIxIRx.

[51] http://www.eia.gov/cfapps/ipdbproject/iedindex3.cfm?tid=50&pid=76&aid=3&cid=UK, &syid=1988&eyid=2005&freq=Q&unit=TBPD.

Market Prices (code YBHA in ONS Quarterly National Accounts).

UK core inflation. The UK core inflation is the log change in the Consumer Price Index: All Items Excluding Food and Energy, Index 2010=100 and NSA (Organisation for Economic Co-operation and Development, Code: GBRCPICORMINMEI, retrieved from FRED, Federal Reserve Bank of St. Louis[52]). The series is seasonally adjusted with Eviews.

UK wage inflation. The UK wage inflation obtained from the log change in UK Total Compensation of Employees at Current Prices (Code DTWM in ONS - UK Output, Income and Expenditure Tables; and LF2G in ONS - LFS).

UK nominal interest rate. The UK nominal interest rate is the Quarterly Average Rate of Discount - 3 Month Treasury Bills (Code IUQAAJNB in Bank of England Statistical Interactive Database[53]).

[52] https://research.stlouisfed.org/fred2/series/GBRCPICORMINMEI/.

[53] http://www.bankofengland.co.uk/boeapps/iadb/index.asp?first=yes&SectionRequired=I&HideNums=-1&ExtraInfo=true&Travel=NIxIRx.

B.3 Data Used to Construct the Steady State Parameters for the UK and Foreign Bloc

As we discussed in the main body of the paper, the steady state parameters of the UK and the foreign country are constructed using observed data. In this appendix we show the data sources for each bloc.

B.3.1 Average Ratios for the UK Economy

Unless otherwise noted, the average ratios are computed for the period 1990-2005.

The UK oil share on nominal gross output is defined as:

$$shareoy = \frac{GVA - GVA\ excl\ Oil\ and\ Gas}{GVA} \tag{B176}$$

where GVA is the total gross value added at basic prices (Code ABMM in ONS) and $GVA\ excl\ Oil\ and\ Gas$ is the gross value added excluding oil and gas at basic prices (Code KLS2 in ONS). Due to data availability for these two series we consider the sample period 1997-2005.

The ratio between oil used in production and oil used in consumption is defined as:

$$ratiooyoc = \frac{O^y}{O^c} \tag{B177}$$

where O^y is the total supply of products at purchasers' prices of coke and refined petroleum products (taken from ONS Input-Output Tables). O^c is the households final consumption expenditure of coke and refined petroleum products (taken ONS Input-Output Tables). Due to data availability for these two series we consider the sample period 1992-2004.

The share of investment on GDP is defined as:

$$shareiy = \frac{I}{Y} \tag{B178}$$

where I is the real total gross fixed capital formation (Code NPQT in ONS) and

Y is the real gross domestic product (Code ABMI in ONS).

The share of government spending on GDP is defined as:

$$sharegy = \frac{G}{Y} \tag{B179}$$

where G is the general government final consumption expenditure (Code NMRY in ONS).

The ratio between oil production and oil demand is defined as:

$$ratioyoo = \frac{Y^o}{O} \tag{B180}$$

where Y^o is the crude oil production of the United Kingdom (taken from the US Energy Information Administration - Monthly Energy Review - Table 11.1b) and O is the petroleum consumption of United Kingdom (taken from the US Energy Information Administration - Monthly Energy Review - Table 11.2).

The share of imports on GDP is defined as:

$$sharemy = \frac{M}{Y} \tag{B181}$$

where M are the real imports of goods and services (Code IKBL in ONS).

The ratio between imports of investment goods and imports of consumption goods is defined as:

$$ratioyoo = \frac{M^i}{M^c} \tag{B182}$$

where M^i are total imports of services (Code IKBC in ONS) and M^c are total imports of goods (Code IKBI in ONS).

Finally, ζ_1 is the sum of the total population of United Kingdom (taken from OECD - Quarterly National Accounts).

B.3.2 Average Ratios for the Foreign Bloc

In order to aggregate data for the foreign countries we use the Loretan (2005) technique. In particular, we proceed as follows. Firstly, from the Direction of Trade Statistics database of the International Monetary Fund we compute the average of imports/exports between the UK and foreign countries for the period 1990-2005. Secondly, we select the major UK trading partners. Specifically, they are the Euro Area, the United States, China, Japan, Sweden, Switzerland, Norway, Canada, Denmark, Australia, India, Saudi Arabia and United Arab Emirates. The average of imports/exports of the UK with this group of countries corresponds to 80% of total UK trade. Thirdly, we compute the average ratios for the foreign bloc by aggregating their data series through the weighted average for the period 1990-2005.

Unless otherwise noted, the average ratios are computed for the period 1990-2005.

Due to data availability in order to construct foreign oil share we only consider the Euro Area and the United States. The Euro Area and the US oil shares on their nominal gross outputs are defined as:

$$shareoy = \frac{Petroleum\ Items\ Exp}{GDP} \tag{B183}$$

For the Euro Area, $Petroleum\ Items\ Exp$ is the sum of crude petroleum and natural gas expenditures and coke, refined petroleum products and nuclear fuels expenditures (taken from Eurostat Input-Output Tables). GDP is the nominal gross domestic product (taken from the Eurostat interactive database). Due to data availability the sample period is 2000-2008.

For the US, $Petroleum\ Items\ Exp$ is the sum of natural gas expenditures and petroleum expenditures (taken from the Annual Energy Outlook of US EIA). GDP is the nominal gross domestic product (taken from FRED).

Due to data availability in order to construct ratio between oil used in production and oil used in consumption we only consider the Euro Area and the

United States. This ratio is defined as:

$$ratiooyoc = \frac{O^y}{O^c} \tag{B184}$$

For the Euro Area, O^y is the total use at basic prices of coke, refined petroleum products and nuclear fuel (taken from the Eurostat Input-Output Tables). O^c is the final consumption expenditure at basic prices of coke, refined petroleum products and nuclear fuel (taken from the Eurostat Input-Output Tables). Due to the availability of these two series we consider the sample period 2000-2005.

For the US, O^y is the total commodity output of petroleum and coal products (taken from the Bureau of Economic Analysis Input-Output Tables). O^c is the personal consumption expenditures of petroleum and coal products (taken from Bureau of Economic Analysis Input-Output Tables). Due to the availability of these two series we consider the sample period 1998-2005.

The share of investment on GDP for foreign countries is defined as:

$$shareiy = \frac{I}{Y} \tag{B185}$$

For the Euro Area, the United States, Japan, Sweden, Switzerland, Norway, Canada, Denmark, Australia and India, I is the gross fixed capital formation (taken from OECD - Quarterly National Accounts) whereas Y is the gross domestic product (taken from OECD - Quarterly National Accounts).

For China (sample period 1998-2005), Saudi Arabia and the United Arab Emirates, I is the gross fixed capital formation (Code 93E.ZF in International Financial Statistics - IMF) whereas Y is the gross domestic product (Code 99B.ZF in International Financial Statistics - IMF).

The share of government spending on GDP for foreign countries is defined as:

$$sharegy = \frac{G}{Y} \tag{B186}$$

For the Euro Area, the United States, Japan, Sweden, Switzerland, Norway, Canada, Denmark, Australia and India, G is the general government final consumption expenditure (taken from OECD - Quarterly National Accounts) whereas Y is the gross domestic product (taken from OECD - Quarterly National Accounts).

For China (sample period 1998-2005), Saudi Arabia and the United Arab Emirates, G is the government consumption expenditure (Code 91F.ZF in International Financial Statistics - IMF) whereas Y is the gross domestic product (Code 99B.ZF in International Financial Statistics - IMF).

The ratio between oil production and oil demand for the foreign bloc is defined as:

$$ratioyoo = \frac{Y^o}{O} \tag{B187}$$

For the Euro Area, the United States, China, Japan, Sweden, Switzerland, Norway, Canada, Denmark, Australia, India, Saudi Arabia and the United Arab Emirates, Y^o is petroleum production (taken from the US Energy Information Administration - International Energy Statistics) whereas O is the petroleum consumption (taken from the US Energy Information Administration - International Energy Statistics).

The ratio between imports of investment goods and imports of consumption goods for the foreign bloc is defined as:

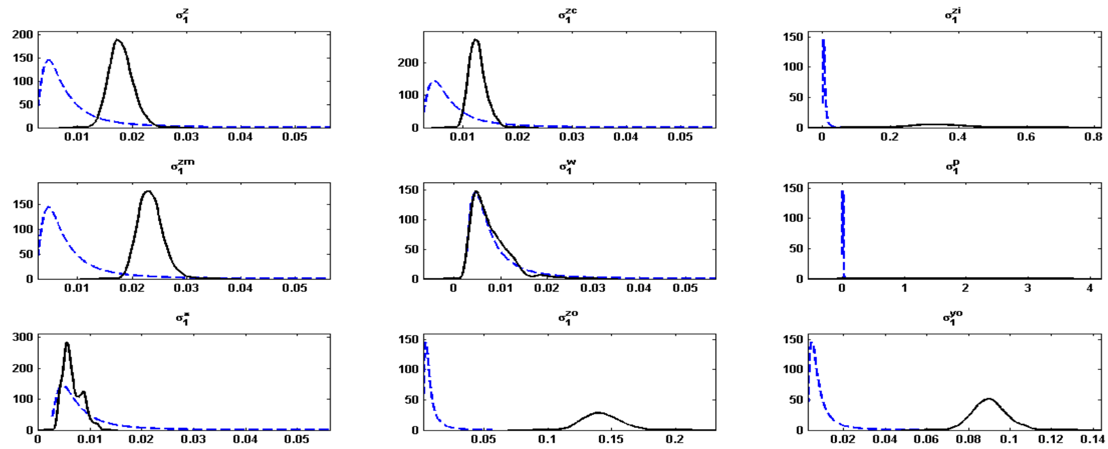
$$ratioyoo = \frac{M^i}{M^c} \tag{B188}$$

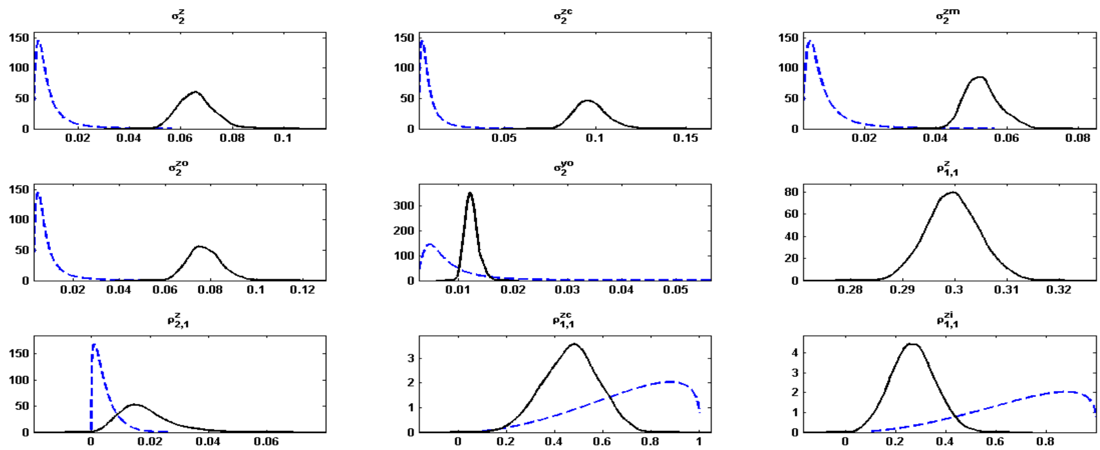
For the Euro Area, the United States, Japan, Sweden, Switzerland, Norway, Canada, Denmark, Australia and India, M^i is the series of imports of goods (taken from OECD - Quarterly National Accounts) whereas M^c is the series of imports of services (taken from OECD - Quarterly National Accounts).

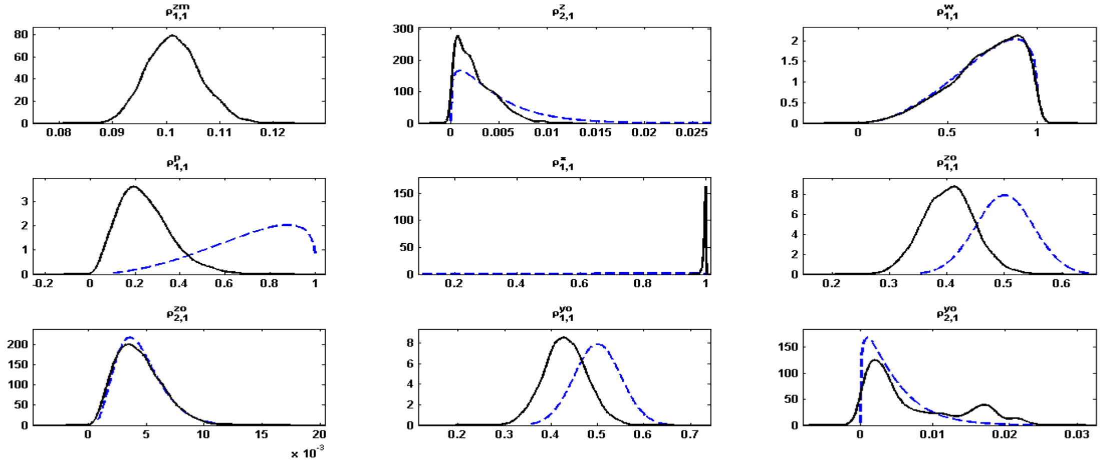
Finally, ζ_2 is the sum of the total population of the Euro Area, the United States, China, Japan, Sweden, Switzerland, Norway, Canada, Denmark, Australia, India, Saudi Arabia and United Arab Emirates (taken from OECD - Quarterly National Accounts).

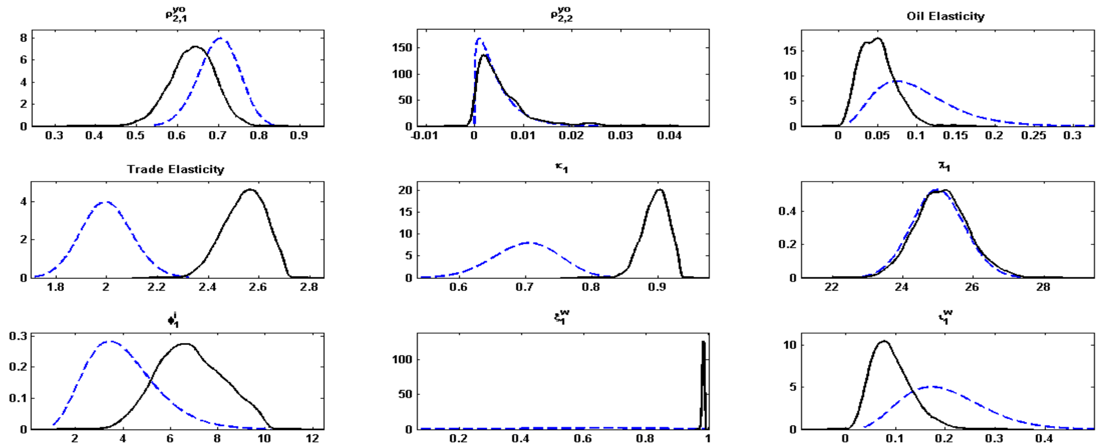
B.4 Prior and Posterior Parameters Distributions

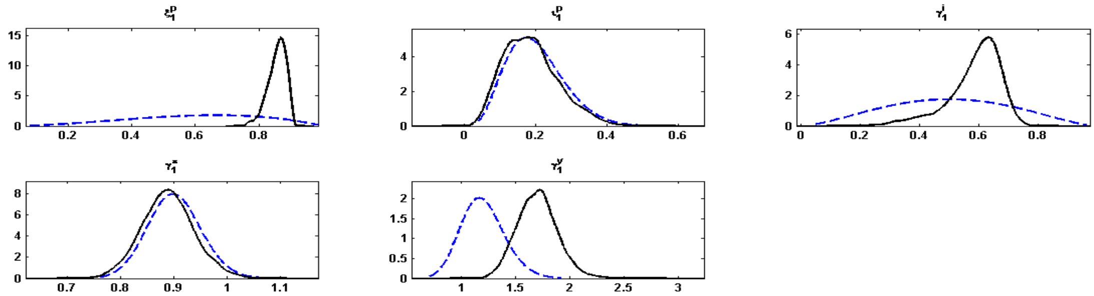
In the following figures, prior distributions correspond to dashed blue lines whereas posterior distributions correspond to solid blue black lines.



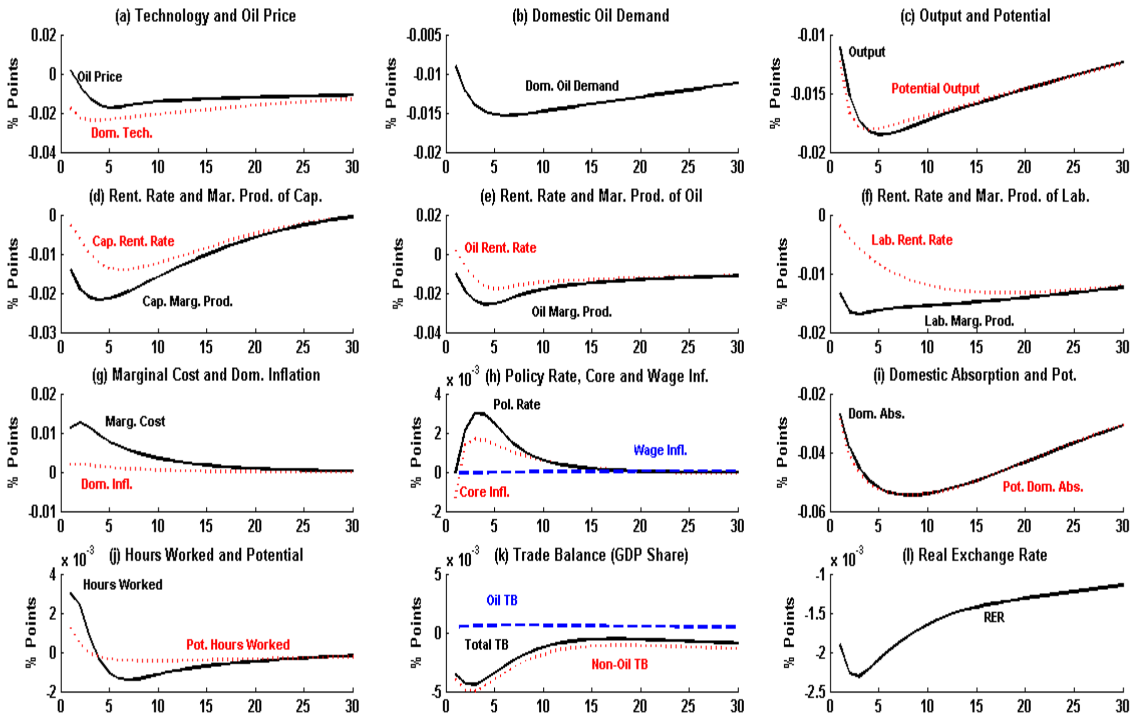





Oil Elasticity
Trade Elasticity



B.5 IRFs: Negative Domestic Technology Shock



Chapter 3: Oil Price Shocks and the UK Fiscal Regime, 1990-2005

3.1 Introduction

In the previous chapter we found that foreign oil intensity shock, foreign oil supply shock and foreign technology shock were important for the evolution of the UK macroeconomy. However, although we allowed monetary policy to operate, we effectively ignored fiscal policy. This was an important omission and in the present chapter we rectify our analysis. Therefore, in the present paper, we develop and estimate an open economy DSGE model in order to evaluate the economic repercussions and fiscal policy responses to oil price fluctuations in the UK economy. Our model is estimated with Bayesian techniques over the period 1990-2005. This sample choice encapsulates the "Non-Inflationary, Consistently Expansionary" (NICE) decade[54] and corresponds to the period in which the UK was a net oil exporter.

Our theoretical framework is in line with the papers of Bodenstein and Guerrieri (2011) and Bodenstein et al. (2012) and assumes the endogenous determination of real oil price and a world economy model in a new Keynesian framework. From a theoretical point of view our paper presents two main contributions with respect to these two papers. Firstly, we assume that domestic households and firms face several distortive taxes that affect their respective behaviours. In this regard, our paper follows the extensive literature on DSGE modelling and fiscal policy (see, among the others, Coenen et al., 2008; Forni et al. 2009; Strulik and Trimborn, 2012; Cogan et al., 2013). Secondly, we set up a detailed fiscal sector which includes several policy rules for these distortive taxes. In this regard, following the paper of Leeper et al. (2009), we employ Bayesian techniques in order to estimate these fiscal policy rules.

[54] According to the definition of King (2003).

We estimate our open economy DSGE model using observed data for the United Kingdom and the rest of the world. In particular, we construct the time series for the foreign bloc using the Loretan (2005) method.

In line with the results of the previous chapter, we find that foreign oil demand and supply shocks explain most of the variation of the UK oil price. Moreover, we find a significant effect of foreign technology shock on the UK oil price variation.

We contribute to existing literature by showing that foreign oil intensity shock contributes significantly to the variation of the UK government debt. The main reason is that foreign oil intensity shock is the most relevant source of the UK oil price fluctuation. Accordingly, relevant changes in oil price imply more volatile oil tax and fuel duty revenues and, in turn, government debt.

Our estimated fiscal rules extend previous literature by showing that the fuel duty tax responds moderately to the UK oil demand whereas the response of the petroleum revenue tax to oil price changes is stronger.

In general, our impulse response analysis confirms that, the effects of an oil price decrease are similar to those following a positive productivity shock. In particular, we find an increase in UK GDP and its major components. Similarly, domestic hours worked tend to increase in response to the reduction of oil price. Moreover, we observe a decline in domestic core inflation that induces monetary authority to loosen its policy rate. Therefore, these results are in line with the findings of the impulse response analysis presented in Chapter 2.

As concerns the external sector, in contrast to the results of Chapter 2, we find that a positive foreign oil intensity shock induces a depreciation of the UK currency. Indeed, the response of UK taxation to this shock stimulates domestic consumption reducing the price of domestic consumption goods with respect to imported goods. In line with the results of Chapter 2, our model predicts a depreciation of the Pound in response to a positive foreign oil supply shock and a negative foreign technology shock. Moreover, we find that the reduction of oil price implies a worsening of the UK oil goods balance since it is a net oil exporter.

In turn, this reduction induces a deterioration of the UK overall trade balance.

We compare our estimates of the fiscal impact of oil shocks with contemporary estimates of leading forecasters, including the HM Treasury, the National Institute of Economic and Social Research (for more details see Powell and Horton, 1985; Hall et al., 1986; Young, 2000; OECD Economic Surveys, 2002; OBR report, 2010; Barrell et al., 2011a and 2011b). In general, we find that domestic public finances suffer in a scenario of low oil price although overall economy improves; the domestic government debt actually increases. In particular, the direct negative effect on petroleum revenue tax, VAT and fuel duty tax receipts more than offset the indirect positive effect on the other tax revenues. In turn, this implies that domestic public finances deteriorate in response to low oil prices. Thus, for instance, following a positive shock to foreign oil intensity, UK government debt increases by £700 millions during the first year and it reaches £1100 millions in four years.

Our results are different from what the HM Treasury and the NIESR found because they did not take into account the several sources of oil price shocks. Secondly, these studies did not estimate directly the persistence of the exogenous shocks affecting the oil price. Thirdly, in their analysis, the HM Treasury and the NIESR were not able to estimate the UK price elasticity of oil demand. Lastly, the HM Treasury and the NIESR did not distinguish between the cases of actual and potential economy.

The rest of this paper is organized as follows. Section 2 presents the theoretical model describing the several sectors of our open economy DSGE model. Section 3 outlines the data used in order to estimate the model, the parameters set up and the estimation results. In Section 4, we quantify the effects of oil price fluctuations on UK public finances. Section 5 presents some of the impulse response functions of our estimated model. Section 6 concludes.

3.2 Model

3.2.1 The Representative Household

The representative household maximizes its lifetime utility function by choosing purchases of the consumption good, $C_{1,t}$, purchases of the investment good, $I_{1,t}$, capital stock, $K_{1,t}$, next period's holdings of both domestic government bonds, $B_{1,t}$, and foreign government bonds, $B^{f}_{1,t}$, given the following intertemporal utility function:

$$E_t \left\{ \sum_{j=0}^{\infty} \beta_1^j \left[\begin{array}{c} \frac{1}{1-\sigma_1} \left(Z^c_{1,t} C_{1,t+j} - \kappa_1 C_{1,t+j-1} \right)^{1-\sigma_1} + \\ \frac{1}{1-\chi_1} \left(1 - L_{1,t+j}\right)^{1-\chi_1} \end{array} \right] \right\} \tag{3.1}$$

where E_t is expectation operator at time t and β_1^j is the discount factor. As we can note from equation (3.1), the representative household consumption, is influenced by the presence of external habit, κ_1, related to aggregate past consumption. The parameter σ_1 is the coefficient of relative risk aversion of the representative household or the inverse of the intertemporal elasticity of substitution. The variable $L_{1,t}$ represents hours worked, while χ_1 is the inverse of the elasticity of work effort with respect to the real wage (or Frisch elasticity). In addition, equation (3.1) also contains a preference shock to consumption denoted by $Z^c_{1,t}$.

The representative household faces the following period-by-period budget constraint:

$$\begin{aligned} & \left(1 + \tau^c_{1,t}\right) P^c_{1,t} C_{1,t} + P^i_{1,t} I_{1,t} + \left(R^b_{1,t}\right)^{-1} B_{1,t+1} + \frac{e_{1,t} \left(R^b_{2,t}\right)^{-1} B^f_{1,t+1}}{\phi^b_{1,t}} \\ = & \left(1 - \tau^l_{1,t} - \tau^{wh}_{1,t}\right) W_{1,t} L_{1,t} + R^k_{1,t} K_{1,t-1} + \left(1 - \tau^d_{1,t}\right) D_{1,t} \\ & + P^o_{1,t} Y^o_{1,t} + B_{1,t} + e_{1,t} B^f_{1,t} \end{aligned} \tag{3.2}$$

where $P^c_{1,t}$ and $P^i_{1,t}$ denote the prices of consumption and investment goods, respectively. The gross nominal return of the domestic government bond is denoted by $R^b_{1,t}$, while, $R^b_{2,t}$ is the gross nominal return of the foreign government bond. The latter is denominated in foreign currency and, thus, its domestic value depends on the nominal exchange rate, $e_{1,t}$, expressed in units of the domestic currency per unit of foreign currency. As in the paper of Bodenstein et al. (2012), we assume that the representative household faces an intermediation cost to purchase the foreign bond, $\phi^b_{1,t}$ in order to ensure that net foreign assets are stationary. We indicate by $W_{1,t}$ the aggregate nominal wage, while $R^k_{1,t}$ is the rental rate for capital services, $K_{1,t-1}$. $D_{1,t}$ represents the dividends paid by production goods firms that are owned by the representative household. $P^o_{1,t}Y^o_{1,t}$ is a share of the country's (unrefined) oil endowment.

The fiscal authority absorbs part of the gross income of the representative household in order to finance its expenditure. In this context, $\tau^c_{1,t}$ denotes the consumption tax rate levied on consumption purchases (VAT tax in the UK fiscal regime). Moreover, $\tau^l_{1,t}$ and $\tau^d_{1,t}$ are the tax rates levied on labour income and dividends, respectively. In the UK taxation system, the former corresponds to the income tax, whereas the latter is the corporation tax. In addition, $\tau^{wh}_{1,t}$ is the additional pay-roll tax rate levied on representative household labour income. Thus, it represents the UK National Insurance Contribution (NIC) tax paid by households.

The capital stock owned by the representative household evolves according to the following capital accumulation equation:

$$K_{1,t} = (1-\delta_1) K_{1,t-1} + \left(1 - S\left(\frac{I_{1,t}}{I_{1,t-1}}\right)^2\right) Z^i_{1,t} I_{1,t} \tag{3.3}$$

where $K_{1,t}$ is the capital stock, δ_1 is the depreciation rate, and the adjustment cost function $S(\cdot)$ is a positive function of changes in investment. In steady state, with a constant level of investment, we assume that $S(\cdot)$ is equal to zero. Moreover, its first derivative around equilibrium equals to zero too. In addition, equation (3.3) includes an investment specific technology shock denoted by $Z^i_{1,t}$.

The representative household chooses $C_{1,t}$, $I_{1,t}$, $K_{1,t}$, $L_{1,t}$, $B_{1,t}$ and $B_{2,t}$ maximizing its intertemporal objective function (3.1) subject to the intertemporal budget constraint (3.2) and the capital accumulation equation (3.3).

Labour Supply. We assume the same wage setting as in Smets and Wouters (2007). Thus, labour service supplied by the representative household is differentiated by a labour union that has some monopoly power. This results in an explicit wage equation and allows for the introduction of sticky nominal wages à la Calvo (1983).

We assume that there is a continuum of households indexed by $h \in [0,1]$. Therefore, the demand for labour from firms of intermediate production goods is given by:

$$L_{1,t}(h) = \left(\frac{W_{1,t}(h)}{W_{1,t}}\right)^{-\frac{1+\theta^w_{1,t}}{\theta^w_{1,t}}} L^d_{1,t} \tag{3.4}$$

where the aggregate labour demand, $L^d_{1,t}$, and the aggregate nominal wage, $W_{1,t}$, correspond to:

$$L^d_{1,t} = \left[\int_0^1 L_{1,t}(h)^{\frac{1}{1+\theta^w_{1,t}}} dh\right]^{1+\theta^w_{1,t}} \tag{3.5}$$

$$W_{1,t} = \left[\int_0^1 W_{1,t}(h)^{-\frac{1}{\theta^w_{1,t}}} dh\right]^{-\theta^w_{1,t}} \tag{3.6}$$

where $\theta^w_{1,t}$ is an exogenous first order autoregressive process with an i.i.d. normal error term reflecting wage markup shocks.

As we described above, the labour union acts as price-setter in the labour market. According to the Calvo-style wage-setting frictions, we assume that, in period t, the labour union can change the nominal wage with probability $1-\xi^w_1$, whereas if the union cannot change the wage in a given period, it keeps the wage as a geometric average of nominal wage inflation in the last period ($\omega_{1,t-1}$) and the inflation rate in steady state (π^{SS}_1). In particular, the labour union solves the following maximization problem:

$$\max_{\{W_{1,t}(h)\}} E_t \sum_{j=0}^{\infty} (\xi_1^w)^j \psi_{1,t,t+j} \begin{bmatrix} \omega_{1,t,,j}^l W_{1,t}(h) L_{1,t+j}(h) - \\ W_{1,t+j}^f L_{1,t+j}(h) \end{bmatrix} \tag{3.7}$$

$$s.t \quad : \quad L_{1,t}(h) = \left(\frac{W_{1,t}(h)}{W_{1,t}} \right)^{-\frac{1+\theta_{1,t}^w}{\theta_{1,t}^w}} L_{1,t}^d \tag{3.8}$$

$$and \quad : \quad \omega_{1,t,,j}^l = \prod_{s=1}^{j} \left\{ (\omega_{1,t-1+s})^{\iota_1^w} \left(\pi_1^{SS} \right)^{1-\iota_1^w} \right\} \tag{3.9}$$

where ι_1^w indicates the degree of wage indexation. We indicate by $W_{1,t+j}^f$ the nominal wage desired by the representative household that corresponds to the marginal rate of substitution between leisure and consumption. The union takes into account $W_{1,t+j}^f$ during the negotiations with labour bundlers and gives to the representative household the markup above the nominal wage desired.

3.2.2 Firms

Production Goods. In each country there is a continuum of monopolistically competitive firms indexed by $i \in [0,1]$ that produces differentiated varieties of intermediate production goods, and a single final production good firm that combines the variety of intermediate production goods under perfect competition.

Final Production Good Sector. The aggregation technology of the final production good firm is given by:

$$Y_{1,t}^d = \left[\int_0^1 Y_{1,t}(i)^{\frac{1}{1+\theta_{1,t}^p}} di \right]^{1+\theta_{1,t}^p} \tag{3.10}$$

where $Y_{1,t}(i)$ denotes the quantity used of differentiated good i at time t. $\theta_{1,t}^p$ is a AR(1) stochastic process that determines the time varying markup in the goods market.

Profit maximization yields the downward-sloping demand for each intermediate input:

$$Y_{1,t}(i) = \left(\frac{P_{1,t}(i)}{P_{1,t}^{d}} \right)^{-\frac{1+\theta_{1,t}^{p}}{\theta_{1,t}^{p}}} Y_{1,t}^{d} \tag{3.11}$$

where $P_{1,t}(i)$ is the price of the intermediate production good i and $P_{1,t}^{d}$ is the price of the final production good. Perfect competition in the final production goods sector implies that $P_{1,t}^{d}$ is given by:

$$P_{1,t}^{d} = \left[\int_{0}^{1} \left(P_{1,t}^{d}(i) \right)^{-\frac{1}{\theta_{1,t}^{p}}} di \right]^{-\theta_{1,t}^{p}} \tag{3.12}$$

Considering the producer currency pricing, the exports are expressed in foreign prices:

$$e_{1,t} = \frac{P_{1,t}^{d}}{P_{2,t}^{m}} \tag{3.13}$$

where $P_{2,t}^{m}$ indicates the price of imported goods of country 2.

Intermediate Production Good Sector. The production function for a typical intermediate production good firm i is assumed to be a nested constant elasticity of substitution with three inputs: capital, labour and oil. Thus, the cost minimization problem of firm i that produces overall output $Y_{1,t}(i)$ can be expressed as:

$$\min_{\left\{K_{1,t-1}(i), L_{1,t}(i), O_{1,t}^{y}(i), V_{1,t}(i)\right\}} \left(\begin{array}{c} R_{1,t}^{k} K_{1,t-1}(i) + \\ \left(1+\tau_{1,t}^{wf}\right) W_{1,t} L_{1,t}(i) + \\ P_{1,t}^{o} O_{1,t}^{y}(i) \end{array} \right) \tag{3.14}$$

$$s.t \;:\; Y_{1,t}(i) = \left(\begin{array}{c} \left(\omega_{1}^{vy}\right)^{\frac{\rho_{1}^{o}}{1+\rho_{1}^{o}}} \left(V_{1,t}(i)\right)^{\frac{1}{1+\rho_{1}^{o}}} + \\ \left(\omega_{1}^{oy}\right)^{\frac{\rho_{1}^{o}}{1+\rho_{1}^{o}}} \left(Z_{1,t}^{o} O_{1,t}^{y}(i)\right)^{\frac{1}{1+\rho_{1}^{o}}} \end{array} \right)^{1+\rho_{1}^{o}} \tag{3.15}$$

$$and \;:\; V_{1,t}(i) = \left(\begin{array}{c} \left(\omega_{1}^{k}\right)^{\frac{\rho_{1}^{v}}{1+\rho_{1}^{v}}} \left(K_{1,t-1}(i)\right)^{\frac{1}{1+\rho_{1}^{v}}} + \\ \left(\omega_{1}^{l}\right)^{\frac{\rho_{1}^{v}}{1+\rho_{1}^{v}}} \left(Z_{1,t} L_{1,t}(i)\right)^{\frac{1}{1+\rho_{1}^{v}}} \end{array} \right)^{1+\rho_{1}^{v}} \tag{3.16}$$

where $V_{1,t}(i)$ represents the value added produced by capital, $K_{1,t}(i)$, and labour, $L_{1,t}(i)$, services. The intermediate production good is produced combining the value added input with oil input $O_{1,t}^{y}(i)$. In addition, we denote by τ_t^{wf} the payroll tax rate levied on wage payments. In the UK fiscal regime, this represents the UK National Insurance Contribution (NIC) tax paid by firms.

The weights of capital and labour in the value added production function are denoted by ω_1^k and ω_1^l, respectively. Similarly, ω_1^{oy} and ω_1^{vy} are the respective weights of oil input and value added input in the overall output production function. Moreover, ρ_1^v indicates the elasticity of substitution between capital and labour services, whereas ρ_1^o denotes the price elasticity of demand for oil.

We assume an exogenous productivity shock, $Z_{1,t}$, that follows an AR(2) stochastic process. In the results section, we will note that this shock significantly influences the variance of the UK oil price.

In addition, we consider an exogenous shock driving the oil intensity in production. We denote it by $Z_{1,t}^o$ and we assume that it is given by second order autoregressive process. As we will show below, this shock has important effects on the UK macroeconomic aggregates. In particular, it explains most of the volatility of the UK oil price and it contributes significantly to the variation of the UK government debt.

In the intermediate production good sector, there is a sluggish price adjustment due to staggered price contracts à la Calvo. Accordingly, firms i receives the permission to optimally reset prices in a given period t with probability $1-\xi_1^p$. Following Smets and Wouters (2003, 2007), firms that cannot change their prices keep their prices as a geometric average of inflation in the last period $(\pi_{1,t-1}^d)$ and the inflation rate in steady state (π_1^{SS}). Thus, the profit maximization problem of firms that are allowed to reoptimize their prices at time t can be expressed as:

$$\max_{\left\{P^d_{1,t}(i)\right\}} E_t \sum_{j=0}^{\infty} \left(\xi^p_1\right)^j \psi_{1,t,t+j} \left[\begin{array}{c} \pi^d_{1,t,,j} P^d_{1,t}(i) Y_{1,t+j}(i) - \\ MC_{1,t+j} Y_{1,t+j}(i) \end{array} \right] \tag{3.17}$$

$$s.t \quad : \quad Y_{1,t}(i) = \left(\frac{P^d_{1,t}(i)}{P^d_{1,t}} \right)^{-\frac{1+\theta^p_1}{\theta^p_1}} Y^d_{1,t} \tag{3.18}$$

$$and \quad : \quad \pi^d_{1,t,,j} = \prod_{s=1}^{j} \left\{ \left(\pi^d_{1,t-1+s}\right)^{\iota^p_1} \left(\pi^{SS}_1\right)^{1-\iota^p_1} \right\} \tag{3.19}$$

where ι^p_1 represents the degree of price indexation, whereas $MC_{1,t}$ denotes the marginal cost at time t that accounts for capital, labour and oil as factor inputs.

Consumption Goods. Final consumption goods, $C_{1,t}$, are produced under perfect competition and sold to the representative household. The representative firm producing final consumption goods uses a nested constant elasticity of substitution production function. In particular, domestic, $C^d_{1,t}$, and foreign, $M^c_{1,t}$, intermediate consumption goods are combined in order to obtain non-oil consumption goods, $C^{ne}_{1,t}$. Accordingly, final consumption goods are produced combining non-oil and oil, $O^c_{1,t}$, consumption goods. The cost minimization problem faced by the representative firm producing final consumption goods is given by:

$$\min_{\left\{C^d_{1,t}, M^c_{1,t}, C^{ne}_{1,t}, O^c_{1,t}\right\}} P^d_{1,t} C^d_{1,t} + P^m_{1,t} M^c_{1,t} + \left(1 + \tau^{oc}_{1,t}\right) P^o_{1,t} O^c_{1,t} \tag{3.20}$$

$$s.t \quad : \quad C_{1,t} = \left(\left(\omega^{cc}_1\right)^{\frac{\rho^o_1}{1+\rho^o_1}} \left(C^{ne}_{1,t}\right)^{\frac{1}{1+\rho^o_1}} + \left(\omega^{oc}_1\right)^{\frac{\rho^o_1}{1+\rho^o_1}} \left(Z^o_{1,t} O^c_{1,t}\right)^{\frac{1}{1+\rho^o_1}} \right)^{1+\rho^o_1} \tag{3.21}$$

$$and \quad : \quad C^{ne}_{1,t} = \left(\left(\omega^{c}_1\right)^{\frac{\rho^c_1}{1+\rho^c_1}} \left(C^{d}_{1,t}\right)^{\frac{1}{1+\rho^c_1}} + \left(\omega^{mc}_1\right)^{\frac{\rho^c_1}{1+\rho^c_1}} \left(Z^m_{1,t} M^c_{1,t}\right)^{\frac{1}{1+\rho^c_1}} \right)^{1+\rho^c_1} \tag{3.22}$$

where τ^{oc}_t indicates a tax on oil used for consumption goods. In the UK taxation system it can be seen as the fuel duty levied on some prices of fuels used by road vehicles. We denote by ω^c_1 and ω^{mc}_1 the weights of domestic and imported goods, whereas ω_1^{cc} and ω_1^{oc} are the weights of non-oil and oil in the production of consumption goods. Moreover, ρ_1^c represents the elasticity of substitution between domestic and foreign intermediate goods, whereas ρ_1^o corresponds to the same price elasticity of oil demand included in equation (3.15). We assume that import preferences are driven by an exogenous shock, $Z_{1,t}^m$, that has the form of an AR(2) process. In addition, we consider an oil intensity shock affecting the production of consumption goods, $Z_{1,t}^o$, that is the same of equation (3.15).

The Lagrange multiplier associated with the cost minimization problem of the representative firm producing final consumption goods is defined as the price of consumption goods $P_{1,t}^c$, whereas the price of non-oil consumption goods corresponds to the core price level $P_{1,t}^{ne}$ of the economy.

Investment Goods. Firms producing investment goods, $I_{1,t}$, use a nested constant elasticity of substitution production function but, contrarily to consumption good firms, without oil as an input factor. These firms operate under perfect competition and sell investment goods to the representative household. In particular, domestic and foreign investment goods, denoted respectively by $I_{1,t}^d$ and $M_{1,t}^i$, are combined in order to obtain final investment goods. We can express the cost minimization problem of typical firm producing investment goods as follows:

$$\min_{\left\{I_{1,t}^d, M_{1,t}^i\right\}} P_{1,t}^d I_{1,t}^d + P_{1,t}^m M_{1,t}^i \tag{3.23}$$

$$s.t \quad : \quad I_{1,t} = \left(\left(\omega_1^i\right)^{\frac{\rho_1^c}{1+\rho_1^c}} \left(I_{1,t}^d\right)^{\frac{1}{1+\rho_1^c}} + \left(\omega_1^{mi}\right)^{\frac{\rho_1^c}{1+\rho_1^c}} \left(Z_{1,t}^m M_{1,t}^i\right)^{\frac{1}{1+\rho_1^c}} \right)^{1+\rho_1^c} \tag{3.24}$$

where ω_1^i and ω_1^{mi} indicate the weights of domestic and foreign investment goods. The elasticity of substitution between domestic and foreign goods is denoted by ρ_1^c, as in the production of consumption goods. We also assume that investment goods are influenced by an import preferences shock, $Z_{1,t}^m$, that is the same we assumed in the production of consumption goods. We note that the Lagrange multiplier associated with the problem of cost minimization of the typical investment goods firm coincides with the price of investment goods $P^i_{1,t}$.

3.2.3 The Oil Sector

The oil sector is defined according to the most recent economic literature (see, for example, Bodenstein and Guerrieri, 2011; Kilian, 2009; Kilian and Hicks, 2011; Kilian and Murphy, 2010 and 2012; Bodenstein et al., 2012). More specifically, we focus on the demand side of the oil market while we set up a simple framework for the supply side. Our decision is motivated by the fact that there is an intense debate on how to model the supply side of the oil market (see, for example, Nakov and Pescatori, 2010a; Balke et al., 2010; Nakov and Nuño, 2011) but, unfortunately, there is lack of relevant economic data (see, for example, Smith, 2005; Almoguera et al., 2011) in order to test these models.

Accordingly, we assume that domestic ($Y^o_{1,t}$) and foreign ($Y^o_{2,t}$) production of oil are exogenously determined and that they have the forms of two distinct second order autoregressive processes. As we will show below, the foreign oil supply shock plays an important role in terms of oil price volatility and, in turn, it affects significantly the behaviour of UK macroeconomic variables.

The real oil price ($P^o_{1,t}$) adjusts endogenously in order to clear the world oil market according to the following condition:

$$Y^o_{1,t} + \frac{\zeta_2}{\zeta_1} Y^o_{2,t} = O_{1,t} + \frac{\zeta_2}{\zeta_1} O_{2,t} \tag{3.26}$$

$$where : O_{1,t} = O^y_{1,t} + O^c_{1,t} \tag{3.27}$$

where $O_{1,t}$ and $O_{2,t}$ are the domestic and foreign oil demand, respectively, while ζ_1 and ζ_2 indicate the relative population sizes of home and foreign country, respectively. Simply, this oil market clearing condition states that the oil produced in the domestic and foreign countries equals the oil consumed by households and firms in domestic and foreign countries.

3.2.4 Fiscal Authority

As we discussed above, the main objective of this paper is to analyse how oil price fluctuations impact on tax receipts, including the rate at which oil price changes work through the economy into the public finances. In order to achieve these goals we set up a detailed fiscal sector that includes several policy rules for the distortive taxes.

In particular, we assume that the fiscal authority's period-by-period budget constraint has the following form:

$$\begin{aligned} P^g_{1,t}G^d_{1,t} + B_{1,t} &= \tau^c_{1,t}P^c_{1,t}C_{1,t} + \left(\tau^l_{1,t} + \tau^{wh}_{1,t} + \tau^{wf}_{1,t}\right) W_{1,t}L_{1,t} + \\ &\quad \tau^d_{1,t}D_{1,t} + \tau^{oc}_{1,t}P^o_{1,t}O^c_{1,t} + \tau^{yo}_{1,t}P^o_{1,t}Y^o_{1,t} + \left(R^b_{1,t}\right)^{-1} B_{1,t+1} \end{aligned} \tag{3.28}$$

where $G^d_{1,t}$ is the government expenditure while $B_{1,t}$ indicates the government debt. As described above, $\tau^c_{1,t}$, $\tau^l_{1,t}$, $\tau^{wh}_{1,t}$, $\tau^{wf}_{1,t}$, $\tau^d_{1,t}$ and τ^{oc}_t are VAT, income, households and firms NIC, corporation, and fuel duty taxes, respectively. Finally, we define τ^{yo}_t as the UK Petroleum Revenue Tax (PRT).

We consider the government expenditure as a fraction of the nominal domestic output:

$$\hat{g}^d_{1,t} = \frac{P^g_{1,t}G^d_{1,t}}{P^d_{1,t}Y^d_{1,t}} \tag{3.29}$$

and we assume that $\hat{g}^d_{1,t}$ follows an exogenous AR(1) process.

We also define the government debt as a fraction of the nominal domestic output:

$$\hat{b}_{1,t} = \frac{B_{1,t}}{P^d_{1,t}Y^d_{1,t}} \tag{3.30}$$

Moreover, we assume that the log-linearized expressions for the fiscal policy rules concerning the distortive taxes are:

$$\begin{aligned}
\hat{\tau}^{c}_{1,t} &= \psi^{cc}_{1}\hat{c}_{1,t} && (3.31)\\
\hat{\tau}^{l}_{1,t} &= \psi^{ly}_{1}\hat{y}^{d}_{1,t} + \psi^{lb}_{1}\hat{b}_{1,t-4} && (3.32)\\
\hat{\tau}^{wh}_{1,t} &= \psi^{wb}_{1}\hat{b}_{1,t-4} && (3.33)\\
\hat{\tau}^{oc}_{1,t} &= \psi^{ococ}_{1}\hat{o}^{c}_{1,t} && (3.34)\\
\hat{\tau}^{wf}_{1,t} &= \psi^{wb}_{1}\hat{b}_{1,t-4} && (3.35)\\
\hat{\tau}^{d}_{1,t} &= \psi^{dd}_{1}\hat{d}_{1,t} && (3.36)\\
\hat{\tau}^{yo}_{1,t} &= \psi^{yopo}_{1}\left[\frac{\hat{P}^{o}}{\hat{P}^{GDP}}\right]_{1,t} && (3.37)
\end{aligned}$$

where the small letters with the hats denote log-deviations of the variables from their respective steady states. Moreover, in line with Leeper et al. (2009), we assume that the coefficients linking taxes to the several variables have positive values (i.e. $\psi^{x}_{1} \geq 0 \; for \; x = \{cc, ly, lb, wb, ococ, dd, yopo\}$).

The fiscal rule (3.31) implies that the consumption tax depends on total final consumption. In particular, the parameter ψ^{cc}_{1} indicates the response of the consumption tax rate to changes in the level of consumption. Our formulation is consistent with the high value of the contemporaneous correlation between the UK VAT rate and the total private consumption expenditure.[55]

As in Leeper et al. (2009), the fiscal rule for the labour income tax (equation (3.32)) allows for a response to the cyclical position of the economy and to changes in the level of government debt. Accordingly, the coefficients ψ^{ly}_{1} and ψ^{lb}_{1} denote the responses of the labour income tax rate to changes in the UK GDP and government debt, respectively. More specifically, we assume that the labour income tax immediately responds to changes in the UK GDP whereas it responds with a delay of one year to variations of the UK government debt. Our choice is motivated by the fact that the estimated correlation between the UK IT rate and the one

[55] In particular, the estimated correlation between the VAT rate and the total private consumption expenditure is equal to 0.62.

year lagged government debt is higher than the correlation between the IT rate and the government debt both at time t.[56]

The fiscal rules (3.33) and (3.35) imply that the National Insurance Contribution paid by households and firms depends only on variations in the level of government debt.[57] Thus, the parameter ψ_1^{wb} represents the response of the NIC rate to one year lagged government debt. Our decision is related to the fact that the correlation between the NIC rate and the one year lagged government debt is higher than the contemporaneous correlation between the NIC rate and the government debt.[58]

As shown in equation (3.36), the fiscal rule for the corporation tax allows for the response to changes in domestic dividends. In particular, ψ_1^{dd} indicates the response of the corporation tax rate to changes in the dividends of firms.

The fiscal rule (3.34) implies that the fuel duty tax depends on the oil demand of the domestic country. More specifically, ψ_1^{ococ} denotes the response of the fuel duty tax rate to current changes in domestic oil demand. Our assumption is consistent with the estimated correlation between the fuel duty tax rate and the UK oil consumption.[59]

Finally, as we can note from equation (3.37), the petroleum revenue tax varies according to the domestic oil price at time t. In particular, ψ_1^{yopo} represents the response of the PRT rate to variations in the real oil price. Our choice is motivated by the important correlation between the PRT rate and the real oil price.[60]

[56] In particular, the estimated correlation between the IT rate and the one year lagged government debt as a share of GDP is equal to 0.015.

[57] We assume that the NIC does not depend on domestic output because we found a negative correlation between the NIC rate and the UK GDP.

[58] In particular, the correlation between NIC rate and the one year lagged government debt over GDP is equal to 0.019.

[59] In particular, the estimated correlation between the fuel duty rate and the UK oil consumption is equal to 0.16.

[60] In particular, the estimated correlation between the PRT rate and the real oil price is equal to 0.28.

3.2.5 Central Bank

The central bank is assumed to follow a Taylor-type interest-rate rule (Taylor, 1993) specified in terms of past nominal interest rate, core inflation and output gap (i.e., the difference between actual and potential output):

$$\begin{aligned} i_{1,t} &= \bar{\imath}_1 + \gamma_1^i \left(i_{1,t-1} - \bar{\imath}_1\right) + \\ &\left(1-\gamma_1^i\right)\left[\left(\pi_{1,t}^{core} - \bar{\pi}_1^{core}\right) + \gamma_1^\pi\left(\pi_{1,t}^{core} - \bar{\bar{\pi}}_1^{core} - \bar{\pi}_{1,t}^{core}\right) + \gamma_1^y y_{1,t}^{gap}\right] \end{aligned} \tag{3.38}$$

where $\bar{\imath}_1$ and $\bar{\pi}_1^{core}$ indicate the steady state values for the nominal interest rate and inflation, respectively. Moreover, we denote by γ_1^i the interest rate smoothing parameter, while γ_1^y and γ_1^π represent the reaction of interest rate on output gap and inflation, respectively. Finally, we assume that the core inflation is given by the logarithmic percentage change in the price of non-oil goods:

$$\pi_{1,t}^{core} = \log\left(\frac{P_{1,t}^{ne}}{P_{1,t-1}^{ne}}\right) \tag{3.39}$$

and that $\bar{\pi}_{1,t}^{core}$ is an exogenous AR(1) process indicating a time varying inflation target.

3.2.6 Equilibrium of the Non-Oil Goods Market

Imposing the market-clearing condition for the non-oil good market of the domestic economy implies the following aggregate resource constraint:

$$\begin{aligned} Y_{1,t}^d &= C_{1,t}^d + I_{1,t}^d + G_{1,t}^d + \frac{\zeta_2}{\zeta_1} M_{2,t} \\ \text{where} &: M_{2,t} = M_{2,t}^c + M_{2,t}^i \end{aligned} \tag{3.40}$$

where $M_{2,t}$ indicates the net imports of the foreign country, while ζ_1 and ζ_2 represent the relative population sizes of home and foreign country, respectively. Simply, the market clearing condition (3.40) states that the production of domestic firms equals the domestic demand of the representative household for consumption and investment goods plus domestic government expenditure and total imports of the foreign country.

Moreover, the domestic holdings of internationally traded bonds (that is, the home country's net foreign assets, denominated in foreign currency) evolve according to:

$$\begin{aligned}\frac{e_{1,t}\left(R_{2,t}^{b}\right)^{-1}B_{1,t+1}^{f}}{\phi_{1,t}^{b}} &= e_{1,t}B_{1,t}^{f}+\frac{\zeta_2}{\zeta_1}e_{1,t}P_{2,t}^{m}\left(M_{2,t}^{c}+M_{2,t}^{i}\right) \\ &\quad -P_{1,t}^{m}\left(M_{1,t}^{c}+M_{1,t}^{i}\right)+P_{1,t}^{o}\left(Y_{1,t}^{o}-O_{1,t}\right)\end{aligned} \tag{3.41}$$

that is, holding bonds of the foreign country is equal to the domestic non-oil trade balance.

Finally, the market clearing condition for the holdings of foreign assets states that $B_{1,t}^{f}+B_{2,t}^{f}=0$.

3.2.7 Shock Processes

According to the framework outlined above, we consider fifteen shocks driving the economy (Table 3.1). More specifically, these shocks affect domestic and foreign productivities, domestic and foreign oil productions, domestic and foreign oil intensities, domestic and foreign consumption preferences, domestic and foreign import preferences, domestic investment specific technology, domestic price markup, domestic wage markup, domestic inflation target and domestic government expenditure.

Shocks	Stochastic Process
Home Prod.	$\ln(Z_{1,t}) = (1+\rho^z_{1,1}-\rho^z_{2,1})\ln(Z_{1,t-1}) - \rho^z_{1,1}\ln(Z_{1,t-2}) + \varepsilon^z_{1,t}$
Foreign Prod.	$\ln(Z_{2,t}) = (1+\rho^z_{1,2}-\rho^z_{2,2})\ln(Z_{2,t-1}) - \rho^z_{1,2}\ln(Z_{2,t-2}) + \varepsilon^z_{2,t}$
Home Oil Sup.	$\ln(Y^o_{1,t}) = (1+\rho^{yo}_{1,1}-\rho^{yo}_{2,1})\ln(Y^o_{1,t-1}) - \rho^{yo}_{1,1}\ln(Y^o_{1,t-2}) + \varepsilon^{yo}_{1,t}$
Foreign Oil Sup.	$\ln(Y^o_{2,t}) = (1+\rho^{yo}_{1,2}-\rho^{yo}_{2,2})\ln(Y^o_{2,t-1}) - \rho^{yo}_{1,2}\ln(Y^o_{2,t-2}) + \varepsilon^{yo}_{2,t}$
Home Oil Int.	$\ln(Z^o_{1,t}) = (1+\rho^{zo}_{1,1}-\rho^{zo}_{2,1})\ln(Z^o_{1,t-1}) - \rho^{zo}_{1,1}\ln(Z^o_{1,t-2}) + \varepsilon^{zo}_{1,t}$
Foreign Oil Int.	$\ln(Z^o_{2,t}) = (1+\rho^{zo}_{1,2}-\rho^{zo}_{2,2})\ln(Z^o_{2,t-1}) - \rho^{zo}_{1,2}\ln(Z^o_{2,t-2}) + \varepsilon^{zo}_{2,t}$
Home Cons.	$\ln(Z^c_{1,t}) = \rho^{zc}_{1,1}\ln(Z^c_{1,t-1}) + \varepsilon^c_{1,t}$
Foreign Cons.	$\ln(Z^c_{2,t}) = \rho^{zc}_{1,2}\ln(Z^c_{2,t-1}) + \varepsilon^c_{2,t}$
Home Imp. Pref.	$\ln(Z^m_{1,t}) = (1+\rho^{zm}_{1,1}-\rho^{zm}_{2,1})\ln(Z^m_{1,t-1}) - \rho^{zm}_{1,1}\ln(Z^m_{1,t-2}) + \varepsilon^{zm}_{1,t}$
Foreign Imp. Pref.	$\ln(Z^m_{2,t}) = (1+\rho^{zm}_{1,2}-\rho^{zm}_{2,2})\ln(Z^m_{2,t-1}) - \rho^{zm}_{1,2}\ln(Z^m_{2,t-2}) + \varepsilon^{zm}_{2,t}$
Home Inv.	$\ln(Z^i_{1,t}) = \rho^{zi}_{1,1}\ln(Z^i_{1,t-1}) + \varepsilon^i_{1,t}$
Home Price Mar.	$\hat{\theta}^p_{1,t} = \rho^p_{1,1}\hat{\theta}^p_{1,t-1} + \varepsilon^p_{1,t}$
Home Wage Mar.	$\hat{\theta}^w_{1,t} = \rho^w_{1,1}\hat{\theta}^w_{1,t-1} + \varepsilon^w_{1,t}$
Home Infl. Target	$\bar{\pi}^{core}_{1,t} = \rho^{\pi}_{1,1}\bar{\pi}^{core}_{1,t-1} + \varepsilon^{\pi}_{1,t}$
Home Gov. Exp.	$\hat{g}^d_{1,t} = \rho^g_{1,1}\hat{g}^d_{1,t-1+}\varepsilon^g_{1,t}$

Table 3.1: Exogenous Shocks

3.3 Estimating the Model

In this section, we estimate the model described in Section 2 using Bayesian techniques. Equilibrium conditions and their log-linearizations around the deterministic steady state are given in Appendix C. Accordingly, we describe the data in Section 3.1 before presenting the model parameters in Section 3.2. Section 3.3 shows the estimated results. In Sections 3.4 and 3.5 we focus on the variance decomposition analysis and the business cycle statistics, respectively.

3.3.1 Data

The model is estimated for the sample period 1990:Q1-2005:Q4.[61] The starting date corresponds to the earliest quarter for which data on Brent oil price was available. Since we are interested in estimating the UK economy in the time period that it was an oil exporter, the end of the sample coincides with the transition of

[61] We use the period 1988:Q1-1989:Q4 as a pre-sample.

the UK economy from an oil exporter to an oil importer country.

We use fifteen data series in the estimation because there are fifteen shocks in the theoretical model (as described in Section 2.7). More specifically, the fifteen time series are: UK and foreign real GDP, UK and foreign crude oil productions, real oil price, UK broad effective exchange rate, UK private consumption expenditure, UK total gross fixed capital formation, UK oil imports, UK non-oil goods imports, UK non-oil goods exports, UK core inflation, UK wage inflation, UK nominal interest rate and UK government debt. The data series used in the present chapter are the same as in Chapter 2, except for the UK government debt. The latter series is taken from ONS and corresponds to the public sector net debt. We seasonally adjust this series and express it as a share of the UK GDP. The data sources and the construction of the remaining observed variables are reported in Appendix C.

3.3.2 Model Parameters

Similarly to Chapter 2, we chose to split the parameters in three different sets. The first set corresponds to parameter values that are kept fixed and are mainly taken from previous economic literature. The second set is constructed from the observed data of the UK and the rest of the world for sample period 1990-2005. Finally, the third set of parameters is estimated with Bayesian methods.

First Set of Fixed Parameters. Table 3.2 presents the first set of parameters which can be viewed as strict priors. In particular, we assume that these parameters have the same values for both the domestic and the foreign countries.

More specifically, we set the discount factor (β_1) equal to 0.99, which implies an annual steady state of the real interest rate of 4%. We assume that the annual steady state of the capital depreciation rate is 10%, implying that δ_1 equals 0.025. We set the value for the intertemporal elasticity of substitution (σ_1) equal to 1. We set L_1^{SS} equal to 0.33, implying that, in steady state, agents devote 1/3 of their time endowment to work. In line with Bodenstein et al. (2011), we assume that the parameter for the bond intermediation cost (ϕ_1^b) is equal to 0.0001. Finally, we fix the elasticity of substitution between capital and labour ($\frac{1+\rho_1^v}{\rho_1^v}$) equal to 0.8.

Parameter	Value	Description	Motivation
β_1	0.99	Discount Factor	Assumption
δ_1	0.025	Depreciation Rate	Assumption
σ_1	1	IES	Assumption
L_1^{SS}	0.33	Labour Steady State	Assumption
ϕ_1^b	0.0001	Bond Intermediation Cost	Bodenstein et al. (2012)
ρ_1^v	-5	Determines K-L Elas. Sub.	$\frac{1+\rho_1^v}{\rho_1^v}= 0.8$

Table 3.2: Calibrated Parameters According to Previous Literature

Second Set of Parameters Constructed from the Actual Data. In Table 3.3, we report the second set of parameters that are constructed from the observed data of UK and the foreign bloc. These parameters values are kept fixed when we estimate the model and, generally, determine average ratios.[62]

As concerns the UK economy, the weight of capital in the value added production function (ω_1^k) corresponds to 0.43, the weight of oil on total production (ω_1^{oy}) is equal to 0.03, while the importance of oil on final consumption (ω_1^{oc}) is 0.01. Moreover, the weight of consumption goods on total imports (ω_1^{mc}) is equal to 0.32, while the importance of services on total imports (ω_1^{mi}) corresponds to 0.38.

In addition, Table 3.3 shows the several parameters for the UK fiscal sector. In particular, we set the steady state tax rates according to their average values for the period 1997-2005.[63] We also assume the same tax rates for National Insurance Contribution paid by households, $\left(\tau_1^{wh}\right)^{SS}$, and firms, $\left(\tau_1^{wf}\right)^{SS}$.

[62] See Appendix C for the derivation of composite parameters of the model.

[63] Appendix C describes in detail the time series used in order to obtain the several UK tax rates.

Parameter Description	Home Country	Foreign Country
Capital Weight in Value Added	$\omega_1^k = 0.43$	$\omega_2^k = 0.56$
Weight of Oil in Production	$\omega_1^{oy} = 0.03$	$\omega_2^{oy} = 0.03$
Weight of Oil in Consumption	$\omega_1^{oc} = 0.01$	$\omega_2^{oc} = 0.01$
Weight of Cons. in Tot. Imp.	$\omega_1^{mc} = 0.32$	$\omega_2^{mc} = 0.48$
Weight of Services in Tot. Imp.	$\omega_1^{mi} = 0.38$	$\omega_2^{mi} = 0.39$
S.S. VAT Rate	$(\tau_1^c)^{SS} = 0.11$	-
S.S. Income Tax Rate	$\left(\tau_1^l\right)^{SS} = 0.19$	-
S.S. NIC Rate (households)	$\left(\tau_1^{wh}\right)^{SS} = 0.12$	-
S.S. Fuel Duty Tax Rate	$(\tau_1^{oc})^{SS} = 0.51$	-
S.S. NIC Rate (firms)	$\left(\tau_1^{wf}\right)^{SS} = 0.12$	-
S.S. Corporation Tax Rate	$\left(\tau_1^d\right)^{SS} = 0.14$	-
S.S. PRT Tax Rate	$(\tau_1^{yo})^{SS} = 0.36$	-
Share Gov. Exp. / GDP	$\frac{\left(G_1^d\right)^{SS}}{\left(Y_1^d\right)^{SS}} = 0.24$	-
Share of Oil Production	$\frac{\frac{\zeta_1}{\zeta_2}\left(Y_1^o\right)^{SS}}{\frac{\zeta_1}{\zeta_2}\left(Y_1^o\right)^{SS}+\left(Y_2^o\right)^{SS}} = 0.06$	$\frac{\left(Y_2^o\right)^{SS}}{\frac{\zeta_1}{\zeta_2}\left(Y_1^o\right)^{SS}+\left(Y_2^o\right)^{SS}} = 0.94$
Share of Oil Consumption	$\frac{\frac{\zeta_1}{\zeta_2}(O_1)^{SS}}{\frac{\zeta_1}{\zeta_2}(O_1)^{SS}+(O_2)^{SS}} = 0.03$	$\frac{(O_2)^{SS}}{\frac{\zeta_1}{\zeta_2}(O_1)^{SS}+(O_2)^{SS}} = 0.97$
Population Size	$\zeta_1 = 0.02$	$\zeta_2 = 0.98$

Table 3.3: Calibrated Parameters According to Observed Data

As concerns the foreign bloc, we construct the several parameters using the Loretan (2005) technique.[64] In particular, the value for the weight of capital in the value added production function (ω_2^k) is equal to 0.56, the parameter capturing the weight of oil in production (ω_2^{oy}) equals 0.03, while the weight of oil in consumption (ω_2^{oc}) corresponds to 0.01. Finally, the parameter determining the importance of consumption goods in total imports (ω_2^{mc}) and the one capturing the weight of services in total imports (ω_2^{mi}) are 0.48 and 0.39, respectively.

[64] See Appendix C for a detailed explanation of the Loretan (2005) method applied to the main UK trading partners.

Third Set of Parameters: Prior Distributions. Table 3.4, 3.5 and 3.6 show the prior distributions for the remaining parameters estimated with Bayesian techniques. We assume priors that are in line with those commonly used in previous literature (see Smets and Wouters, 2007; Del Negro and Schorfheide, 2008; Leeper et al., 2010).

Table 3.4 shows the prior distributions for the endogenous parameters of the model. In particular, the parameter for investment adjustment costs (φ_1^i) and the consumption habit coefficient (κ_1) are the same as in Del Negro and Schorfheide (2008). We set the parameter determining the labour supply elasticity (χ_1) in line with the paper of Bodenstein et al. (2012).

Moreover, we assume Calvo probabilities for wages (ι_1^w) and prices (ξ_1^p) as well as indexation parameters for both wages (ι_1^w) and prices (ι_1^p) in line with Del Negro and Schorfheide (2008).

Our assumed prior for the inflation weight in the Taylor rule (γ_1^π) has a higher mean value than that of the output gap (γ_1^y). In addition, the policy rate smoothing parameter (γ_1^i) has the same prior as in Del Negro and Schorfheide (2008).

Turning to the price elasticity of oil demand ($\frac{1+\rho_1^o}{\rho_1^o}$), its prior mean value is broadly in line with empirical studies that have estimated the price elasticity of oil demand for the US economy.[65] Moreover, the prior mean for the elasticity of substitution between domestic and foreign non oil goods ($\frac{1+\rho_1^c}{\rho_1^c}$) is slightly higher than the estimated value of Hooper et al. (2000).

In general, the priors for the fiscal parameters concerning the distortive taxes are chosen to be fairly diffuse and cover a reasonable large range of parameter values. In particular, the response of the VAT to total consumption (ψ_1^{cc}) is assumed to have a Gamma distribution with a mean of 0.5 and a standard deviation of 0.4. This prior mean value is consistent with the estimated correlation between the UK VAT rate and the total private consumption expenditure.

[65] See for example Kilian and Murphy (2010), Bodenstein and Guerrieri (2011) and Bodenstein et al. (2012).

Par.	Description	Distrib.	Mean	St. Dev.
κ_1	Degree of Habit Persistence in Cons.	Beta	0.70	0.05
φ_1^i	Investment Adjustment Cost	Gamma	4.00	1.50
χ_1	Lab. Sup. El. $(\frac{1}{2\chi})$	Gamma	25.00	0.75
ξ_1^w	Calvo Wages Probability	Beta	0.60	0.20
ξ_1^p	Calvo Prices Probability	Beta	0.60	0.20
ι_1^w	Degree of Wage Indexation	Beta	0.20	0.08
ι_1^p	Degree of Price Indexation	Beta	0.20	0.08
γ_1^π	Taylor Rule Coefficient on Inflation	Gamma	0.20	0.10
γ_1^y	Taylor Rule Coefficient on Output	Gamma	0.30	0.10
γ_1^i	Degree of Int. Rate Smoothing in T.R.	Beta	0.50	0.20
$\frac{1+\rho_1^o}{\rho_1^o}$	Price Elasticity of Oil Demand	Gamma	0.40	0.20
$\frac{1+\rho_1^c}{\rho_1^c}$	Sub. El. between Dom. and For. Goods	Gamma	2.50	0.10
ψ_1^{cc}	VAT / Priv. Cons. Coeff.	Gamma	0.50	0.40
ψ_1^{ly}	Labour Income Tax / GDP Coeff.	Gamma	0.30	0.20
ψ_1^{lb}	Labour Income Tax / Debt Coeff.	Normal	0.05	0.10
ψ_1^{wb}	NIC (hh and firms) / Debt Coeff.	Normal	0.05	0.10
ψ_1^{ococ}	Fuel Duty Tax / Oil Dem. Coeff.	Gamma	0.30	0.20
ψ_1^{dd}	Corporation Tax / Div. Coeff.	Gamma	0.20	0.10
ψ_1^{yopo}	Petroleum Revenue Tax / Oil Price Coeff.	Gamma	0.30	0.10

Table 3.4: Prior Distributions for the Endogenous Parameters

The response of the labour income tax to output (ψ_1^{ly}) is assumed to have Gamma distribution with a mean of 0.3 and a standard deviation of 0.2. This prior mean value is slightly lower than the one assumed by Leeper et al. (2010) for the US economy.

The responses of the labour income tax (ψ_1^{lb}) and the NIC (ψ_1^{wb}) to the lagged government debt are assumed to have Normal distributions with means of 0.05 and standard deviations of 0.10. These prior mean values are in line with the estimated correlations of the IT tax rate and the NIC rate with the one year lagged government debt.

The response of corporation tax to domestic dividends is assumed to be Gamma distributed with a mean of 0.2 and a standard deviation of 0.1. This prior ensures that the domain covers the range of values corresponding to the estimated correlation between the corporation tax rate and the gross operating surplus of corporations.

The response of fuel duty tax to oil demand (ψ_1^{ococ}) and the response of petroleum revenue tax to oil price (ψ_1^{yopo}) are assumed to be Gamma distributed with both means of 0.3 whereas their standard deviations correspond to 0.2 and 0.1, respectively. These prior mean values are consistent with the estimated correlation between the fuel duty tax rate and UK oil consumption and, in turn, the estimated correlation between the PRT rate and the real oil price.

Autocorrelation Coefficients	**Distribution**	**Mean**	**St. Dev.**
UK Productivity: $\rho_{1,1}^{z}$	Beta	0.010	0.005
UK Productivity: $\rho_{2,1}^{z}$	Beta	0.0045	0.0040
UK Oil Supply: $\rho_{1,1}^{yo}$	Beta	0.90	0.05
UK Oil Supply: $\rho_{2,1}^{yo}$	Beta	0.0045	0.0040
Foreign Oil Supply: $\rho_{1,2}^{yo}$	Beta	0.90	0.05
Foreign Oil Supply: $\rho_{2,2}^{yo}$	Beta	0.0045	0.0040
UK Oil Intensity: $\rho_{1,1}^{zo}$	Beta	0.90	0.05
UK Oil Intensity: $\rho_{2,1}^{zo}$	Beta	0.0045	0.0020
UK Consumption: $\rho_{1,1}^{zc}$	Beta	0.70	0.20
UK Investment: $\rho_{1,1}^{zi}$	Beta	0.70	0.20
UK Import Preferences: $\rho_{1,1}^{zm}$	Beta	0.030	0.005
UK Import Preferences: $\rho_{2,1}^{zm}$	Beta	0.0045	0.0040
UK Price Markup: $\rho_{1,1}^{p}$	Beta	0.70	0.20
UK Wage Markup: $\rho_{1,1}^{w}$	Beta	0.70	0.20
UK Inflation Target: $\rho_{1,1}^{\pi}$	Beta	0.70	0.20
UK Gov. Expenditure: $\rho_{1,1}^{g}$	Beta	0.70	0.20

Table 3.5: Prior Distributions for the Shock Processes: Persistence Parameters

Table 3.5 shows the prior distributions for the persistence parameters of the shock processes. Beta distributions are chosen for all the autoregressive coefficients. We assume prior values implying that the domestic import preferences shock is more persistent than the domestic technological shock. Moreover, we assume that the persistence of oil supply shocks for domestic and foreign countries have the same priors.

As concerns the domestic oil intensity shock, $\rho_{1,1}^{zo}$ is assumed to have a mean of 0.90 and a standard deviation of 0.05, whereas $\rho_{2,1}^{zo}$ has a mean equal to 0.0045 and a standard deviation equal to 0.0020. Regarding to the persistences of AR(1) processes we set their prior means equal to 0.70 and their prior standard deviations equal to 0.20. Finally, we use inverse Gamma distributions for standard errors of all exogenous shocks with means equal to 0.01 and infinite degrees of freedom (Table 3.6).

Shock Standard Error	**Distribution**	**Mean**	**St. Dev.**
UK Productivity: σ_1^z	Inv-Gamma	0.01	Inf
Foreign Productivity: σ_2^z	Inv-Gamma	0.01	Inf
UK Oil Supply: σ_1^{yo}	Inv-Gamma	0.01	Inf
Foreign Oil Supply: σ_2^{yo}	Inv-Gamma	0.01	Inf
UK Oil Intensity: σ_1^{zo}	Inv-Gamma	0.01	Inf
Foreign Oil Intensity: σ_2^{zo}	Inv-Gamma	0.01	Inf
UK Consumption: σ_1^{zc}	Inv-Gamma	0.01	Inf
Foreign Private Consumption: σ_2^{zc}	Inv-Gamma	0.01	Inf
UK Import Preferences: σ_1^{zm}	Inv-Gamma	0.01	Inf
Foreign Import Preferences: σ_2^{zm}	Inv-Gamma	0.01	Inf
UK Investment: σ_1^{zi}	Inv-Gamma	0.01	Inf
UK Price Markup: σ_1^p	Inv-Gamma	0.01	Inf
UK Wage Markup: σ_1^w	Inv-Gamma	0.01	Inf
UK Inflation Target: σ_1^π	Inv-Gamma	0.01	Inf
UK Gov. Expenditure: σ_1^g	Inv-Gamma	0.01	Inf

Table 3.6: Prior Distributions for the Shock Processes: St. Errors

3.3.3 Estimated Results

In order to estimate the model we detrend each variable[66] using HP filter with smoothing parameter equal to 1,600.[67] As we mentioned before, the model is estimated with Bayesian methods. Our acceptance rate corresponds to 28%. In order to test the stability of the sample we use the convergence diagnostic of Brooks and Gelman (1998) that compares between and within moments of multiple chains.[68]

Table 3.7 reports the modes and the means with 5% and 95% of the posterior distributions of the endogenous parameters of the estimated model.[69] In particular, we observe that the estimate of the habit formation parameter (κ_1) is well identified by the data with a posterior mean of 0.91. This value is larger than the previous UK estimates of the same parameter.[70] Turning to the capital adjustment cost coefficient (φ_1^i), its posterior mean estimate is higher than its prior suggesting a lower response of investment to changes in the value of capital.

Our estimated value for χ_1 is much higher than the ones found by Harrison and Oomen (2010) and Millard (2011). Indeed, our theoretical framework (based on the two blocs open economy model) implies additional channels that affect real wages with respect to the standard small open economy models. More specifically, small open economy models miss the variation stemming from the endogenous oil price.

Turning to nominal rigidities, the posterior mean estimates suggest that wages

[66] As an alternative strategy, we also estimated the model demeaning the series of UK core inflation, wage inflation and nominal interest and detrending the remaining series. Then we compared the estimated results of these two different specifications and we did not find any particular difference in the posterior estimates.

[67] As noticed by Leeper et al. (2010), incorporating common stochastic trends into a model with fiscal policy is non-trivial since several fiscal variables appear to have their own trends which require particular adjustments.

[68] All estimates were made using Dynare (http://www.dynare.org/).

[69] In Appendix C we also show the prior and posterior probability density functions for all the estimated parameters.

[70] The estimates of DiCecio and Nelson (2007), Harrison and Oomen (2010), Millard (2011) range from 0.42 and 0.78.

are very sticky. The probability of optimally resetting nominal wages is 0.01. Our estimated value is lower than the one found by Harrison and Oomen (2010) of about 0.15. Moreover, wage changes are hardly indexed to lagged wage inflation.[71]

Par.	Description	Post. Mode	Post. Mean	Conf. Inter.	
κ_1	Cons. Habit	0.93	0.91	0.89	0.93
φ_1^i	Inv. Adj. Cost	4.02	4.40	2.53	6.26
χ_1	Lab. Sup. El. $(\frac{1}{2\chi})$	24.92	24.92	23.70	26.17
ξ_1^w	Calvo Wages Prob.	0.99	0.99	0.99	0.99
ξ_1^p	Calvo Prices Prob.	0.91	0.91	0.89	0.93
ι_1^w	Degree of Wage Ind.	0.12	0.13	0.04	0.21
ι_1^p	Degree of Price Ind.	0.11	0.17	0.05	0.28
γ_1^π	T. R. Coef. on Inflation	0.28	0.28	0.08	0.42
γ_1^y	T. R. Coef. on Output	0.19	0.24	0.14	0.34
γ_1^i	Int. Rate Smoothing Par.	0.90	0.91	0.88	0.95
$\frac{1+\rho_1^o}{\rho_1^o}$	Oil Elasticity	0.30	0.31	0.21	0.40
$\frac{1+\rho_1^c}{\rho_1^c}$	Trade Elasticity	2.83	2.81	2.65	2.96
ψ_1^{cc}	VAT / Priv. Cons. Coeff.	0.14	0.41	0.00	0.85
ψ_1^{ly}	Lab. Tax / GDP Coeff.	0.40	0.67	0.05	1.28
ψ_1^{lb}	Lab. Tax / Debt Coeff.	0.06	0.10	-0.03	0.24
ψ_1^{wb}	NIC / Debt Coeff.	0.05	0.08	-0.05	0.23
ψ_1^{ococ}	F. D. Tax / Oil Dem. Coeff.	0.14	0.18	0.04	0.31
ψ_1^{dd}	Corpor. Tax / Div. Coeff.	0.09	0.12	0.03	0.21
ψ_1^{yopo}	PRT / Oil Price Coeff.	0.16	0.22	0.05	0.38

Table 3.7: Estimation Results of Endogenous Parameters

The posterior mean estimates also show that prices are quite sticky, being changed roughly every ten quarters on average. The estimated value of ξ_1^p is in line with the Calvo price probability found by Millard (2011).[72] Moreover, price

[71] In particular, our posterior mean of ι_1^w is 0.13 in line with the 0.19 estimated by Millard (2011).

[72] In particular, Millard (2011) found that the probability of not being able to change price in the non-energy sector is 0.90.

indexation is quite low suggesting little inflation persistence. Our estimated value of ι_1^p is very similar as in Millard (2011).[73]

The estimated parameters of the Taylor Rule are all well identified. Our results imply that in our sample period the interest rate shows a higher responsiveness to inflation variation than output changes. Moreover, the posterior mean of γ_1^i implies that the nominal interest rate is highly autocorrelated.

Focusing on the price elasticity of oil demand ($\frac{1+\rho_1^o}{\rho_1^o}$), we find that its posterior mean estimate is well identified. In particular, our estimated value is in line with the results obtained by Kilian and Murphy (2010) for the US economy.[74] Moreover, our estimated trade elasticity ($\frac{1+\rho_1^c}{\rho_1^c}$) is larger than the one found by Hooper et al. (2000).[75]

Turning to the results of the fiscal policy parameters we observe that, in general, most of the posterior estimates are well identified. In particular, the estimated value of ψ_1^{ly} indicates that the labour income tax rate has a highly procyclical response to domestic output. Moreover, the estimates of the parameters ψ_1^{lb} and ψ_1^{wb} show that the labour income tax and the National Insurance Contribution do not respond strongly to debt.[76]

Our results also indicate a high mean value of ψ_1^{cc} implying that the response of the VAT rate to private consumption expenditure is important. Conversely, the low estimated value of ψ_1^{dd} implies that the corporation tax rate does not respond strongly to variations in firms' dividends.

The posterior mean estimate ψ_1^{ococ} indicates that the fuel duty tax rate has a moderate response to oil demand. On the contrary, our estimated value of ψ_1^{yopo} shows that the PRT rate responds strongly to oil price changes.

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[73] In particular, Millard (2011) found that price indexation in the non-energy sector is 0.15.

[74] In particular, Kilian and Murphy (2010) have distinguished between two different short run price elasticities of US oil demand: in production and in use. The absolute values of their posterior median estimates were 0.44 and 0.26, respectively.

[75] In particular, these authors estimated a long-run elasticity between domestic and foreign goods of 1.6 for the UK economy.

[76] Note that the estimated fiscal policy parameters in Table 3.7 are all positive, as sign restrictions are imposed in equations (3.31)-(3.37).

Finally, we focus on the estimated parameters of the stochastic shock processes (Tables 3.8 and 3.9).

Autocorrelation Coefficients	**Post. Mode**	**Post. Mean**	**Conf. Inter.**	
UK Productivity: $\rho^{z}_{1,1}$	0.0067	0.0091	0.0020	0.0156
UK Productivity: $\rho^{z}_{2,1}$	0.0006	0.0039	0.0001	0.0078
UK Oil Supply: $\rho^{yo}_{1,1}$	0.9205	0.8285	0.6875	0.9633
UK Oil Supply: $\rho^{yo}_{2,1}$	0.0011	0.0024	0.0003	0.0052
Foreign Oil Supply: $\rho^{yo}_{1,2}$	0.9727	0.9659	0.9429	0.9899
Foreign Oil Supply: $\rho^{yo}_{2,2}$	0.0019	0.0024	0.0011	0.0035
UK Oil Intensity: $\rho^{zo}_{1,1}$	0.5599	0.5858	0.4574	0.7116
UK Oil Intensity: $\rho^{zo}_{2,1}$	0.0052	0.0056	0.0019	0.0092
UK Private Consumption: $\rho^{zc}_{1,1}$	0.2334	0.3025	0.1179	0.4942
UK Private Investment: $\rho^{zi}_{1,1}$	0.1615	0.1901	0.0423	0.3287
UK Import Preferences: $\rho^{zm}_{1,1}$	0.0292	0.0298	0.0217	0.0376
UK Import Preferences: $\rho^{zm}_{2,1}$	0.0004	0.0028	0.0001	0.0068
UK Price Markup: $\rho^{p}_{1,1}$	0.3568	0.2872	0.1250	0.4391
UK Wage Markup: $\rho^{w}_{1,1}$	0.2691	0.3292	0.1710	0.4823
UK Inflation Target: $\rho^{\pi}_{1,1}$	0.8335	0.8064	0.6979	0.8990
UK Gov. Expenditure: $\rho^{g}_{1,1}$	0.5166	0.5107	0.3456	0.6693

Table 3.8: Estimation Results of Shock Processes: Persistence Parameters

Focusing on the AR(1) processes the posterior estimates suggest that the UK inflation target shock is fairly persistent but the other shocks much less so. Concerning AR(2) processes, the UK import preferences shock is more persistent than the UK productivity shock. Turning to oil shocks, the foreign oil supply shock is the most persistent followed by the UK oil supply shock and the UK oil intensity shock. The estimated standard deviations of these stochastic processes are in general well identified and in most of the cases significantly higher than the prior means (Table 3.9).

Shock Standard Error	Post. Mode	Post. Mean	Conf. Inter.	
UK Productivity: σ_1^z	0.0850	0.0869	0.0737	0.1000
Foreign Productivity: σ_2^z	0.0847	0.0952	0.0773	0.1122
UK Oil Supply: σ_1^{yo}	0.1146	0.1112	0.0926	0.1290
Foreign Oil Supply: σ_2^{yo}	0.0141	0.0143	0.0120	0.0164
UK Oil Intensity: σ_1^{zo}	0.2187	0.2333	0.1773	0.2856
Foreign Oil Intensity: σ_2^{zo}	0.0172	0.0160	0.0128	0.0189
UK Private Consumption: σ_1^{zc}	0.0105	0.0115	0.0094	0.0136
Foreign Private Consumption: σ_2^{zc}	0.0697	0.0778	0.0645	0.0897
UK Import Preferences: σ_1^{zm}	0.0195	0.0199	0.0169	0.0228
Foreign Import Preferences: σ_2^{zm}	0.0358	0.0370	0.0312	0.0425
UK Private Investment: σ_1^{zi}	0.1777	0.1930	0.1090	0.2760
UK Price Markup: σ_1^p	3.1062	3.5997	1.9652	5.3767
UK Wage Markup: σ_1^w	3.8985	4.4667	3.0784	5.7339
UK Inflation Target: σ_1^π	0.0451	0.0714	0.0052	0.1188
UK Gov. Expenditure: σ_1^g	0.0432	0.0440	0.0374	0.0504

Table 3.9: Estimation Results of Shock Processes: St. Errors

3.3.4 Variance Decomposition Analysis

In order to interpret the estimates of the parameters governing all the shock processes we focus on Table 3.10. The latter table shows the variance decomposition of the key variables obtained by simulating the model once the parameters have been estimated. The simulation results are obtained through 10,000 iterations (neglecting the first 1,000) and are filtered by HP filter with smoothing parameter equal to 1,600.

As expected, oil price changes are mostly explained by foreign shocks, whereas domestic shocks do not play a significant role. In particular, the foreign oil intensity shock is clearly the most important in explaining the oil price, accounting for almost half of the variation in the oil price. Moreover, the foreign oil supply shock and the foreign productivity shock explain 28% and 18% of the oil price variance, respectively.

The price of oil is not the only channel for the transmission of oil shocks. Indeed, the foreign oil intensity shock plays a significant role in influencing the variance of many UK observed variables (such as private investment, headline inflation, overall trade balance, private consumption, government debt and GDP).

	Oil Price (real)	UK GDP (real)	UK Cons. (GDP share)	UK Inv. (GDP share)	For. GDP (real)	UK Head. Infl.	UK Ov. Bal. (GDP share)	UK Ex. Rate (real)	UK G. Debt (GDP share)
H. Prod.	0	50	33	23	0	4	9	2	45
F. Prod.	18	1	1	7	76	5	10	2	9
H. Cons.	0	1	1	0	0	0	1	0	0
F. Cons.	2	2	5	4	3	4	24	0	2
H. Imp.	0	0	0	0	0	5	0	10	0
F. Imp.	0	1	1	0	0	8	2	76	0
H. Oil S.	6	12	15	2	1	4	16	0	2
F. Oil S.	28	5	6	19	4	16	10	1	9
H. Oil I.	1	4	8	1	0	11	6	6	1
F. Oil I.	44	9	14	35	12	27	15	2	13
H. Inv.	0	1	2	5	0	0	1	0	0
H. W. M.	0	1	1	0	1	0	1	0	0
H. P. M.	0	1	1	0	0	12	0	0	2
H. M. P.	1	12	11	3	3	3	5	1	3
H. G. Ex.	0	1	2	0	0	0	0	0	14

Table 3.10: Variance Decompositions (Percentage) - All Shocks

Similarly, the foreign oil supply shock accounts for a significant variation in several UK macroeconomic aggregates (such as private investment, headline inflation and overall trade balance). Interestingly, the UK oil supply shock has a relevant impact on the variation of some UK observed variables such as total trade balance, private consumption and GDP.

In general, these findings highlight the importance of general equilibrium effects for the transmission of shocks that are specific to the oil market and are in line with previous results on the US economy (see for example Bodestein et al., 2011, and Bodenstein et al., 2012).

The UK government debt variance is mostly explained by the domestic productivity shock. This outcome can be justified as follows. The change in domestic productivity directly affects the total tax base. Since government spending has been fairly stable during the period 1990-2005, the variation of the tax base strongly influenced the UK debt level.

Interestingly, we find that the foreign oil intensity shock contributes significantly to the variation of UK government debt. The main reason is that the foreign oil intensity shock strongly affects the oil price. Accordingly, relevant changes in the oil price imply more volatile oil tax revenues and, in turn, debt levels. Finally, the variation of the UK government debt is also explained by the domestic government spending shock.

3.3.5 Business Cycle Statistics

We will now proceed by verifying if our estimated model is able to capture the business cycle properties of the key variables. To do so we compare the actual business cycle moments with those implied by our model.

As in the variance decomposition analysis, we simulate the model once the parameters have been estimated. Table 3.11 shows the relative standard deviations of the key variables with respect to GDP.

Variable	Model	Data
UK GDP	1.00	1.00
UK Oil Production	5.54	7.58
Foreign Oil Production	0.76	1.74
UK Oil Imports (GDP Share)	0.57	0.16
Real Oil Price	20.64	20.95
UK Non Oil Goods Imports (GDP Share)	0.23	0.93
UK Goods Exports (GDP Share)	0.27	0.78
UK Real Exchange Rate (qr.)	3.45	4.39
UK Private Consumption (GDP share)	0.49	0.48
UK Private Investment (GDP share)	0.37	0.64
UK Headline Inflation	0.19	0.56
UK 3 Months Treasury Bills (qr.)	2.10	1.22
UK Wage Inflation	0.03	0.07
UK Government Debt	2.80	2.05

Table 3.11: Observed Data and Model Implications - Relative St. Deviations to GDP

In general, the model is able to reproduce the volatilities of the actual variables. More specifically, we note that the real oil price is extremely volatile. Moreover, the UK oil production, the UK real effective exchange rate and the nominal interest rate display higher volatilities than the UK GDP. Interestingly, the volatility of the UK government debt is almost double than the one of the UK GDP. On the contrary, the UK headline inflation and the UK wage inflation show small standard deviations compared to the UK GDP.

Table 3.12 shows the autocorrelations of the key variables of the model. In general, all the variables display a strong persistence except the UK headline inflation and the wage inflation.

In general, from these batteries of statistics we can conclude that the business cycle moments implied by model fit well the ones of actual data.

Variable	Model	Data
UK GDP	0.89	0.96
UK Oil Production	0.96	0.85
Foreign Oil Production	0.97	0.93
UK Oil Imports (GDP Share)	0.92	0.81
Real Oil Price	0.90	0.84
UK Non Oil Goods Imports (GDP Share)	0.72	0.90
UK Goods Exports (GDP Share)	0.86	0.94
UK Real Exchange Rate (qr.)	0.76	0.96
UK Private Consumption (GDP share)	0.91	0.92
UK Private Investment (GDP share)	0.95	0.89
UK Headline Inflation	0.49	0.53
UK 3 Months Treasury Bills (qr.)	0.88	0.97
UK Wage Inflation	0.82	0.57
UK Government Debt	0.96	0.99

Table 3.12: Observed Data and Model Implications - Autocorrelations

3.4 How Do Oil Price Changes Impact on UK Public Finances?

In this section, we are going to analyse the specific effects of oil price fluctuations on the UK fiscal sector and, in particular, at which rate oil price changes work through the economy into UK public finances. With respect to previous papers that have investigated this issue[77], both the theoretical framework and the empirical strategy adopted in this paper present several advantages.

[77] See for example, Powell and Horton (1985), Hall et al. (1986), Young (2000), NIESR (2000), OECD Economic Surveys (2002), OBR (2010) and Barrell et al. (2011a) and (2011b).

Firstly, our analysis takes into account the several sources of oil price shocks. The particular implications of an oil price shock for UK public finances differ depending on whether the shock is global or UK specific. Similarly, the effects implied by oil demand shocks are different from the ones generated by oil supply shocks.

Secondly, the impact of oil price fluctuations on UK public finances also depends significantly on how long the oil price change lasts. Accordingly, our empirical strategy allows us to estimate directly the persistence of the exogenous shocks affecting oil prices.

Thirdly, the effects of oil price movements on UK public finances are related to the size of the UK price elasticity of oil demand. Thus, we estimate the latter through Bayesian techniques.

Finally, our theoretical framework allows us to consider the response of the UK fiscal sector in the case of actual and potential economy. In particular, our model includes both real (adjustment costs and consumption habits) and nominal (price and wage rigidities) frictions. Accordingly, we are able to assess the behaviours of UK fiscal variables in the rigid and flexible economy.

In Tables 3.13-3.14 and 3.15-3.16 we show the assessment of the effects of oil price fluctuations on UK public finances. In particular, we consider foreign oil intensity and foreign oil supply shocks. The shocks are chosen in order to induce a drop in the oil price. Moreover, we distinguish between rigid and flexible economy cases. The values shown in the tables are obtained from the estimates of our model. In particular, they follow a temporary one standard deviation change in each exogenous shock. Finally, in order to construct the numbers reported in the tables, we use the average value of each variable (expressed in £ billions) for the sample period 1990-2005.

As we can see from Tables 3.13 and 3.15 a change in oil price affects UK oil revenues. In particular, a lower oil price depresses the petroleum revenue tax. Our estimated model indicates a decline of £300 millions in oil revenues one year after a positive shock to foreign oil intensity. This loss decreases from the second year onwards and is equal to 200 millions of Sterling Pounds. PRT revenues decrease at lower pace in the case of a positive foreign oil supply shock.

	Year 1	Year 2	Year 3	Year 4
Oil Revenues (billions £)	-0.3	-0.2	-0.2	-0.2
VAT Revenues (billions £)	-0.1	-0.1	-0.1	0.0
Fuel Duty Revenues (billions £)	-0.4	-0.3	-0.3	-0.2
Corporation Tax Revenues (billions £)	0.0	0.0	0.0	0.0
Income Tax Revenues (billions £)	0.2	0.2	0.2	0.1
NIC Revenues (billions £)	0.1	0.1	0.1	0.1
Government Net Debt (billions £)	0.7	1.0	1.1	1.1
GDP (billions £)	1.0	0.9	0.5	0.3

Table 3.13: Impact of the Foreign Oil Intensity Shock - Rigid Economy (One Positive Estimated St. Dev. Shock to Foreign Oil Intensity)

	Year 1	Year 2	Year 3	Year 4
Oil Revenues (billions £)	-0.3	-0.2	-0.2	-0.2
VAT Revenues (billions £)	-0.1	-0.1	-0.0	0.0
Fuel Duty Revenues (billions £)	-0.4	-0.3	-0.3	-0.2
Corporation Tax Revenues (billions £)	0.0	0.0	0.0	0.0
Income Tax Revenues (billions £)	0.2	0.2	0.2	0.2
NIC Revenues (billions £)	0.1	0.1	0.1	0.1
Government Net Debt (billions £)	0.4	0.8	0.9	1.0
GDP (billions £)	0.2	0.2	0.2	0.2

Table 3.14: Impact of the Foreign Oil Intensity Shock - Flexible Economy (One Positive Estimated St. Dev. Shock to Foreign Oil Intensity)

As we will explain in the impulse response analysis, our estimated model predicts a large drop in the oil price which prevails on the expansion of oil demand by households. Consequently, we find a loss of fuel duty revenues. As we can observe from Tables 3.13 and 3.15, fuel duty revenues diminish following both shocks. Again, we notice a stronger effect after the foreign oil intensity shock (£400 millions the first year after the shock).

	Year 1	Year 2	Year 3	Year 4
Oil Revenues (billions £)	-0.2	-0.2	-0.1	-0.1
VAT Revenues (billions £)	-0.1	-0.1	0.0	0.0
Fuel Duty Revenues (billions £)	-0.3	-0.2	-0.2	-0.1
Corporation Tax Revenues (billions £)	0.0	0.0	0.0	0.0
Income Tax Revenues (billions £)	0.2	0.2	0.1	0.1
NIC Revenues (billions £)	0.0	0.1	0.0	0.0
Government Net Debt (billions £)	0.7	0.9	1.0	0.9
GDP (billions £)	0.7	0.6	0.3	0.1

Table 3.15: Impact of the Foreign Oil Supply Shock - Rigid Economy (One Positive Estimated St. Dev. Shock to Foreign Oil Supply)

	Year 1	Year 2	Year 3	Year 4
Oil Revenues (billions £)	-0.2	-0.2	-0.1	-0.1
VAT Revenues (billions £)	-0.1	-0.1	0.0	0.0
Fuel Duty Revenues (billions £)	-0.3	-0.2	-0.2	-0.1
Corporation Tax Revenues (billions £)	0.0	0.0	0.0	0.0
Income Tax Revenues (billions £)	0.2	0.2	0.1	0.1
NIC Revenues (billions £)	0.1	0.1	0.1	0.0
Government Net Debt (billions £)	0.3	0.6	0.7	0.7
GDP (billions £)	0.2	0.2	0.2	0.1

Table 3.16: Impact of the Foreign Oil Supply Shock - Flexible Economy (One Positive Estimated St. Dev. Shock to Foreign Oil Supply)

Table 3.13 and 3.15 show that VAT revenues fall after both shocks for two main reasons. Firstly, the lower oil price implies the drop of oil sales. Secondly, both shocks induce the reduction in the sales of non-oil imported goods. Consequently, in response to the foreign oil intensity shock VAT receipts decrease by £100 millions for the three years following the shock. The drop of VAT revenues is less persistent in response to the foreign oil supply shock.

As we can note from Tables 3.13 and 3.15, the remaining tax receipts increase benefitting from the positive effects of the lower oil price on the UK economy.

Generally, in terms of tax revenues, we do not observe significant differences between flexible and rigid economy cases (Tables 3.13-3.14 and 3.15-3.16). On the contrary, the responses of GDP and government debt are different in the cases of actual and potential economy.

In terms of the effects on GDP, a change in the oil price affects the quantity of output that firms wish to supply and therefore affects the economy's supply. Similarly, the variation of oil price impacts on household incomes and influences their decisions in terms of consumption and savings. In turn, this implies a variation in the economy's demand. Moreover, in response to lower oil price, the firms' marginal cost drops implying a fall in the domestic inflation. As a consequence, Central Bank decreases its policy rate further boosting domestic output. Nominal and real rigidities are particularly relevant in the transmission channels of oil price variations. As we can observe from Tables 3.13-3.14 and 3.15-3.16, the positive responses of actual GDP to foreign oil intensity and oil supply shocks are always higher than the ones of potential GDP.

Regarding domestic government debt, as we will explain in Sections 5.1 and 5.2, our model assumes that foreign oil intensity and foreign oil supply shocks do not affect UK government expenditure. Accordingly, the response of UK government debt depends on the changes of tax revenues. In particular, the negative direct effects of oil price decrease on PRT, fuel duty and VAT revenues prevail on the positive indirect effects on the remaining tax receipts. As a consequence, UK public finances worsen following both shocks. In particular, in response to a foreign oil intensity shock, government debt increases by £700 millions during the first year and it reaches £1100 millions in four years. In the case of a foreign oil supply shock, government debt rises by £700 millions during the first year and it peaks in three years (£1000 millions). Finally, we note that the deterioration of UK public finances is less pronounced for the potential economy than in the case of the rigid economy (Tables 3.13-3.14 and 3.15-3.16).

3.4.1 Some Comparisons with Previous Studies

Although the previous studies on the effects of oil price changes on the UK public finances suffer from the four limitations we explained above, it is useful to compare our results with their findings. Firstly, we compare our model with a set of less recent analysis by the NIESR (Hall et al., 1986), the HM Treasury (Powell and Horton, 1986) and the London Business School (Sunday Times, February 1986 and a communication from Goffrey Dicks). Secondly, we compare our results with the findings of a more recent study by the Office for Budget Responsibility (2010).

Considering the first comparison (Table 3.17), there are two important reasons why the results from our model and the analysis of the NIESR, the HMT and the LBS are not directly comparable. Firstly, the sample periods are different. As we explained above, our analysis covers the period 1990-2005, whereas the other three studies focus on the data of the 1986. Secondly, the scale of the assumed changes in the price of oil between our model and the other three studies is very different. As we explained above, in our model the variation in the oil price corresponds to the estimated standard deviation change in each exogenous shock. Conversely, the LBS simulation considers a 25% fall in the oil price, whereas the other two simulations assume a 10% fall.

Nevertheless, our results and the findings of the NIESR, the HMT and the LBS agree on several aspects. For example, our model confirms the findings of those studies by showing that a drop in the oil price induces a fall in the UK oil revenues. However, our results indicate that the magnitude of the reduction in the oil revenues is less intense than the one predicted by NIESR, the HMT and the LBS.

There is also a substantial measure of agreement between our results and the other three studies over the effects of oil price decreases on the government finances. Indeed, according to the analysis of the NIESR, the HMT and the LBS the decrease in the oil price induces an important increase in the government budget deficit. Similarly, our results show a relevant increase in the government debt in response to a drop in the oil price.

Finally, in accordance with the results of the NIESR, the HMT and the LBS, we find that the UK GDP increases after a fall in the oil price. However, in contrast with those three studies we find that the persistence of this effect is lower.

		Year 1	Year 2	Year 3	Year 4
NIESR (10% fall)	Oil Revenues (billions £)	-0.03	-0.44	-1.28	-1.19
	PSBR (billions £)	0.04	0.38	1.23	0.92
	GDP (%)	0.04	0.10	0.15	0.20
HMT (10% fall)	Oil Revenues (billions £)	-0.70	-1.10	-1.20	-1.10
	PSBR (billions £)	0.70	1.10	1.00	1.10
	GDP (%)	0.10	0.20	0.10	0.00
LBS (25% fall)	Oil Revenues (billions £)	-1.56	-2.14	-2.01	-1.96
	PSBR (billions £)	1.29	1.27	0.52	0.19
	GDP (%)	0.44	1.21	1.28	0.94

Table 3.17: First Comparison: NIESR, HMT and LBS

Turning to the second comparison with the OBR report of 2010, from Table 3.18, we note many similarities with our results. More specifically, the OBR report of 2010 simulates the effects on UK public finances of a permanent £10 decrease in the oil price for the period 2000-2010.

In particular, our results agree with those of the OBR in showing a fall in oil revenues after a drop in the oil price. However, this fall is less intense in our case than in the OBR simulation. Secondly, both the OBR results and our findings predict a decrease in VAT revenues. In contrast with the OBR simulation, we find a fall in fuel duty revenues in response to a drop in the oil price. Finally, as in the OBR results, we find that the UK GDP increases after a fall in the oil price. However, our findings show that the magnitude of this effect is weaker than in the OBR case.

	Year 1	Year 2	Year 3	Year 4
Oil Revenues (billions £)	-2.4	-2.4	-2.4	-2.4
VAT Revenues (billions £)	-0.2	-0.2	-0.1	0.0
Fuel Duty Revenues (billions £)	0.2	0.3	0.3	0.3
GDP (billions £)	1.7	3.5	4.1	4.5

Table 3.18: Second Comparison: OBR (Perm. 10 Pounds Decrease in the Oil Price)

3.5 Impulse Response Analysis

This section presents some impulse response functions for the estimated model. In particular, we focus on IRFs related to the shocks that mainly affect the changes in the oil price according to our variance decomposition analysis.

The lines displayed in the various charts are generated by the mean estimates of the posterior distributions of the model. In each figure, we show the impulse responses following a temporary one-standard deviation change in the exogenous shock. We chose the signs of the shocks in order to induce a decrease in the oil price. In general, the impacts of the shocks on UK macroeconomic aggregates displayed in the figures below are in line with results obtained in Chapter 2.

3.5.1 Foreign Oil Intensity Shock

We start by analysing the effects of a positive shock to foreign oil intensity (Figures 3.1 and 3.2). An increase of $Z^o_{2,t}$ implies that the foreign country improves its oil efficiency and decreases its oil demand. As a consequence, we observe a drop in the real oil price in Sterling terms (Graph (a)) and a rise of the UK oil demand (Graph (b)).

From Graph (a), we note that the shock is very persistent. This aspect implies that the effects on all endogenous variables last for a long time horizon.

Graphs (c) and (i) show the positive responses of GDP and domestic absorption (defined as the sum of UK consumption and investment). Similarly, hours worked increase in response to the shock (Graph (j)).

Turning to external sector, we observe a deficit of the UK overall trade balance after the shock (Graph (k)). In particular, since the UK is a net oil exporter, a positive foreign oil intensity shock implies a reduction of UK oil exports. As we can note from Graph (k), the domestic non-oil trade balance is not influenced by the shock.

Graph (l) shows the pattern of the UK real exchange rate that we define as the price of the foreign consumption basket over the price of the domestic consumption basket in a common currency. We note an immediate appreciation of the Pound. However, from the third quarter onwards, the domestic exchange rate depreciates. The depreciation of the UK currency is caused by the increase of the relative price of imported goods with respect to domestic goods.

This result is different from what we found in Chapter 2 and it can be explained considering the behaviour of UK taxation in response to the shock.

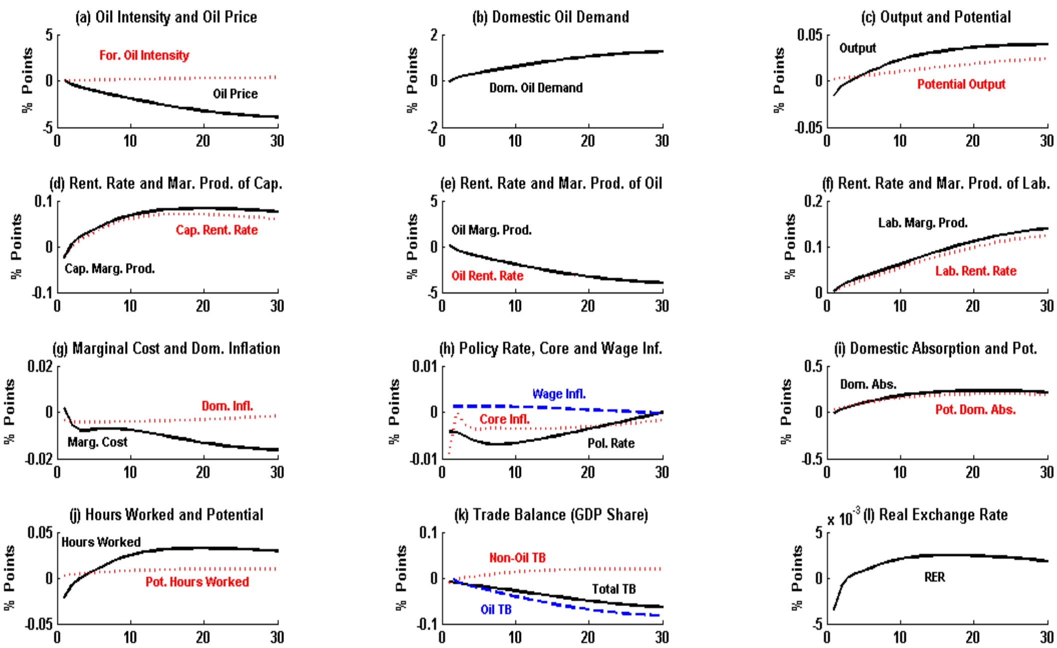


Figure 3.1: IRFs of Main Variables to a Positive Foreign Oil Intensity Shock

Indeed, in the UK, the value added tax is also charged on road fuel. In particular, VAT is charged on the pre-tax plus duty price. Therefore, the decrease in the oil price (due to the positive shock to foreign oil intensity) induces a reduction in the VAT on oil products.[78] In turn, this reduction stimulates the consumption of domestic oil goods. Since in our model final consumption goods are a combination of non-oil and oil goods, we observe the reduction of the price of domestic consumption goods. Therefore, the relative price of imported goods with respect to domestic goods increases inducing the depreciation of the Pound.

As we can see from Graph (g), the response of the marginal cost is negative implying a reduction in inflation. In particular, the drop of the marginal cost is due to the negative gaps between the rental rates and the marginal products of each factor input.[79] From Graph (e), we note that the negative difference between the oil rental rate and the oil marginal product does not contribute substantially to the fall of marginal cost. Conversely, the negative differences between the rental rates and the marginal products of the other two factors induce the drop of the marginal cost (Graphs (d) and (f)).

Graph (h) shows that, after the shock, wage inflation does not change substantially. On the contrary, core inflation remains negative for almost all of the quarters. As a consequence, Bank of England reduces the nominal interest rate.

Turning to the fiscal sector, Figure 3.2 displays the responses of government debt and main tax revenues to the positive shock of foreign oil intensity.[80] As we can observe from Graph (m), the UK government debt expands persistently. In particular, since the foreign oil intensity shock is very persistent the return of government debt to its steady state value occurs beyond the horizons shown in the

[78] Our result is in line with the paper of Leicester (2005) concerning fuel taxation in UK for the period 1990-2005.

[79] See relation (C154) in Appendix C for the equation expressing domestic marginal cost.

[80] In Figures 3.2, 3.4 and 3.6 the solid black lines correspond to the actual responses of fiscal variables whereas the dotted red lines represent the responses of fiscal variables in the case of a flexible economy.

figure.

This result confirms the findings of several papers that have analysed how UK public finances react to changes in the oil price (see, for example, Powell and Horton, 1985; Hall et al., 1986; Young, 2000 and OECD Economic Surveys, United Kingdom - 2002). In particular, all these studies have shown that a fall in the oil price implies the reduction of oil revenues and, in turn, the worsening of UK public finances.

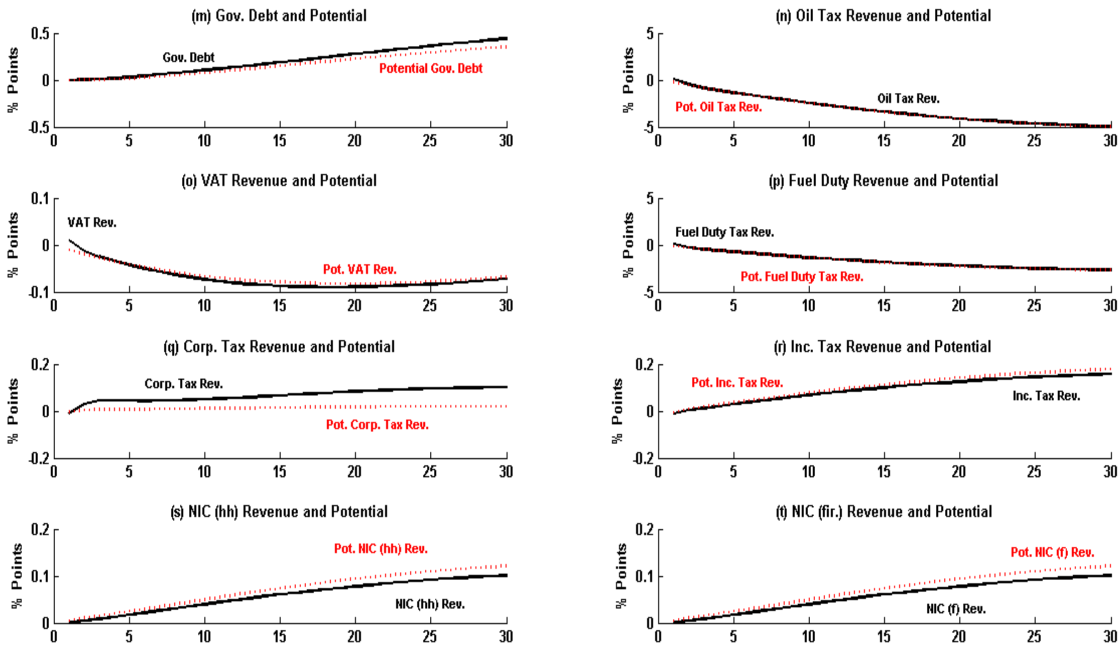


Figure 3.2: IRFs of Fiscal Variables to a Positive Foreign Oil Intensity Shock

Moreover, our results are in line with the UK actual data that show a negative relationship between the real oil price (expressed in Sterling Pounds) and the share of UK government debt on GDP for the period 1990-2005.[81]

[81] The correlation between the detrended series of real oil price and the share of public sector net debt on GDP is -0.17. Moreover, the correlation for these original series (not detrended) corresponds to -0.38.

Contrary to the papers mentioned above, our model takes into account several transmission mechanisms of oil shocks on public finances. Thus, we need to be very careful in describing each single effect. In particular, considering a positive oil intensity shock generated abroad we assume that government expenditure is constant (since it is one of the exogenous variables of the model). Thus, the positive response of government debt is mainly due to the decrease of total tax receipts. Accordingly, Graphs (n)-(t) provide a breakdown of the several tax revenues responses to the shock.

From Graph (n), we can observe that oil revenues reduce consistently in response to the fall of oil price. Moreover, Graph (p) shows that fuel duty tax revenues diminish considerably. In particular, although the oil demand by households increases in response to the lower oil price, the value of oil sales diminishes. Therefore, the large drop in the oil price prevails on the expansion of oil demand by households inducing fuel duty tax revenues to fall.

Graph (o) shows that, in response to the shock, consumption tax revenues fall. In particular, with the VAT paid on the oil and non-oil elements of the pump price, VAT receipts on oil decrease. Similarly, VAT revenues from consumption of imported non-oil goods fall. As a consequence, we observe a negative response of total VAT revenues.

Turning to the remaining tax receipts, Graph (q) shows that corporation tax revenues increase after the shock. Since the UK experiences a productivity expansion due to the lower oil price, the firms' profits are higher, inducing a raise in corporation tax revenues. Finally, in response to the shock, income tax and NIC revenues increase because of the higher labour income experienced by the households (Graphs (r), (s) and (t)) .

As we have stated above, the overall effect of these tax revenues induces the expansion of UK government debt (Graph (m)). In order to understand this outcome we need to analyse several aspects. Although, the receipts from PRT, VAT and fuel duty tax accounts for only 1/3 of total tax receipts, we should consider the net effects of the lower oil price on each tax receipt. In particular, our model implies that oil price changes have both direct and indirect effects on these revenues. More specifically, we observe a direct effect of oil price changes on PRT and fuel duty revenues, whereas on the other revenues the effects are indirect. Accordingly, after thirty periods the shock occurs, the reductions of oil and fuel duty revenues are relevant (they decrease 5% and 2.7%, respectively). On the contrary, the improvements of income tax and NICs revenues are relatively small (they increase 0.15% and 0.10%, respectively). This implies that the increases of income tax, NIC and corporation tax revenues are not sufficient to offset the decreases of PRT, fuel duty and VAT revenues. As a consequence domestic government debt expands.

3.5.2 Foreign Oil Supply Shock

Figures 3.3 and 3.4 show the effects of a positive foreign oil supply shock ($Y^o_{2,t}$). In particular, the increase in the foreign oil supply causes a drop in foreign oil demand. As a consequence, the real oil price expressed in Sterling Pounds decreases (Graph (a)) and, in turn, the UK oil demand expands (Graph (b)). Also in this case, the shock is extremely persistent (Graph (a)).

Similarly to the case described in the previous section, GDP (Graph (c)) and domestic absorption (Graph (i)) increase. As we can observe from Graph (j), hours worked mimic the behaviour of domestic output.

Considering the trade sector, the UK overall trade balance deteriorates. In particular, the reduction of foreign oil demand implies that the UK oil balance worsens whereas the domestic non-oil trade balance remains mostly unchanged after the shock (Graph (k)). As in the case of the foreign oil intensity shock, after an initial appreciation of the Pound, the UK exchange rate depreciates (Graph (l)).

Graph (g) shows that the domestic marginal cost decreases in response to the shock. As we can observe from Graphs (f), there is a substantial difference between labour marginal product and nominal wage. Similarly, the gap between capital marginal product and real rental rate is also relevant (Graph (d)). As a consequence, these two gaps imply the fall in the marginal cost.

Graph (h) shows that core inflation contracts in response to the shock. Accordingly, the Bank of England decreases the nominal interest rate. On the contrary, the response of wage inflation is close to zero throughout all quarters.

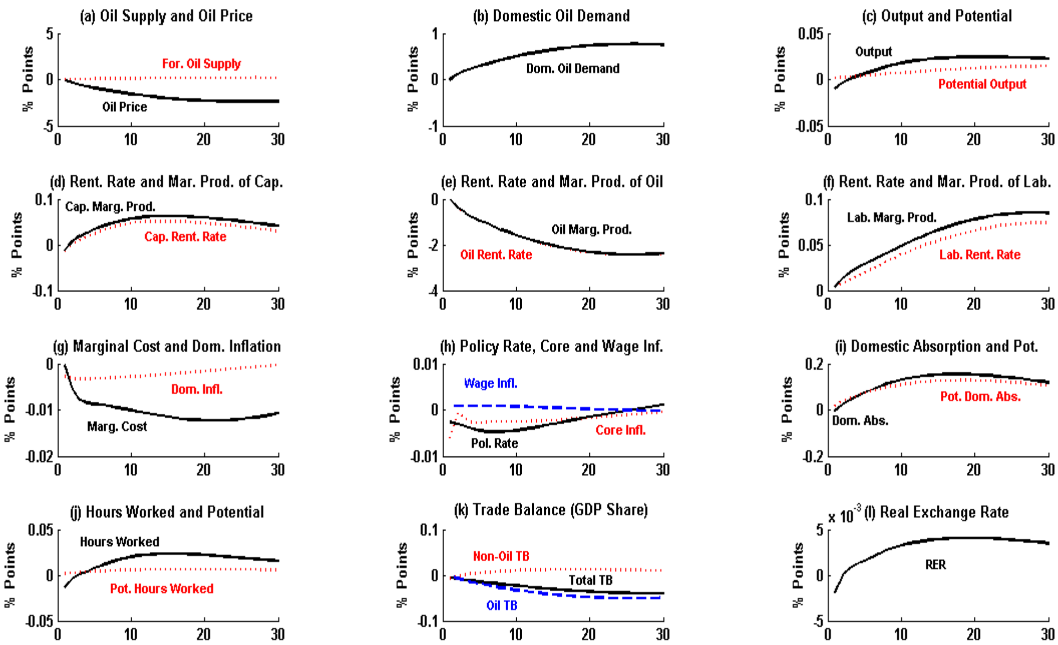


Figure 3.3: IRFs of Main Variables to a Positive Foreign Oil Supply Shock

Turning to the responses of fiscal variables, Figure 3.4 shows the IRFs for UK government debt and the several tax receipts. Again, we consider government spending to be unchanged after the shock.

In general, the patterns of the responses displayed in Figure 3.4 mimic those analysed in the case of the positive foreign oil intensity shock (Figure 3.2). The only difference lies in terms of magnitudes of the responses. More specifically, since foreign oil supply shock is less volatile than foreign oil intensity shock the effects on the several fiscal variables are also smaller.

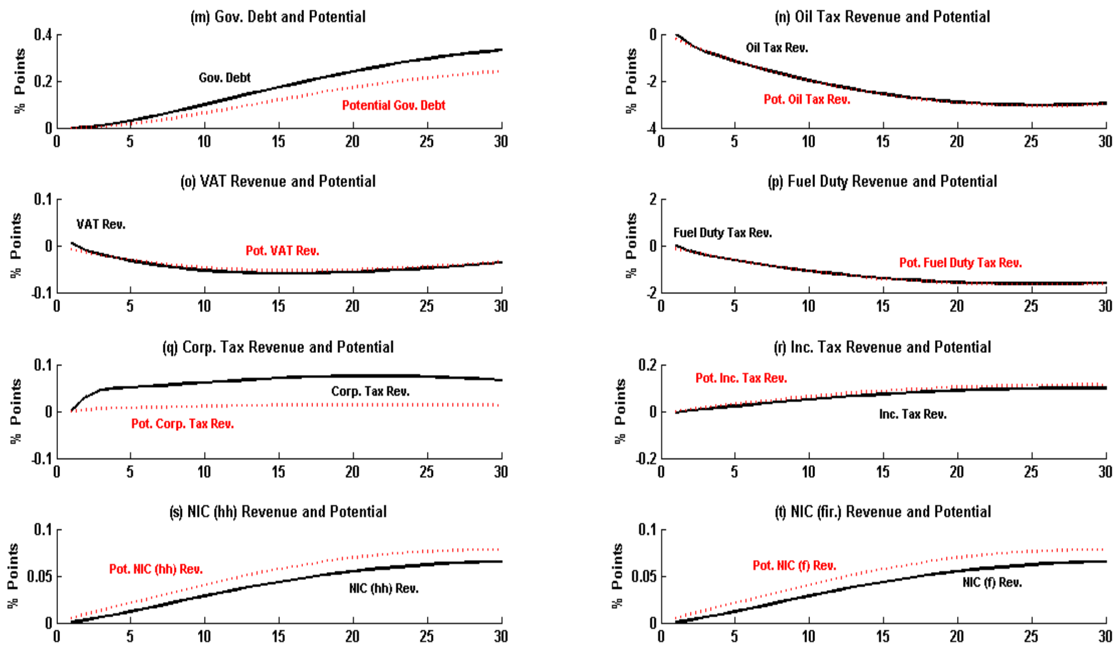


Figure 3.4: IRFs of Fiscal Variables to a Positive Foreign Oil Supply Shock

As we can observe from Graphs (n) and (p) oil revenues and fuel duty tax revenues contract because of the drop in the oil price. Similarly, VAT receipts (Graph (o)) reduce because of the lower value-added tax receipts on oil products and imported non-oil goods.

On the contrary, corporation tax revenues (Graph (q)) increase since firms profits expand in response to the shock. Similarly, we observe the positive responses of income tax and NIC receipts (Graphs (r)-(s)) due to the improvement of the household's labour income.

The total effect of these tax receipts implies a worsening of the UK public finances. Indeed, the domestic government debt increases in response to the shock (Graph (m)). As we explained in Section 5.1, the negative direct effect of the lower oil price on PRT and fuel duty receipts more than offsets the positive indirect effect of the lower oil price on the other tax revenues.

3.5.3 Foreign Technology Shock

According to our variance decomposition analysis the foreign technology shock plays an important role in terms of explanation of UK oil price volatility. Thus, it is particularly interesting to analyse the responses of the UK economy to this shock. In particular, Figures 3.5 and 3.6 show the impulse response functions of a negative foreign technology shock ($Z_{2,t}$).

As we found in Chapter 2, we note that the effects generated by the oil market channels dominate the typical effects of a technology shock.

The negative foreign technology shock induces a drop in the foreign oil demand and a consequent fall of the real oil price. As we can observe from Graph (a), UK oil price decreases. This implies an increase of domestic oil demand (Graph (b)). Moreover, from Graph (a), we note that the shock displays a strong persistence causing long lasting effects on the several variables.

In terms of the domestic economy, the drop of UK oil price generates positive effects on GDP (Graph (b)) and domestic absorption (Graph (i)). Moreover, hours worked display a pattern that is very similar to domestic output (Graph (j)).

Considering the international trade, from Graph (l), we observe that UK real effective exchange rate depreciates. Indeed, the negative shock to foreign productivity induces an increase of the relative price of imported goods with respect to domestic goods.

Graph (k) shows the deterioration of UK oil balance. In particular, the fall of foreign oil demand negatively affects the UK oil exports. Differently from the results of Chapter 2, UK non-oil goods balance improves after the negative foreign technology shock (Graph (k)). The explanation of this result can be found in the behaviour of UK taxation in response to this shock. In particular, the initial drop in the price of domestic non-oil consumption goods (due to the lower oil price) is strengthened by the fall of VAT on oil products. Indeed, as we explained in Sections 5.1 and 5.2, the fall in the oil price induces a reduction in VAT for oil products. The lower VAT pushes down the price of domestic final consumption goods and, in turn, the price of domestic non-oil goods. This large drop in the price of domestic non-oil goods stimulate foreign demand. Therefore, as shown in Graph (k), UK non-oil goods exports improve. However, this increase of non-oil trade balance is not able to offset the fall of oil balance. Consequently, domestic total trade balance deteriorates (Graph (k)).

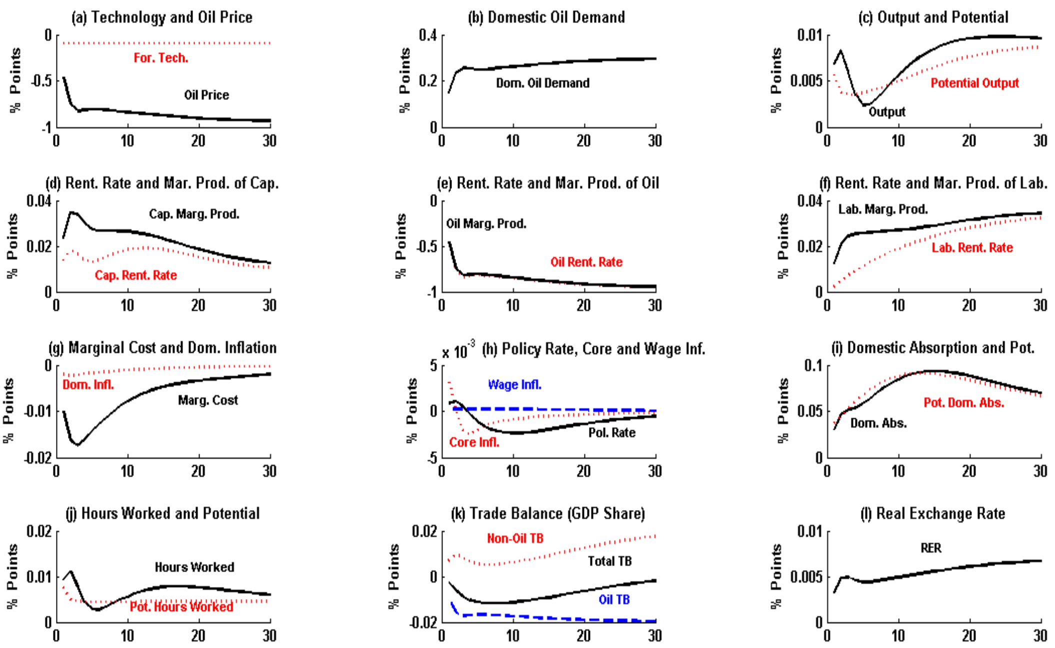


Figure 3.5: IRFs of Main Variables to a Negative Foreign Technology Shock

In response to the shock, domestic goods inflation drops because of the fall of domestic marginal cost (Graph (g)). As we can see from Graphs (d) and (f), the largest gaps correspond to capital and labour inputs, respectively. On shock impact, the response of UK core inflation rises because of the import prices increase (Graph (h)). However, after three quarters it turns to be negative and remains below zero for all the quarters considered. Moreover, from Graph (h) we note that the nominal interest rate, after an initial increase, reduces throughout all quarters.

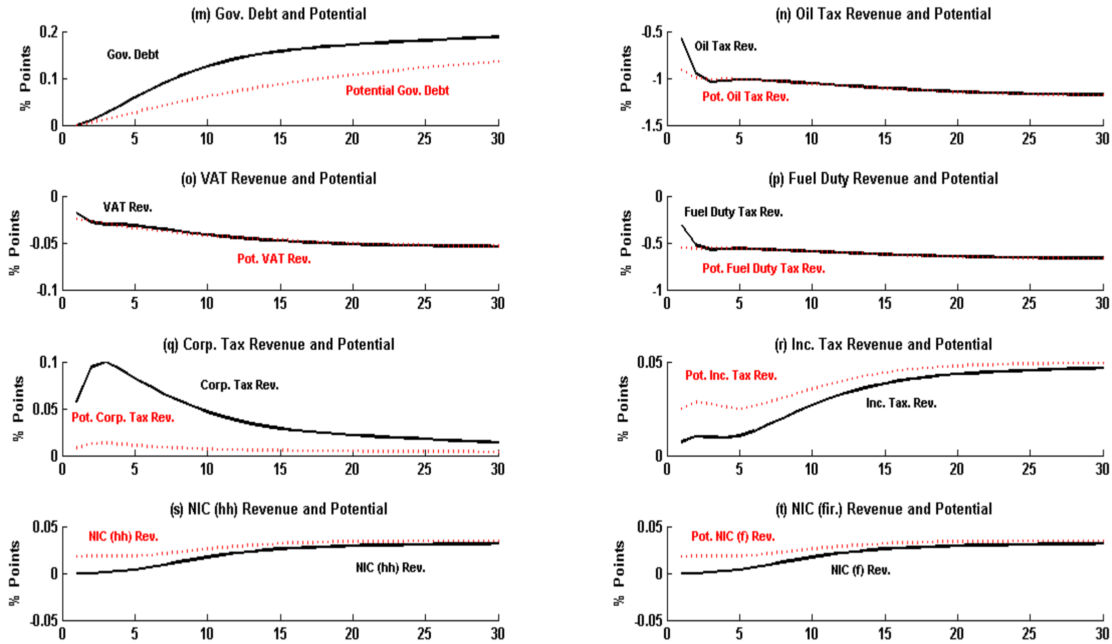


Figure 3.6: IRFs of Fiscal Variables to a Negative Foreign Technology Shock

Finally, we analyse the responses of UK public finances (Figure 3.6). As in Sections 5.1 and 5.2, we assume that, in response to the shock, domestic public spending does not vary. As we can see from Graphs (n) and (p), the drop of oil price implies that PRT and fuel duty tax revenues diminish. We also observe that VAT receipts (Graph (o)) fall because of the lower value-added revenues on oil products and imported non-oil goods.

On other hand, the improvement of firms' profits induces the increase of corporation tax receipts (Graph (q)). Similarly, the cheaper oil price implies a higher labour income for households. In turn, income tax and NIC revenues increase (Graphs (r), (s) and (t)). Again, the negative direct effects on oil and fuel duty revenues prevail on the positive indirect effects on income, NIC and corporate tax revenues. As a consequence, UK government debt is steadily positive for all the quarters considered (Graph (m)).

3.6 Conclusion

Using an open economy DSGE model with an endogenously determined price of oil, we analysed the effects of oil price fluctuations on the UK economy with particular focus on its public finances. In this regard, our theoretical framework and the empirical strategy present several advantages with respect to existing literature. Firstly, our analysis takes into account the several sources of oil price shocks. Secondly, we are able to estimate directly the persistence of the exogenous shocks affecting oil prices and, in turn, their effects on UK public finances. Finally, our theoretical framework allows us to consider the response of UK fiscal sector in the case of actual and potential economy.

The sample period of our study corresponds to the period in which the UK was a net oil exporter and includes the NICE decade. In order to estimate our model we used fifteen observed series for the UK economy and the rest of the world. As an estimation strategy we adopted Bayesian techniques on data for the period 1990:Q1-2005:Q4. In general, our estimated model is able to reproduce the business cycle moments of actual data.

Our theoretical model includes a detailed fiscal sector with several policy rules for distortive taxes affecting the economy. We are able to estimate these fiscal policy rules and we find that labour income tax rate has a highly procyclical response to the level of output. Labour income tax and National Insurance Contribution tax do not respond strongly to debt. The response of VAT rate to private consumption expenditure is important while corporation tax rate is not strongly respondent to dividends. Moreover, fuel duty tax rate responds moderately to oil demand changes. Finally, our results show a stronger response of petroleum revenue tax to oil price variations.

In general, our findings confirm the importance of global oil shocks for the UK economy. In particular, our variance decomposition analysis indicates that foreign oil intensity shock, foreign oil supply shock and foreign productivity shock are the most important ones in terms of UK oil price variation. We also find that the foreign oil intensity shock influences substantially the variation of UK government debt.

Our impulse response analysis shows that UK macroeconomic fundamentals improve after the reduction in the real oil price. In particular, GDP and its main components increase together with hours worked. Moreover, we observe a reduction of domestic core inflation that allows UK monetary authority to decrease its policy rate.

Turning to trade, since the UK is a net oil exporter its oil balance deteriorates inducing a reduction of UK overall trade balance. Moreover, we find that the Pound depreciates in response to positive shocks of foreign oil intensity and supply as well as to the negative shock of foreign productivity.

Despite the fact that the UK economy benefits from the low oil price, its public finances worsen. In particular, the UK fiscal position is adversely affected by the reduction of North Sea revenues. Similarly, fuel duty revenues decrease because the drop in the oil price prevails on the increase of domestic oil demand. Finally, value-added tax falls due to the reduction of oil sales together with the consumption of non-oil imported goods. As a consequence, the drop in the real oil price induces an expansion of UK government debt.

C Appendix: Chapter 3

C.1 Model Solution

This appendix shows the non-linearized and linearized versions of the key optimality and market clearing conditions used in our analysis of the model's equilibrium dynamics. Here, we focus on the endogenous variables of the model whereas the stochastic processes and the relative exogenous variables are reported in Table 3.1. We denote by small letters with hat, $\hat{x}_{i,t}$, the log-deviation of a given variable, $X_{1,t}$, from its steady state value, while $(X_1)^{SS}$ stands for its steady state value.

C.1.1 Country-Specific Relations

In what follows we derive the relations for the domestic country assuming that the same conditions apply to the foreign country because the model is symmetric.

Representative Household Maximization Problem. The representative household solves the following intertemporal problem:

$$E_t \left\{ \sum_{j=0}^{\infty} \beta_1^j \left[\begin{array}{c} \frac{1}{1-\sigma_1} \left(Z_{1,t}^c C_{1,t+j} - \kappa_1 C_{1,t+j-1} \right)^{1-\sigma_1} + \\ \frac{1}{1-\chi_1} \left(1 - L_{1,t+j} \right)^{1-\chi_1} \end{array} \right] \right\} \tag{C1}$$

subject to the budget constraint:

$$\begin{aligned} & \left(1+\tau_{1,t}^c\right) P_{1,t}^c C_{1,t} + P_{1,t}^i I_{1,t} + \left(R_{1,t}^b\right)^{-1} B_{1,t+1} + \frac{e_{1,t}\left(R_{2,t}^b\right)^{-1} B_{1,t+1}^f}{\phi_{1,t}^b} \qquad \text{(C2)} \\ = \; & \left(1-\tau_{1,t}^l-\tau_{1,t}^{wh}\right) W_{1,t} L_{1,t} + R_{1,t}^k K_{1,t-1} + \left(1-\tau_{1,t}^d\right) D_{1,t} \\ & + P_{1,t}^o Y_{1,t}^o + B_{1,t} + e_{1,t} B_{1,t}^f \end{aligned}$$

and the capital accumulation equation:

$$K_{1,t} = (1-\delta_1) K_{1,t-1} + \left(1 - S\left(\frac{I_{1,t}}{I_{1,t-1}}\right)^2\right) Z^i_{1,t} I_{1,t} \tag{C3}$$

The first order condition for $C_{1,t}$ is:

$$\left(Z^c_{1,t} C_{1,t} - \kappa_1 C_{1,t-1}\right)^{-1} Z^c_{1,t} = \lambda^q_{1,t}\left(1+\tau^c_{1,t}\right)\frac{P^c_{1,t}}{P^d_{1,t}} \tag{C4}$$

where:

$$\lambda^q_{1,t} = \lambda^c_{1,t} P^d_{1,t}$$

and $\lambda^c_{1,t}$ is the Lagrange multiplier associated with the representative household budget constraint. The linearized equation is given by:

$$\begin{aligned} \frac{1}{1-\kappa_1}\left(\hat{c}_{1,t} + \hat{z}^c_{1,t}\right) \quad &= \quad \frac{\kappa_1}{1-\kappa_1}\hat{c}_{1,t-1} + \hat{z}^c_{1,t} - \hat{\lambda}^q_{1,t} \\ &\quad -\frac{\left(\tau^c_1\right)^{SS}}{\left(1+\left(\tau^c_1\right)^{SS}\right)}\hat{\tau}^c_{1,t} - \left[\frac{\hat{P}^c}{\hat{P}^d}\right]_{1,t} \end{aligned} \tag{C5}$$

The first order condition for $L_{1,t}$ is:

$$\left(1 - L_{1,t}\right)^{-\chi_1} = \lambda^q_{1,t}\left(1 - \tau^l_{1,t} - \tau^{wh}_{1,t}\right) w^f_{1,t}$$

where:

$$w^f_{1,t} = \frac{W^f_{1,t}}{P^d_{1,t}} \tag{C6}$$

that is $w^f_{1,t}$ is the desired real wage expressed in terms of $P^d_{1,t}$. The linearized equation is given by:

$$\begin{aligned} \hat{w}^f_{1,t} \quad &= \quad \frac{\left(L_1\right)^{SS}}{1-\left(L_1\right)^{SS}}\chi_1 \hat{l}_{1,t} + \frac{\left(\tau^l_1\right)^{SS}}{\left(1-\left(\tau^l_1\right)^{SS} - \left(\tau^{wh}_1\right)^{SS}\right)}\hat{\tau}^l_{1,t} \\ &\quad + \frac{\left(\tau^{wh}_1\right)^{SS}}{\left(1-\left(\tau^l_1\right)^{SS} - \left(\tau^{wh}_1\right)^{SS}\right)}\hat{\tau}^{wh}_{1,t} - \hat{\lambda}^q_{1,t} \end{aligned} \tag{C7}$$

The first order condition for $B_{1,t+1}$ is:

$$\beta_1 R^b_{1,t} \left[\frac{\lambda^q_{1,t+1}}{\lambda^q_{1,t}} \frac{P^d_{1,t}}{P^d_{1,t+1}} \right] = 1 \tag{C8}$$

The linearized equation is given by:

$$\hat{r}^b_{1,t} = -\left(\hat{\lambda}^q_{1,t+1} - \hat{\lambda}^q_{1,t} \right) + \hat{\pi}^d_{1,t+1} \tag{C9}$$

The first order condition for $B^f_{1,t+1}$ is:

$$\beta_1 R^b_{2,t} \left[\frac{\lambda^q_{1,t+1}}{\lambda^q_{1,t}} \frac{P^d_{1,t}}{P^d_{1,t+1}} \frac{e_{1,t+1}}{e_{1,t}} \right] \phi^b_{1,t} = 1 \tag{C10}$$

where:

$$\phi^b_{1,t} = \phi^b_1 B^f_{1,t}$$

The linearized equation is given by:

$$\begin{aligned} \hat{r}^b_{2,t} &= -\left(\hat{\lambda}^q_{1,t+1} - \hat{\lambda}^q_{1,t} \right) + \hat{\pi}^d_{1,t+1} \\ &\quad - \left(\hat{e}_{1,t+1} - \hat{e}_{1,t} \right) - \phi^b_1 \hat{b}^f_{1,t} \end{aligned} \tag{C11}$$

Labour Supply Decision. If wages are flexible:

$$\hat{w}_{1,t} = \hat{w}^f_{1,t} + \frac{(\theta^w_1)^{SS}}{1 + (\theta^w_1)^{SS}} \hat{\theta}^w_{1,t} \tag{C12}$$

If wages are sticky, the labour union solves the following maximization problem:

$$\max_{\{W_{1,t}(h)\}} E_t \sum_{j=0}^{\infty} (\xi^w_1)^j \psi_{1,t,t+j} \left[\begin{array}{c} \omega^l_{1,t,,j} W_{1,t}(h) L_{1,t+j}(h) - \\ W^f_{1,t+j} L_{1,t+j}(h) \end{array} \right] \tag{C13}$$

$$s.t \quad : \quad L_{1,t}(h) = \left(\frac{W_{1,t}(h)}{W_{1,t}} \right)^{-\frac{1+\theta^w_{1,t}}{\theta^w_{1,t}}} L^d_{1,t} \tag{C14}$$

$$and \quad : \quad \omega^l_{1,t,,j} = \prod_{s=1}^{j} \left\{ (\omega_{1,t-1+s})^{\iota^w_1} \left(\pi^{SS}_1 \right)^{1-\iota^w_1} \right\} \tag{C15}$$

the first order condition is given by:

$$E_t \sum_{j=0}^{\infty} \Xi_{1,t+j}^{w} \left[\begin{array}{c} \frac{W_{1,t}(h)}{W_{1,t}} \frac{1}{\theta_{1,t+j}^{w}} - \\ \frac{W_{1,t+j}^{f}}{P_{1,t+j}^{d}} \frac{P_{1,t+j}^{d}}{W_{1,t+j}} \left(\frac{W_{1,t}\omega_{1,t,j}^{l}}{W_{1,t+j}} \right)^{-1} \frac{1+\theta_{1,t+j}^{w}}{\theta_{1,t+j}^{w}} \end{array} \right] = 0 \tag{C16}$$

where:

$$\Xi_{1,t+j}^{w} = \left(\xi_1^w\right)^j \psi_{1,t,t+j} L_{1,t+j}\left(h\right) \omega_{1,t,j}^{l}$$

The linearized equation is given by:

$$\begin{aligned} & \frac{1}{\pi_1^{SS}} \left(\hat{\omega}_{1,t} - \iota_1^w \hat{\omega}_{1,t-1}\right) - \frac{\beta_1}{\pi_1^{SS}} \left(\hat{\omega}_{1,t+1} - \iota_1^w \hat{\omega}_{1,t}\right) \\ = \quad & \frac{\left(1-\xi_1^w \beta_1\right)\left(1-\xi_1^w\right)}{\xi_1^w} \left(\hat{w}_{1,t+j}^{f} - \hat{w}_{1,t+j} + \frac{\left(\theta_1^w\right)^{SS}}{1+\left(\theta_1^w\right)^{SS}} \hat{\theta}_{1,t}^{w} \right) \end{aligned} \tag{C17}$$

where:

$$\frac{1}{\pi_1^{SS}} \left(\hat{\omega}_{1,t} - \iota_1^w \hat{\omega}_{1,t-1}\right) = \hat{\omega}_{1,t} - \iota_1^w \hat{\omega}_{1,t-1}$$

The wage inflation is:

$$\omega_{1,t} = \log\left(\frac{W_{1,t}}{W_{1,t-1}}\right) \tag{C18}$$

the linearized equation is given by:

$$\hat{\omega}_{1,t} = \hat{w}_{1,t} - \hat{w}_{1,t-1} + \hat{\pi}_{1,t}^{d} \tag{C19}$$

Capital Accumulation. The representative household solves the following intertemporal problem:

$$E_t \left\{ \sum_{j=0}^{\infty} \beta_1^j \left[\begin{array}{c} \frac{1}{1-\sigma_1} \left(Z_{1,t}^{c} C_{1,t+j} - \kappa_1 C_{1,t+j-1}\right)^{1-\sigma_1} + \\ \frac{1}{1-\chi_1} \left(1 - L_{1,t+j}\right)^{1-\chi_1} \end{array} \right] \right\} \tag{C20}$$

subject to the budget constraint:

$$\begin{aligned}
& \left(1+\tau_{1,t}^{c}\right) P_{1,t}^{c} C_{1,t}+P_{1,t}^{i} I_{1,t}+ \\
& \left(R_{1,t}^{b}\right)^{-1} B_{1,t+1}+\frac{e_{1,t}\left(R_{2,t}^{b}\right)^{-1} B_{1,t+1}^{f}}{\phi_{1,t}^{b}} \\
= & \left(1-\tau_{1,t}^{l}-\tau_{1,t}^{wh}\right) W_{1,t} L_{1,t}+R_{1,t}^{k} K_{1,t-1}+\left(1-\tau_{1,t}^{d}\right) D_{1,t} \\
& +P_{1,t}^{o} Y_{1,t}^{o}+B_{1,t}+e_{1,t} B_{1,t}^{f}
\end{aligned} \tag{C21}$$

and the capital accumulation equation:

$$K_{1,t}=\left(1-\delta_{1}\right) K_{1,t-1}+\left(1-S\left(\frac{I_{1,t}}{I_{1,t-1}}\right)^{2}\right) Z_{1,t}^{i} I_{1,t} \tag{C22}$$

The first order condition for $I_{1,t}$ is:

$$\begin{aligned}
0 = & \ 1-q_{1,t} Z_{1,t}^{i}\left[1-\frac{1}{2} \varphi_{1}^{i}\left(\frac{I_{1,t}}{I_{1,t-1}}-1\right)^{2}\right]+ \\
& q_{1,t} Z_{1,t}^{i} I_{1,t} \varphi_{1}^{i}\left(\frac{I_{1,t}}{I_{1,t-1}}-1\right) \frac{1}{I_{1,t-1}}- \\
& \beta_{1} \frac{P_{1,t+1}^{i} \lambda_{1,t+1}^{c}}{P_{1,t}^{i} \lambda_{1,t}^{c}} q_{1,t+1} Z_{1,t+1}^{i} I_{1,t+1} \varphi_{1}^{i}\left(\frac{I_{1,t+1}}{I_{1,t}}-1\right) \frac{I_{1,t+1}}{\left(I_{1,t}\right)^{2}}
\end{aligned} \tag{C23}$$

where:

$$q_{1,t}=\frac{Q_{1,t}}{P_{1,t}^{i} \lambda_{1,t}^{c}}$$

and $Q_{1,t}$ is the Lagrange multiplier associated with the capital accumulation equation. The linearized equation is given by:

$$\hat{q}_{1,t}=\varphi_{1}^{i}\left(\hat{\imath}_{1,t}-\hat{\imath}_{1,t-1}\right)-\varphi_{1}^{i} \beta_{1}\left(\hat{\imath}_{1,t+1}-\hat{\imath}_{1,t}\right)-\hat{z}_{1,t}^{i} \tag{C24}$$

The first order condition for $K_{1,t}$ is:

$$\begin{aligned} q_{1,t} &= \beta_1 \frac{\lambda^q_{1,t+1}}{\lambda^q_{1,t}} \frac{P^d_{1,t}}{P^i_{1,t}} \frac{R^k_{1,t+1}}{P^d_{1,t+1}} \\ &\quad + \beta_1 \left(1-\delta_1\right) q_{1,t+1} \frac{P^i_{1,t+1}}{P^d_{1,t+1}} \frac{P^d_{1,t}}{P^i_{1,t}} \frac{\lambda^q_{1,t+1}}{\lambda^q_{1,t}} \end{aligned} \tag{C25}$$

The linearized equation is given by:

$$\begin{aligned} \hat{q}_{1,t} &= \hat{\lambda}^q_{1,t+1} - \hat{\lambda}^q_{1,t} + \left(1 - \left(1-\delta_1\right)\beta_1\right) \left(\hat{r}^k_{1,t+1} - \left[\frac{\hat{P}^i}{\hat{P}^d}\right]_{1,t} \right) \\ &\quad + \left(1 - \delta_1 \beta_1\right) \left(\hat{q}_{1,t+1} \left[\frac{\hat{P}^i}{\hat{P}^d}\right]_{1,t+1} - \left[\frac{\hat{P}^i}{\hat{P}^d}\right]_{1,t} \right) \end{aligned} \tag{C26}$$

The linearized capital accumulation equation is:

$$\hat{k}_{1,t} = \left(1-\delta_1\right) \hat{k}_{1,t-1} + \delta_1 \left(\hat{z}^i_{1,t} + \hat{\imath}_{1,t}\right) \tag{C27}$$

Firms - Production of Consumption Goods. The consumption basket equation is:

$$C_{1,t} = \left(\left(\omega^{cc}_1\right)^{\frac{\rho^o_1}{1+\rho^o_1}} \left(C^{ne}_{1,t}\right)^{\frac{1}{1+\rho^o_1}} + \left(\omega^{oc}_1\right)^{\frac{\rho^o_1}{1+\rho^o_1}} \left(Z^o_{1,t} O^c_{1,t}\right)^{\frac{1}{1+\rho^o_1}} \right)^{1+\rho^o_1} \tag{C28}$$

the linearized equation is given by:

$$\hat{c}_{1,t} = \omega^{cc}_1 \hat{c}^{ne}_{1,t} + \omega^{oc}_1 \left(\hat{o}^c_{1,t} + \hat{z}^o_{1,t}\right) \tag{C29}$$

The non-oil consumption aggregate equation is:

$$C^{ne}_{1,t} = \left(\left(\omega^c_1\right)^{\frac{\rho^c_1}{1+\rho^c_1}} \left(C^d_{1,t}\right)^{\frac{1}{1+\rho^c_1}} + \left(\omega^{mc}_1\right)^{\frac{\rho^c_1}{1+\rho^c_1}} \left(Z^m_{1,t} M^c_{1,t}\right)^{\frac{1}{1+\rho^c_1}} \right)^{1+\rho^c_1} \tag{C30}$$

the linearized equation is given by:

$$\hat{c}^{ne}_{1,t} = \omega^{c}_{1}\hat{c}^{d}_{1,t} + \omega^{mc}_{1}\left(\hat{m}^{c}_{1,t} + \hat{z}^{m}_{1,t}\right) \tag{C31}$$

The first order condition for $C^{d}_{1,t}$ in the consumption basket equation is:

$$\frac{P^{c}_{1,t}}{P^{d}_{1,t}}\left(\omega^{cc}_{1}\frac{C_{1,t}}{C^{ne}_{1,t}}\right)^{\frac{\rho^{o}_{1}}{1+\rho^{o}_{1}}}\left(\omega^{c}_{1}\frac{C^{ne}_{1,t}}{C^{d}_{1,t}}\right)^{\frac{\rho^{c}_{1}}{1+\rho^{c}_{1}}} = 1 \tag{C32}$$

the linearized equation is given by:

$$\left[\frac{\hat{P}^{c}}{\hat{P}^{d}}\right]_{1,t} = -\frac{\rho^{o}_{1}}{1+\rho^{o}_{1}}\left(\hat{c}_{1,t} - \hat{c}^{ne}_{1,t}\right) - \frac{\rho^{c}_{1}}{1+\rho^{c}_{1}}\left(\hat{c}^{ne}_{1,t} - \hat{c}^{d}_{1,t}\right) \tag{C33}$$

The first order condition for $M^{c}_{1,t}$ in the consumption basket equation is:

$$\frac{P^{m}_{1,t}}{P^{d}_{1,t}} = \frac{P^{c}_{1,t}}{P^{d}_{1,t}}\left(\omega^{cc}_{1}\frac{C_{1,t}}{C^{ne}_{1,t}}\right)^{\frac{\rho^{o}_{1}}{1+\rho^{o}_{1}}}\left(\omega^{c}_{1}\frac{C^{ne}_{1,t}}{Z^{m}_{1,t}M^{c}_{1,t}}\right)^{\frac{\rho^{c}_{1}}{1+\rho^{c}_{1}}} Z^{m}_{1,t} \tag{C34}$$

the linearized equation is given by:

$$\begin{aligned}\left[\frac{\hat{P}^{m}}{\hat{P}^{d}}\right]_{1,t} \quad = \quad & \left[\frac{\hat{P}^{c}}{\hat{P}^{d}}\right]_{1,t} + \frac{\rho^{o}_{1}}{1+\rho^{o}_{1}}\left(\hat{c}_{1,t} - \hat{c}^{ne}_{1,t}\right) \\ & + \frac{\rho^{c}_{1}}{1+\rho^{c}_{1}}\left(\hat{c}^{ne}_{1,t} - \hat{m}^{c}_{1,t} - \hat{z}^{m}_{1,t}\right) + \hat{z}^{m}_{1,t}\end{aligned} \tag{C35}$$

The first order condition for $O^{c}_{1,t}$ in the consumption basket equation is:

$$\left(1+\tau^{oc}_{1,t}\right)\frac{P^{o}_{1,t}}{P^{d}_{1,t}} = \frac{P^{c}_{1,t}}{P^{d}_{1,t}}\left(\omega^{cc}_{1}\frac{C_{1,t}}{Z^{o}_{1,t}O^{c}_{1,t}}\right)^{\frac{\rho^{o}_{1}}{1+\rho^{o}_{1}}} Z^{o}_{1,t} \tag{C36}$$

the linearized equation is given by:

$$\left[\frac{\hat{P}^{o}}{\hat{P}^{d}}\right]_{1,t} = -\frac{\left(\tau_1^{oc}\right)^{SS}}{\left(1+\left(\tau_1^{oc}\right)^{SS}\right)}\hat{\tau}_{1,t}^{oc} + \left[\frac{\hat{P}^{c}}{\hat{P}^{d}}\right]_{1,t} + \frac{\rho_1^{o}}{1+\rho_1^{o}}\left(\hat{c}_{1,t} - \hat{o}_{1,t}^{c} - \hat{z}_{1,t}^{o}\right) + \hat{z}_{1,t}^{o} \tag{C37}$$

Firms - Production of Investment Goods. The investment basket equation is:

$$I_{1,t} = \left(\left(\omega_1^{i}\right)^{\frac{\rho_1^c}{1+\rho_1^c}}\left(I_{1,t}^{d}\right)^{\frac{1}{1+\rho_1^c}} + \left(\omega_1^{mi}\right)^{\frac{\rho_1^c}{1+\rho_1^c}}\left(Z_{1,t}^{m}M_{1,t}^{i}\right)^{\frac{1}{1+\rho_1^c}}\right)^{1+\rho_1^c} \tag{C38}$$

the linearized equation is given by:

$$\hat{\imath}_{1,t} = \omega_1^{i}\hat{\imath}_{1,t}^{d} + \omega_1^{mi}\left(\hat{m}_{1,t}^{i} + \hat{z}_{1,t}^{m}\right) \tag{C39}$$

The first order condition for $I_{1,t}^{d}$ in the investment basket equation is:

$$\frac{P_{1,t}^{i}}{P_{1,t}^{d}}\left(\omega_1^{i}\frac{I_{1,t}}{I_{1,t}^{d}}\right)^{\frac{\rho_1^c}{1+\rho_1^c}} = 1 \tag{C40}$$

the linearized equation is given by:

$$\left[\frac{\hat{P}^{i}}{\hat{P}^{d}}\right]_{1,t} = -\frac{\rho_1^{c}}{1+\rho_1^{c}}\left(\hat{\imath}_{1,t} - \hat{\imath}_{1,t}^{d}\right) \tag{C41}$$

The first order condition for $M_{1,t}^{i}$ in the investment basket equation is:

$$\frac{P_{1,t}^{m}}{P_{1,t}^{d}} = \frac{P_{1,t}^{i}}{P_{1,t}^{d}}\left(\omega_1^{mi}\frac{I_{1,t}}{Z_{1,t}^{m}M_{1,t}^{i}}\right)^{\frac{\rho_1^c}{1+\rho_1^c}} Z_{1,t}^{m} \tag{C42}$$

the linearized equation is given by:

$$\left[\frac{\hat{P}^{m}}{\hat{P}^{d}}\right]_{1,t} = \left[\frac{\hat{P}^{i}}{\hat{P}^{d}}\right]_{1,t} + \frac{\rho_1^{c}}{1+\rho_1^{c}}\left(\hat{\imath}_{1,t} - \hat{m}_{1,t}^{i} - \hat{z}_{1,t}^{m}\right) + \hat{z}_{1,t}^{m} \tag{C43}$$

Firms - Production of Domestic Intermediate Goods. The value added aggregate production function is:

$$V_{1,t}(i) = \left(\left(\omega_1^k\right)^{\frac{\rho_1^v}{1+\rho_1^v}} \left(K_{1,t-1}\right)^{\frac{1}{1+\rho_1^v}} + \left(\omega_1^l\right)^{\frac{\rho_1^v}{1+\rho_1^v}} \left(Z_{1,t}L_{1,t}\right)^{\frac{1}{1+\rho_1^v}} \right)^{1+\rho_1^v} \tag{C44}$$

the linearized equation is given by:

$$\hat{v}_{1,t} = \phi_1^k \hat{k}_{1,t-1} + \phi_1^l \left(\hat{l}_{1,t} + \hat{z}_{1,t}\right) \tag{C45}$$

where:

$$\phi_1^k = \left(\omega_1^k\right)^{\frac{\rho_1^v}{1+\rho_1^v}} \left(\frac{(K_1)^{SS}}{(V_1)^{SS}}\right)^{\frac{1}{1+\rho_1^v}} \tag{C46}$$

$$\phi_1^l = \left(\omega_1^l\right)^{\frac{\rho_1^v}{1+\rho_1^v}} \left(\frac{(L_1)^{SS}}{(V_1)^{SS}}\right)^{\frac{1}{1+\rho_1^v}} \tag{C47}$$

and:

$$\phi_1^k + \phi_1^l = 1$$

The gross output aggregate production function is:

$$Y_{1,t} = \left(\left(\omega_1^{vy}\right)^{\frac{\rho_1^o}{1+\rho_1^o}} \left(V_{1,t}\right)^{\frac{1}{1+\rho_1^o}} + \left(\omega_1^{oy}\right)^{\frac{\rho_1^o}{1+\rho_1^o}} \left(Z_{1,t}^o O_{1,t}^y\right)^{\frac{1}{1+\rho_1^o}} \right)^{1+\rho_1^o} \tag{C48}$$

the linearized equation is given by:

$$\hat{y}_{1,t} = \omega_1^{vy} \hat{v}_{1,t} + \omega_1^{oy} \left(\hat{o}_{1,t}^y + \hat{z}_{1,t}^o\right) \tag{C49}$$

The first order condition for $K_{1,t-1}$ in the output aggregator:

$$\frac{R_{1,t}^k}{P_{1,t}^d} = \frac{MC_{1,t}}{P_{1,t}^d} \left(\omega_1^{vy} \frac{Y_{1,t}}{V_{1,t}}\right)^{\frac{\rho_1^o}{1+\rho_1^o}} \left(\omega_1^k \frac{V_{1,t}}{K_{1,t-1}}\right)^{\frac{\rho_1^v}{1+\rho_1^v}} \tag{C50}$$

the linearized equation is given by:

$$r^k_{1,t} = m\hat{c}_{1,t} + \frac{\rho^o_1}{1+\rho^o_1}\left(\hat{y}_{1,t} - \hat{v}_{1,t}\right) - \frac{\rho^v_1}{1+\rho^v_1}\left(\hat{v}_{1,t} - \hat{k}_{1,t-1}\right) \tag{C51}$$

The first order condition for $L_{1,t}$ in the output aggregator:

$$\left(1+\tau^{wf}_{1,t}\right)\frac{W_{1,t}}{P^d_{1,t}} = \frac{MC_{1,t}}{P^d_{1,t}}\left(\omega^{vy}_1\frac{Y_{1,t}}{V_{1,t}}\right)^{\frac{\rho^o_1}{1+\rho^o_1}}\left(\omega^l_1\frac{V_{1,t}}{Z_{1,t}L_{1,t}}\right)^{\frac{\rho^v_1}{1+\rho^v_1}} Z_{1,t} \tag{C52}$$

the linearized equation is given by:

$$\begin{aligned}\hat{w}_{1,t} \quad = \quad & -\frac{\left(\tau^{wf}_1\right)^{SS}}{\left(1+\left(\tau^{wf}_1\right)^{SS}\right)}\hat{\tau}^{wf}_{1,t} + m\hat{c}_{1,t} + \frac{\rho^o_1}{1+\rho^o_1}\left(\hat{y}_{1,t} - \hat{v}_{1,t}\right) \\ & + \frac{\rho^v_1}{1+\rho^v_1}\left(\hat{v}_{1,t} - \hat{l}_{1,t} - \hat{z}_{1,t}\right) + \hat{z}_{1,t}\end{aligned} \tag{C53}$$

The first order condition for $O^y_{1,t}$ in the output aggregator:

$$\frac{P^o_{1,t}}{P^d_{1,t}} = \frac{MC_{1,t}}{P^d_{1,t}}\left(\omega^{oy}_1\frac{Y_{1,t}}{Z^o_{1,t}O^y_{1,t}}\right)^{\frac{\rho^o_1}{1+\rho^o_1}} Z^o_{1,t} \tag{C54}$$

the linearized equation is given by:

$$\left[\frac{\hat{P}^o}{\hat{P}^d}\right]_{1,t} = m\hat{c}_{1,t} + \frac{\rho^o_1}{1+\rho^o_1}\left(\hat{y}_{1,t} - \hat{o}^y_{1,t} - \hat{z}^o_{1,t}\right) + \hat{z}^o_{1,t} \tag{C55}$$

Evolution of the Marginal Cost. If prices are flexible:

$$\frac{MC_{1,t}}{P^d_{1,t}} = \frac{1}{1+\theta^p_{1,t}} \tag{C56}$$

the linearized equation is given by:

$$m\hat{c}_{1,t} = -\frac{1}{1+\left(\theta^p_1\right)^{SS}}\hat{\theta}^p_{1,t} \tag{C57}$$

If prices are sticky, the profit maximization problem of firms that are allowed to reoptimize their prices at time t can be expressed as:

$$\max_{\left\{P_{1,t}^{d}(i)\right\}} E_t \sum_{j=0}^{\infty} (\xi_1^p)^j \, \psi_{1,t,t+j} \left[\begin{array}{c} \pi_{1,t,,j}^{d} P_{1,t}^{d}(i)\, Y_{1,t+j}(i) - \\ MC_{1,t+j} Y_{1,t+j}(i) \end{array} \right] \tag{C58}$$

$$s.t \quad : \quad Y_{1,t}(i) = \left(\frac{P_{1,t}^{d}(i)}{P_{1,t}^{d}} \right)^{-\frac{1+\theta_1^p}{\theta_1^p}} Y_{1,t}^{d} \tag{C59}$$

$$and \quad : \quad \pi_{1,t,,j}^{d} = \prod_{s=1}^{j} \left\{ \left(\pi_{1,t-1+s}^{d}\right)^{\iota_1^p} \left(\pi_1^{SS}\right)^{1-\iota_1^p} \right\} \tag{C60}$$

the first order condition is given by:

$$E_t \sum_{j=0}^{\infty} \Xi_{1,t+j}^{p} \left[\begin{array}{c} \frac{P_{1,t}^{d}(i)}{P_{1,t}^{d}} \frac{1}{\theta_{1,t+j}^{p}} - \\ \frac{MC_{1,t+J}}{P_{1,t+J}^{d}} \left(\frac{P_{1,t}^{d}(i)\pi_{1,t,,j}^{d}}{P_{1,t+j}^{d}} \right) \frac{1+\theta_{1,t+j}^{p}}{\theta_{1,t+j}^{p}} \end{array} \right] = 0 \tag{C61}$$

where:

$$\Xi_{1,t+j}^{p} = (\xi_1^p \beta_1)^j \, \frac{\lambda_{1,t+j}^{c}}{\lambda_{1,t}^{c}} \left(\frac{P_{1,t}^{d} \pi_{1,t,,j}^{d}}{P_{1,t+j}^{d}} \right)^{-\frac{1}{\theta_{1,t+j}^{p}}} \left(\frac{P_{1,t}^{d}(i)}{P_{1,t}^{d}} \right)^{-\frac{1+\theta_{1,t+j}^{p}}{\theta_{1,t+j}^{p}}} Y_{1,t+j}^{d} \tag{C62}$$

The linearized equation is given by:

$$\begin{aligned} \frac{1}{\pi_1^{SS}} \left(\hat{\pi}_{1,t}^{d} - \iota_1^p \hat{\pi}_{1,t-1}^{d} \right) &= \frac{\beta_1}{\pi_1^{SS}} \left(\hat{\pi}_{1,t+1}^{d} - \iota_1^p \hat{\pi}_{1,t}^{d} \right) \\ &+ \frac{(1-\xi_1^p \beta_1)(1-\xi_1^p)}{\xi_1^p} \left(m\hat{c}_{1,t} + \frac{(\theta_1^p)^{SS}}{1+(\theta_1^p)^{SS}} \hat{\theta}_{1,t}^{p} \right) \end{aligned} \tag{C63}$$

where:

$$\frac{1}{\pi_1^{SS}} \left(\hat{\pi}_{1,t}^{d} - \iota_1^p \hat{\pi}_{1,t-1}^{d} \right) = \hat{\pi}_{1,t}^{d} - \iota_1^p \hat{\pi}_{1,t-1}^{d} \tag{C64}$$

Fiscal Sector. The government budget constraint is:

$$\begin{aligned} P^g_{1,t}G^d_{1,t} + B_{1,t} &= \tau^c_{1,t}P^c_{1,t}C_{1,t} + \left(\tau^l_{1,t} + \tau^{wh}_{1,t} + \tau^{wf}_{1,t}\right)W_{1,t}L_{1,t} + \\ & \tau^d_{1,t}D_{1,t} + \tau^{oc}_{1,t}P^o_{1,t}O^c_{1,t} + \tau^{yo}_{1,t}P^o_{1,t}Y^o_{1,t} + \left(R^b_{1,t}\right)^{-1}B_{1,t+1} \end{aligned} \quad \text{(C65)}$$

the linearized equation is given by:

$$\hat{b}_{1,t+1} = \frac{1}{\beta}\left\{ \begin{array}{c} \hat{b}_{1,t} + \hat{g}^d_{1,t} - \left(\frac{P^c_1}{P^d_1}\right)^{SS} \frac{(C_1)^{SS}}{\left(Y^d_1\right)^{SS}} (\tau^c_1)^{SS} \left[\hat{\tau}^c_{1,t} + \left[\frac{\hat{P}^c}{\hat{P}^d}\right]_{1,t} + \hat{c}_{1,t} - \hat{y}^d_{1,t}\right] \\ -(w_1)^{SS} \frac{(L_1)^{SS}}{\left(Y^d_1\right)^{SS}} \left(\tau^l_1\right)^{SS} \left[\hat{\tau}^l_{1,t} + \hat{w}_{1,t} + \hat{l}_{1,t} - \hat{y}^d_{1,t}\right] \\ -(w_1)^{SS} \frac{(L_1)^{SS}}{\left(Y^d_1\right)^{SS}} \left(\tau^{wh}_1\right)^{SS} \left[\hat{\tau}^{wh}_{1,t} + \hat{w}_{1,t} + \hat{l}_{1,t} - \hat{y}^d_{1,t}\right] \\ -(w_1)^{SS} \frac{(L_1)^{SS}}{\left(Y^d_1\right)^{SS}} \left(\tau^{wf}_1\right)^{SS} \left[\hat{\tau}^{wf}_{1,t} + \hat{w}_{1,t} + \hat{l}_{1,t} - \hat{y}^d_{1,t}\right] \\ -\frac{(d_1)^{SS}}{\left(Y^d_1\right)^{SS}} \left(\tau^d_1\right)^{SS} \left[\hat{\tau}^d_{1,t} + \hat{d}_{1,t} - \hat{y}^d_{1,t}\right] \\ -\left(\frac{P^o_1}{P^d_1}\right)^{SS} \frac{\left(O^c_1\right)^{SS}}{\left(Y^d_1\right)^{SS}} (\tau^{oc}_1)^{SS} \left[\hat{\tau}^{oc}_{1,t} + \left[\frac{\hat{P}^o}{\hat{P}^d}\right]_{1,t} + \hat{o}^c_{1,t} - \hat{y}^d_{1,t}\right] \\ -\left(\frac{P^o_1}{P^d_1}\right)^{SS} \frac{\left(Y^o_1\right)^{SS}}{\left(Y^d_1\right)^{SS}} (\tau^{yo}_1)^{SS} \left[\hat{\tau}^{yo}_{1,t} + \left[\frac{\hat{P}^o}{\hat{P}^d}\right]_{1,t} + \hat{y}^o_{1,t} - \hat{y}^d_{1,t}\right] \end{array} \right\} \quad \text{(C66)}$$

where the linearized equation for dividends is given by:

$$\hat{d}_{1,t} = \hat{y}^d_{1,t} - \frac{(MC_1)^{SS}}{1-(MC_1)^{SS}} m\hat{c}_{1,t} \quad \text{(C67)}$$

The oil revenues are:

$$OILREV_{1,t} = \tau^{yo}_{1,t}P^o_{1,t}Y^o_{1,t} \quad \text{(C68)}$$

the linearized equation is given by:

$$oi\hat{l}rev_{1,t} = \hat{\tau}^{yo}_{1,t} + \left[\frac{\hat{P}^o}{\hat{P}^d}\right]_{1,t} + \hat{y}^o_{1,t} - \hat{y}^d_{1,t} \quad \text{(C69)}$$

The consumption tax (VAT) revenues are:

$$CONSTAXREV_{1,t} = \tau^c_{1,t}P^c_{1,t}C_{1,t} \quad \text{(C70)}$$

the linearized equation is given by:

$$cons\hat{t}axrev_{1,t} = \hat{\tau}^{c}_{1,t} + \left[\frac{\hat{P}^{c}}{\hat{P}^{d}}\right]_{1,t} + \hat{c}_{1,t} - \hat{y}^{d}_{1,t} \tag{C71}$$

The fuel duty revenues are:

$$FUELDUTYREV_{1,t} = \tau^{oc}_{1,t} P^{o}_{1,t} O^{c}_{1,t} \tag{C72}$$

the linearized equation is given by:

$$fueld\hat{u}tyrev_{1,t} = \hat{\tau}^{oc}_{1,t} + \left[\frac{\hat{P}^{o}}{\hat{P}^{d}}\right]_{1,t} + \hat{o}^{c}_{1,t} - \hat{y}^{d}_{1,t} \tag{C73}$$

The dividends (corporation) tax revenues are:

$$CORTAXREV_{1,t} = \tau^{d}_{1,t} D_{1,t} \tag{C74}$$

the linearized equation is given by:

$$cort\hat{a}xrev_{1,t} = \hat{\tau}^{d}_{1,t} + \hat{d}_{1,t} - \hat{y}^{d}_{1,t} \tag{C75}$$

The labour income tax revenues are:

$$INCTAXREV_{1,t} = \tau^{l}_{1,t} W_{1,t} L_{1,t} \tag{C76}$$

the linearized equation is given by:

$$inct\hat{a}xrev_{1,t} = \hat{\tau}^{l}_{1,t} + \hat{w}_{1,t} + \hat{l}_{1,t} - \hat{y}^{d}_{1,t} \tag{C77}$$

The households National Insurance Contribution revenues are:

$$NICHTAXREV_{1,t} = \tau^{wh}_{1,t} W_{1,t} L_{1,t} \tag{C78}$$

the linearized equation is given by:

$$nicht\hat{a}xrev_{1,t} = \hat{\tau}^{wh}_{1,t} + \hat{w}_{1,t} + \hat{l}_{1,t} - \hat{y}^{d}_{1,t} \tag{C79}$$

The firms National Insurance Contribution revenues are:

$$NICFTAXREV_{1,t} = \tau^{wf}_{1,t} W_{1,t} L_{1,t} \tag{C80}$$

the linearized equation is given by:

$$nicft\hat{a}xrev_{1,t} = \hat{\tau}^{wf}_{1,t} + \hat{w}_{1,t} + \hat{l}_{1,t} - \hat{y}^{d}_{1,t} \tag{C81}$$

Remaining Relations. The market clearing condition for the domestic non-oil goods market is:

$$Y^{d}_{1,t} = C^{d}_{1,t} + I^{d}_{1,t} + G^{d}_{1,t} + X_{1,t} \tag{C82}$$

the linearized equation is given by:

$$\hat{y}^{d}_{1,t} = \frac{\left(C^{d}_{1}\right)^{SS}}{\left(Y^{d}_{1}\right)^{SS}} \hat{c}^{d}_{1,t} + \frac{\left(I^{d}_{1}\right)^{SS}}{\left(Y^{d}_{1}\right)^{SS}} \hat{\imath}^{d}_{1,t} + \frac{\left(G^{d}_{1}\right)^{SS}}{\left(Y^{d}_{1}\right)^{SS}} \hat{g}^{d}_{1,t} + \frac{\left(X_{1}\right)^{SS}}{\left(Y^{d}_{1}\right)^{SS}} \hat{x}_{1,t} \tag{C83}$$

The oil demand equation is:

$$O_{1,t} = O^{y}_{1,t} + O^{c}_{1,t} \tag{C84}$$

the linearized equation is given by:

$$\hat{o}_{1,t} = \frac{(O^{y}_{1})^{SS}}{(O_{1})^{SS}} \hat{o}^{y}_{1,t} + \frac{(O^{c}_{1})^{SS}}{(O_{1})^{SS}} \hat{o}^{c}_{1,t} \tag{C85}$$

The linearized expression for the real interest rate is given by:

$$\hat{r}^{rb}_{1,t} = \hat{r}^{b}_{1,t} - \hat{\pi}^{d}_{1,t+1} = -\left(\hat{\lambda}^{q}_{1,t+1} - \hat{\lambda}^{q}_{1,t}\right) \tag{C86}$$

The Taylor rule is:

$$\begin{aligned} i_{1,t} &= \bar{\imath}_1 + \gamma_1^i \left(i_{1,t-1} - \bar{\imath}_1 \right) + \\ & \left(1-\gamma_1^i\right) \left[\left(\pi_{1,t}^{core} - \bar{\pi}_1^{core} \right) + \gamma_1^\pi \left(\pi_{1,t}^{core} - \bar{\pi}_1^{core} - \bar{\pi}_{1,t}^{core} \right) + \gamma_1^y y_{1,t}^{gap} \right] \end{aligned} \tag{C87}$$

where:

$$i_{1,t} = R_{1,t}^b - 1 \tag{C88}$$

the linearized equation is given by:

$$\hat{r}_{1,t}^b = \gamma_1^i \hat{r}_{1,t-1}^b + \left(1-\gamma_1^i\right) \left[\hat{\pi}_{1,t}^{core} + \gamma_1^\pi \left(\hat{\pi}_{1,t}^{core} - \bar{\pi}_{1,t}^{core} \right) + \gamma_1^y \hat{y}_{1,t}^{gap} \right] \tag{C89}$$

The core price level $P_{1,t}^{ne}$ is given by:

$$P_{1,t}^{ne} = P_{1,t}^c \left(\omega_1^{cc} \frac{C_{1,t}}{C_{1,t}^{ne}} \right)^{\frac{\rho_1^o}{1+\rho_1^o}} \tag{C90}$$

the linearized expression is given by:

$$\begin{aligned} \left[\frac{\hat{P}^{ne}}{\hat{P}^d} \right]_{1,t} &= \left[\frac{\hat{P}^c}{\hat{P}^d} \right]_{1,t} + \frac{\rho_1^o}{1+\rho_1^o} \left(\hat{c}_{1,t} - \hat{c}_{1,t}^{ne} \right) \\ &= \frac{1}{\omega_1^{cc}} \left[\frac{\hat{P}^c}{\hat{P}^d} \right]_{1,t} - \frac{\omega_1^{oc}}{\omega_1^{cc}} \left(\left[\frac{\hat{P}^o}{\hat{P}^d} \right]_{1,t} - \hat{z}_{1,t}^o \right) \end{aligned} \tag{C91}$$

As we can note from expression (C91) the shock to oil intensity enters since it affects the headline price $\hat{P}_{1,t}^c$.

The inflation of domestic prices is given by:

$$\pi_{1,t}^d = \log \left(\frac{P_{1,t}^d}{P_{1,t-1}^d} \right) \tag{C92}$$

the linearized equation is given by:

$$\hat{\pi}_{1,t}^d = \hat{p}_{1,t}^d - \hat{p}_{1,t-1}^d \tag{C93}$$

The inflation of core prices is given by:

$$\pi_{1,t}^{core} = \log\left(\frac{P_{1,t}^{ne}}{P_{1,t-1}^{ne}}\right) \tag{C94}$$

the linearized equation is given by:

$$\hat{\pi}_{1,t}^{core} = \left[\frac{\hat{P}^{ne}}{\hat{P}^{d}}\right]_{1,t} - \left[\frac{\hat{P}^{ne}}{\hat{P}^{d}}\right]_{1,t-1} + \hat{\pi}_{1,t}^{d} \tag{C95}$$

The inflation of headline prices is given by:

$$\pi_{1,t}^{head} = \log\left(\frac{P_{1,t}^{c}}{P_{1,t-1}^{c}}\right) \tag{C96}$$

the linearized equation is given by:

$$\hat{\pi}_{1,t}^{head} = \left[\frac{\hat{P}^{c}}{\hat{P}^{d}}\right]_{1,t} - \left[\frac{\hat{P}^{c}}{\hat{P}^{d}}\right]_{1,t-1} + \hat{\pi}_{1,t}^{d} \tag{C97}$$

The equation for aggregate imports is given by:

$$M_{1,t} = \frac{P_{1,t}^{m}}{P_{1,t}^{d}} M_{1,t}^{c} + \frac{P_{1,t}^{m}}{P_{1,t}^{d}} M_{1,t}^{i} \tag{C98}$$

the linearized expression is given by:

$$\hat{m}_{1,t} = \frac{(M_1^c)^{SS}}{(M_1)^{SS}} \left(\left[\frac{\hat{P}^{m}}{\hat{P}^{d}}\right]_{1,t} + \hat{m}_{1,t}^{c}\right) + \frac{(M_1^i)^{SS}}{(M_1)^{SS}} \left(\left[\frac{\hat{P}^{m}}{\hat{P}^{d}}\right]_{1,t} + \hat{m}_{1,t}^{i}\right) \tag{C99}$$

because relative prices are assumed to be 1 in steady state.

The equation for aggregate exports is given by:

$$X_{1,t} = \frac{\zeta_2}{\zeta_1}\left(M_{2,t}^{c} + M_{2,t}^{i}\right) \tag{C100}$$

because country 1 real per capita exports, $X_{1,t}$, and country 2 real per capita imports, $M_{2,t}$, are related by the relative population weight, $\frac{\zeta_2}{\zeta_1}$.

The linearized expression is given by:

$$\hat{x}_{1,t} = \frac{(M_2^c)^{SS}}{(M_2^c)^{SS} + (M_2^i)^{SS}} \hat{m}_{2,t}^c + \frac{(M_2^i)^{SS}}{(M_2^c)^{SS} + (M_2^i)^{SS}} \hat{m}_{2,t}^i \tag{C101}$$

The ratio between total trade balance and gross output is given by:

$$\frac{T_{1,t}^{bal}}{P_{1,t}^d Y_{1,t}^d} = \frac{X_{1,t} - M_{1,t} + \frac{P_{1,t}^o}{P_{1,t}^d}\left(Y_{1,t}^o - O_{1,t}\right)}{Y_{1,t}^d} \tag{C102}$$

the linearized equation is given by:

$$\begin{aligned}
\hat{t}_{1,t}^{bal} \quad = \quad & \frac{(X_1)^{SS}}{\left(Y_1^d\right)^{SS}} \hat{x}_{1,t} - \frac{(M_1)^{SS}}{\left(Y_1^d\right)^{SS}} \hat{m}_{1,t} + \frac{(P_1^o)^{SS}\,(Y_1^o)^{SS}}{\left(P_1^d\right)^{SS}\left(Y_1^d\right)^{SS}} \hat{y}_{1,t}^o \\
& - \frac{(P_1^o)^{SS}\,(O_1)^{SS}}{\left(P_1^d\right)^{SS}\left(Y_1^d\right)^{SS}} \hat{o}_{1,t} - \frac{(P_1^o)^{SS}\left[(O_1)^{SS} - (Y_1^o)^{SS}\right]}{\left(P_1^d\right)^{SS}\left(Y_1^d\right)^{SS}} \left[\frac{\hat{P}^o}{\hat{P}^d}\right]_{1,t}
\end{aligned} \tag{C103}$$

The ratio between non-oil goods trade balance and gross output is given by:

$$\frac{G_{1,t}^{bal}}{P_{1,t}^d Y_{1,t}^d} = \frac{X_{1,t} - M_{1,t}}{Y_{1,t}^d} \tag{C104}$$

the linearized equation is given by:

$$\hat{g}_{1,t}^{bal} = \frac{(X_1)^{SS}}{\left(Y_1^d\right)^{SS}} \hat{x}_{1,t} - \frac{(M_1)^{SS}}{\left(Y_1^d\right)^{SS}} \hat{m}_{1,t} + \left[\frac{(X_1)^{SS}}{\left(Y_1^d\right)^{SS}} - \frac{(M_1)^{SS}}{\left(Y_1^d\right)^{SS}}\right] \hat{y}_{1,t}^d \tag{C105}$$

C.1.2 Bilateral Relations

For country 1, the relative import prices can be expressed as follows:

$$\frac{P_{1,t}^m}{P_{1,t}^d} = \frac{e_{1,t} P_{2,t}^c}{P_{1,t}^c} \frac{P_{2,t}^d}{P_{2,t}^c} \frac{P_{1,t}^c}{P_{1,t}^d} \tag{C106}$$

where $e_{1,t}$ is the nominal exchange rate. Considering that the consumption real exchange rate is:

$$rer_{1,t} = \frac{e_{1,t} P^c_{2,t}}{P^c_{1,t}} \tag{C107}$$

the linearized expression for (C106) is given by:

$$\left[\frac{\hat{P}^m}{\hat{P}^d}\right]_{1,t} = r\hat{e}r_{1,t} - \left[\frac{\hat{P}^c}{\hat{P}^d}\right]_{2,t} + \left[\frac{\hat{P}^c}{\hat{P}^d}\right]_{1,t} \tag{C108}$$

For country 2, the linearized expression for the relative import prices is given by:

$$\left[\frac{\hat{P}^m}{\hat{P}^d}\right]_{2,t} = -r\hat{e}r_{1,t} + \left[\frac{\hat{P}^c}{\hat{P}^d}\right]_{2,t} - \left[\frac{\hat{P}^c}{\hat{P}^d}\right]_{1,t} \tag{C109}$$

The uncovered interest rate parity condition is:

$$\frac{\lambda^q_{2,t+1}}{\lambda^q_{2,t}} \frac{P^d_{2,t}}{P^c_{2,t}} \frac{P^c_{2,t+1}}{P^d_{2,t+1}} = \phi^b_{1,t} \frac{rer_{1,t+1}}{rer_{1,t}} \frac{\lambda^q_{1,t+1}}{\lambda^q_{1,t}} \frac{P^d_{1,t}}{P^c_{1,t}} \frac{P^c_{1,t+1}}{P^d_{1,t+1}} \tag{C110}$$

the linearized equation is given by:

$$\begin{aligned} \left(\hat{\lambda}^q_{2,t+1} - \hat{\lambda}^q_{2,t}\right) &= \left(\hat{\lambda}^q_{1,t+1} - \hat{\lambda}^q_{1,t}\right) + \phi^b_1 \hat{b}^f_{1,t} + r\hat{e}r_{1,t+1} - r\hat{e}r_{1,t} \\ &\quad - \left[\frac{\hat{P}^c}{\hat{P}^d}\right]_{1,t} + \left[\frac{\hat{P}^c}{\hat{P}^d}\right]_{1,t+1} + \left[\frac{\hat{P}^c}{\hat{P}^d}\right]_{2,t} - \left[\frac{\hat{P}^c}{\hat{P}^d}\right]_{2,t+1} \end{aligned} \tag{C111}$$

The net foreign asset condition is:

$$\begin{aligned} \frac{e_{1,t}\left(R^b_{2,t}\right)^{-1} B^f_{1,t+1}}{\phi^b_{1,t}} &= e_{1,t} B^f_{1,t} + \frac{\zeta_2}{\zeta_1} e_{1,t} P^m_{2,t}\left(M^c_{2,t} + M^i_{2,t}\right) \\ &\quad - P^m_{1,t}\left(M^c_{1,t} + M^i_{1,t}\right) + P^o_{1,t}\left(Y^o_{1,t} - O_{1,t}\right) \end{aligned} \tag{C112}$$

the linearized equation is given by:

$$\beta_1 \hat{b}^f_{1,t+1} = \hat{b}^f_{1,t} + \hat{t}^{bal}_{1,t} \tag{C113}$$

where:

$$\hat{b}^f_{1,t} = \frac{e_{1,t}B^f_{1,t}}{P^d_{1,t}Y^d_{1,t}} \tag{C114}$$

The oil market clearing condition is:

$$Y^o_{1,t} + \frac{\zeta_2}{\zeta_1}Y^o_{2,t} = O_{1,t} + \frac{\zeta_2}{\zeta_1}O_{2,t} \tag{C115}$$

the linearized equation is given by:

$$\begin{aligned} & \frac{\frac{\zeta_1}{\zeta_2}\left(Y^o_1\right)^{SS}}{\frac{\zeta_1}{\zeta_2}\left(Y^o_1\right)^{SS} + \left(Y^o_2\right)^{SS}}\hat{y}^o_{1,t} + \frac{\left(Y^o_2\right)^{SS}}{\frac{\zeta_1}{\zeta_2}\left(Y^o_1\right)^{SS} + \left(Y^o_2\right)^{SS}}\hat{y}^o_{2,t} \\ = \quad & \frac{\frac{\zeta_1}{\zeta_2}\left(O_1\right)^{SS}}{\frac{\zeta_1}{\zeta_2}\left(O_1\right)^{SS} + \left(O_2\right)^{SS}}\hat{o}_{1,t} + \frac{\left(O_2\right)^{SS}}{\frac{\zeta_1}{\zeta_2}\left(O_1\right)^{SS} + \left(O_2\right)^{SS}}\hat{o}_{2,t} \end{aligned} \tag{C116}$$

The law of one price for oil is:

$$\frac{P^o_{1,t}}{P^d_{1,t}} = rer_{1,t}\frac{P^c_{1,t}}{P^d_{1,t}}\frac{P^d_{2,t}}{P^c_{2,t}}\frac{P^o_{2,t}}{P^d_{2,t}} \tag{C117}$$

the linearized equation is given by:

$$\left[\frac{\hat{P}^o}{\hat{P}^d}\right]_{1,t} = \hat{rer}_{1,t} + \left[\frac{\hat{P}^c}{\hat{P}^d}\right]_{1,t} - \left[\frac{\hat{P}^c}{\hat{P}^d}\right]_{2,t} + \left[\frac{\hat{P}^o}{\hat{P}^d}\right]_{2,t} \tag{C118}$$

C.1.3 Important Definitions

The definition of $GDP_{1,t}$ using Laspeyres index is:

$$GDP_{1,t} = GDP_{1,t-1}\frac{P^d_{1,t-1}Y_{1,t} - P^o_{1,t-1}O^y_{1,t} + P^o_{1,t-1}Y^o_{1,t}}{P^d_{1,t-1}Y_{1,t-1} - P^o_{1,t-1}O^y_{1,t-1} + P^o_{1,t-1}Y^o_{1,t-1}} \tag{C119}$$

the linearized equation is given by:

$$
\begin{aligned}
&\left(1-\frac{\left(P_1^o\right)^{SS}\left(O_1^y\right)^{SS}}{\left(P_1^d\right)^{SS}\left(Y_1^d\right)^{SS}}+\frac{\left(P_1^o\right)^{SS}\left(Y_1^o\right)^{SS}}{\left(P_1^d\right)^{SS}\left(Y_1^d\right)^{SS}}\right) \\
&\left(g\hat{d}p_{1,t}-g\hat{d}p_{1,t-1}\right)-\left(\hat{y}_{1,t}-\hat{y}_{1,t-1}\right) \\
= \quad & -\left(\frac{\left(P_1^o\right)^{SS}\left(O_1^y\right)^{SS}}{\left(P_1^d\right)^{SS}\left(Y_1^d\right)^{SS}}\right)\left(\hat{o}_{1,t}^y-\hat{o}_{1,t-1}^y\right) \\
&+\left(\frac{\left(P_1^o\right)^{SS}\left(Y_1^o\right)^{SS}}{\left(P_1^d\right)^{SS}\left(Y_1^d\right)^{SS}}\right)\left(\hat{y}_{1,t}^o-\hat{y}_{1,t-1}^o\right)
\end{aligned}
\tag{C120}
$$

The ratio between nominal GDP and nominal gross output is:

$$
\frac{NGDP_{1,t}}{P_{1,t}^dY_{1,t}}=1-\frac{P_{1,t}^oO_{1,t}^y}{P_{1,t}^dY_{1,t}}+\frac{P_{1,t}^oY_{1,t}^o}{P_{1,t}^dY_{1,t}}
\tag{C121}
$$

the linearized equation is given by:

$$
\begin{aligned}
&\frac{\left(NGDP_1\right)^{SS}}{\left(P_1^d\right)^{SS}\left(Y_1^d\right)^{SS}}\left[\frac{NG\hat{D}P}{\hat{P}^d\hat{Y}}\right]_{1,t} \\
= \quad & \left(\frac{\left(P_1^o\right)^{SS}\left(O_1^y\right)^{SS}}{\left(P_1^d\right)^{SS}\left(Y_1^d\right)^{SS}}-\frac{\left(P_1^o\right)^{SS}\left(Y_1^o\right)^{SS}}{\left(P_1^d\right)^{SS}\left(Y_1^d\right)^{SS}}\right)\left(\hat{y}_{1,t}-\left[\frac{\hat{P}^o}{\hat{P}^d}\right]_{1,t}\right) \\
&-\frac{\left(P_1^o\right)^{SS}\left(O_1^y\right)^{SS}}{\left(P_1^d\right)^{SS}\left(Y_1^d\right)^{SS}}\hat{o}_{1,t}^y+\frac{\left(P_1^o\right)^{SS}\left(O_1^y\right)^{SS}}{\left(P_1^d\right)^{SS}\left(Y_1^d\right)^{SS}}\hat{y}_{1,t}^o
\end{aligned}
\tag{C122}
$$

The equation for the oil price deflated by the GDP deflator is:

$$
\frac{P_{1,t}^o}{P_{1,t}^{GDP}}\frac{P_{1,t}^{GDP}}{P_{1,t-1}^o}=\frac{P_{1,t}^o}{P_{1,t}^d}\frac{P_{1,t-1}^d}{P_{1,t-1}^o}\frac{\frac{NGDP_{1,t-1}}{P_{1,t-1}^dY_{1,t-1}}}{\frac{NGDP_{1,t}}{P_{1,t}^dY_{1,t}}}\frac{GDP_{1,t}}{GDP_{1,t-1}}\frac{Y_{1,t-1}}{Y_{1,t}}
\tag{C123}
$$

the linearized equation is given by:

$$\begin{aligned}
&\log\left(\left[\frac{P^o_{1,t}}{P^{GDP}_{1,t}}\right]^{obs}\right) - \log\left(\left[\frac{P^o_{1,t-1}}{P^{GDP}_{1,t-1}}\right]^{obs}\right) \\
= \quad & -\left(\left[\frac{NG\hat{D}P}{\hat{P}^d\hat{Y}}\right]_{1,t} - \left[\frac{NG\hat{D}P}{\hat{P}^d\hat{Y}}\right]_{1,t-1}\right) - (\hat{y}_{1,t} - \hat{y}_{1,t-1}) \\
& + \left[\frac{\hat{P}^o}{\hat{P}^d}\right]_{1,t} - \left[\frac{\hat{P}^o}{\hat{P}^d}\right]_{1,t-1} + g\hat{d}p_{1,t} - g\hat{d}p_{1,t-1}
\end{aligned} \tag{C124}$$

The ratio between the total trade balance and nominal GDP is:

$$\frac{T^{bal}_{1,t}}{NGDP_{1,t}} = \frac{T^{bal}_{1,t}}{P^d_{1,t}Y_{1,t}} \frac{P^d_{1,t}Y_{1,t}}{NGDP_{1,t}} \tag{C125}$$

the linearized equation is given by:

$$\left[\frac{\hat{T}^{bal}}{NG\hat{D}P}\right]_{1,t} = \frac{\left(P^d_1\right)^{SS}\left(Y^d_1\right)^{SS}}{\left(NGDP_1\right)^{SS}} \hat{t}^{bal}_{1,t} \tag{C126}$$

The ratio between the non-oil goods trade balance and nominal GDP is:

$$\frac{G^{bal}_{1,t}}{NGDP_{1,t}} = \frac{1}{\frac{NGDP_{1,t}}{P^d_{1,t}Y_{1,t}}} \left(\frac{X_{1,t}}{Y_{1,t}} - \frac{P^d_{1,t}}{P^d_{1,t}}\frac{M_{1,t}}{Y_{1,t}}\right) \tag{C127}$$

the linearized equation is given by:

$$\begin{aligned}
\left[\frac{\hat{G}^{bal}}{NG\hat{D}P}\right]_{1,t} \quad = \quad & -\frac{1}{\frac{(NGDP_1)^{SS}}{\left(P^d_1\right)^{SS}(Y_1)^{SS}}} \left(\frac{(X_1)^{SS}}{\left(Y^d_1\right)^{SS}} - \frac{\left(P^d_1\right)^{SS}(M_1)^{SS}}{\left(P^d_1\right)^{SS}(Y_1)^{SS}}\right) \\
& \left[\frac{NG\hat{D}P}{\hat{P}^d\hat{Y}}\right]_{1,t} + \frac{1}{\frac{(NGDP_1)^{SS}}{\left(P^d_1\right)^{SS}(Y_1)^{SS}}} \hat{g}^{bal}_{1,t}
\end{aligned} \tag{C128}$$

C.1.4 Observation Equations

In what follows we denote by $X_{i,t}^{obs}$ the observed data series associated with a given linearized variable, $\hat{x}_{i,t}$. We start listing the observation equations for country 1.

The observation equation for GDP is:

$$\log\left(GDP_{1,t}^{obs}\right) - \log\left(GDP_{1,t-1}^{obs}\right) = g\hat{d}p_{1,t} - g\hat{d}p_{1,t-1} \tag{C129}$$

The observation equation for oil production is:

$$\log\left(Y_{1,t}^{o,obs}\right) - \log\left(Y_{1,t-1}^{o,obs}\right) = \hat{y}_{1,t}^{o} - \hat{y}_{1,t-1}^{o} \tag{C130}$$

The observation equation for oil imports as a share of nominal GDP is:

$$\begin{aligned}\frac{OIL\ IMP_{1,t}^{obs}}{NGDP_{1,t}^{obs}} \quad = \quad & \frac{\left(P_1^d\right)^{SS}\left(Y_1^d\right)^{SS}}{\left(NGDP_1\right)^{SS}}\left(\frac{\left(O_1\right)^{SS}}{\left(Y_1^d\right)^{SS}} - \frac{\left(Y_1^o\right)^{SS}}{\left(Y_1^d\right)^{SS}}\right) \\ & \left[-\left[\frac{NG\hat{D}P}{\hat{P}^d\hat{Y}}\right]_{1,t} + \left[\frac{\hat{P}^o}{\hat{P}^d}\right]_{1,t} - \hat{y}_{1,t}\right] \\ & + \frac{\left(P_1^d\right)^{SS}\left(Y_1^d\right)^{SS}}{\left(NGDP_1\right)^{SS}}\left(\frac{\left(O_1\right)^{SS}}{\left(Y_1^d\right)^{SS}}\hat{o}_{1,t} - \frac{\left(Y_1^o\right)^{SS}}{\left(Y_1^d\right)^{SS}}\hat{y}_{1,t}^{o}\right)\end{aligned} \tag{C131}$$

The observation equation for the real oil price is:

$$\log\left(\left[\frac{P_{1,t}^o}{P_{1,t}^{GDP}}\right]^{obs}\right) - \log\left(\left[\frac{P_{1,t-1}^o}{P_{1,t-1}^{GDP}}\right]^{obs}\right) = \left[\frac{\hat{P}^o}{\hat{P}^{GDP}}\right]_{1,t} - \left[\frac{\hat{P}^o}{\hat{P}^{GDP}}\right]_{1,t-1} \tag{C132}$$

The observation equation for non-oil imports as a share of nominal GDP is:

$$\begin{aligned}\frac{NONOIL\ IMP_{1,t}^{obs}}{NGDP_{1,t}^{obs}} \quad = \quad & \frac{\left(P_1^d\right)^{SS}\left(M_1\right)^{SS}}{\left(P_1^d\right)^{SS}\left(Y_1^d\right)^{SS}}\frac{\left(NGDP_1\right)^{SS}}{\left(P_1^d\right)^{SS}\left(Y_1^d\right)^{SS}} \\ & \left(\hat{m}_{1,t} - \hat{y}_{1,t} - \left[\frac{NG\hat{D}P}{\hat{P}^d\hat{Y}}\right]_{1,t}\right)\end{aligned} \tag{C133}$$

The observation equation for non-oil exports as a share of nominal GDP is:

$$\frac{NONOIL\ EXP_{1,t}^{obs}}{NGDP_{1,t}^{obs}} = \frac{\left(P_1^d\right)^{SS}(X_1)^{SS}}{\left(P_1^d\right)^{SS}\left(Y_1^d\right)^{SS}}\frac{(NGDP_1)^{SS}}{\left(P_1^d\right)^{SS}\left(Y_1^d\right)^{SS}} \left(\hat{x}_{1,t} - \hat{y}_{1,t} - \left[\frac{NG\hat{D}P}{\hat{P}^d\hat{Y}}\right]_{1,t}\right) \tag{C134}$$

The observation equation for the real exchange rate is:

$$rer_{1,t}^{obs} = r\hat{e}r_{1,t} \tag{C135}$$

The observation equation for consumption as a share of nominal GDP is:

$$\frac{CONS_{1,t}^{obs}}{NGDP_{1,t}^{obs}} = \frac{\left(P_1^c\right)^{SS}(C_1)^{SS}}{\left(P_1^d\right)^{SS}\left(Y_1^d\right)^{SS}}\frac{(NGDP_1)^{SS}}{\left(P_1^d\right)^{SS}\left(Y_1^d\right)^{SS}} \left(\hat{c}_{1,t} + \left[\frac{\hat{P}^c}{\hat{P}^d}\right]_{1,t} - \hat{y}_{1,t} - \left[\frac{NG\hat{D}P}{\hat{P}^d\hat{Y}}\right]_{1,t}\right) \tag{C136}$$

The observation equation for total gross fixed capital formation as a share of nominal GDP is:

$$\frac{INV_{1,t}^{obs}}{NGDP_{1,t}^{obs}} = \frac{\left(P_1^i\right)^{SS}(I_1)^{SS}}{\left(P_1^d\right)^{SS}\left(Y_1^d\right)^{SS}}\frac{(NGDP_1)^{SS}}{\left(P_1^d\right)^{SS}\left(Y_1^d\right)^{SS}} \left(\hat{\imath}_{1,t} + \left[\frac{\hat{P}^i}{\hat{P}^d}\right]_{1,t} - \hat{y}_{1,t} - \left[\frac{NG\hat{D}P}{\hat{P}^d\hat{Y}}\right]_{1,t}\right) \tag{C137}$$

The observation equation for core price inflation is:

$$\pi_{1,t}^{core,obs} = \hat{\pi}_{1,t}^{core} \tag{C138}$$

The observation equation for wage inflation is:

$$\omega_{1,t}^{obs} = \hat{\omega}_{1,t} \tag{C139}$$

The observation equation for nominal interest rate is:

$$r_{1,t}^{b,obs} = \hat{r}_{1,t}^{b} \tag{C140}$$

The observation equation for government debt as share of nominal GDP is:

$$\frac{GOV\ DEBT_{1,t}^{obs}}{NGDP_{1,t}^{obs}} = \frac{\left(P_1^d\right)^{SS}\left(Y_1^d\right)^{SS}}{\left(NGDP_1\right)^{SS}}\hat{b}_{1,t} \tag{C141}$$

For country 2 the observation equations are the following.

The observation equation for GDP is:

$$\log\left(GDP_{2,t}^{obs}\right) - \log\left(GDP_{2,t-1}^{obs}\right) = g\hat{d}p_{2,t} - g\hat{d}p_{2,t-1} \tag{C142}$$

The observation equation for oil production is:

$$\log\left(Y_{2,t}^{o,obs}\right) - \log\left(Y_{2,t-1}^{o,obs}\right) = \hat{y}_{2,t}^{o} - \hat{y}_{2,t-1}^{o} \tag{C143}$$

C.1.5 Decomposition of the Marginal Costs

As we derived above, from the profit maximization problem of firms producing intermediate domestic goods we have that:

$$\phi_1^k = \left(\omega_1^k\right)^{\frac{\rho_1^v}{1+\rho_1^v}}\left(\frac{\left(K_1\right)^{SS}}{\left(V_1\right)^{SS}}\right)^{\frac{1}{1+\rho_1^v}} \tag{C144}$$

$$\phi_1^l = \left(\omega_1^l\right)^{\frac{\rho_1^v}{1+\rho_1^v}}\left(\frac{\left(L_1\right)^{SS}}{\left(V_1\right)^{SS}}\right)^{\frac{1}{1+\rho_1^v}} \tag{C145}$$

and:

$$\phi_1^k + \phi_1^l = 1$$

Thus, recasting (C144) and (C145), respectively:

$$\phi_1^k = \omega_1^k \left(\frac{sharek y_1}{\omega_1^k sharev y_1} \right)^{\frac{1}{1+\rho_1^v}} \quad \text{(C146)}$$

$$\phi_1^l = \omega_1^l \left(\frac{sharel y_1}{\omega_1^l sharev y_1} \right)^{\frac{1}{1+\rho_1^v}} \quad \text{(C147)}$$

and:

$$\phi_1^k + \phi_1^l = 1$$

The marginal products of oil, capital and labour are respectively:

$$m\hat{p}o_{1,t} = \frac{\rho_1^o}{1+\rho_1^o} \left(\hat{y}_{1,t} - \hat{o}_{1,t}^y - \hat{z}_{1,t}^o \right) + \hat{z}_{1,t}^o \quad \text{(C148)}$$

$$m\hat{p}k_{1,t} = \frac{\rho_1^o}{1+\rho_1^o} \left(\hat{y}_{1,t} - \hat{v}_{1,t} \right) + \frac{\rho_1^v}{1+\rho_1^v} \left(\hat{v}_{1,t} - \hat{k}_{1,t-1} \right) \quad \text{(C149)}$$

$$\begin{aligned} m\hat{p}l_{1,t} = {} & \frac{\rho_1^o}{1+\rho_1^o} \left(\hat{y}_{1,t} - \hat{v}_{1,t} \right) \\ & + \frac{\rho_1^v}{1+\rho_1^v} \left(\hat{v}_{1,t} - \hat{l}_{1,t} - \hat{z}_{1,t} \right) + \hat{z}_{1,t} \\ & - \frac{\left(\tau_1^{wf} \right)^{SS}}{1 + \left(\tau_1^{wf} \right)^{SS}} \hat{\tau}_{1,t}^{wf} \end{aligned} \quad \text{(C150)}$$

and from the first order conditions:

$$\left[\frac{\hat{P}^o}{\hat{P}^d} \right]_{1,t} = m\hat{c}_{1,t} + m\hat{p}o_{1,t} \quad \text{(C151)}$$

$$\hat{r}_{1,t}^k = m\hat{c}_{1,t} + m\hat{p}k_{1,t} \quad \text{(C152)}$$

$$\hat{w}_{1,t} = m\hat{c}_{1,t} + m\hat{p}l_{1,t} \quad \text{(C153)}$$

Multiplying equation (C151) by ω_1^{oy}, equation (C152) by $\omega_1^{vy}\phi_1^k$, and equation (C153) by $\omega_1^{vy}\left(1-\phi_1^k\right)$, and summing up these three equations we have that:

$$\begin{aligned} m\hat{c}_{1,t} &= \omega_1^{oy}\left(\left[\frac{\hat{P}^o}{\hat{P}^d}\right]_{1,t} - m\hat{p}o_{1,t}\right) \\ &\quad +\omega_1^{vy}\phi_1^k\left(\hat{r}_{1,t}^k - m\hat{p}k_{1,t}\right) \\ &\quad +\omega_1^{vy}\left(1-\phi_1^k\right)\left(\hat{w}_{1,t} - m\hat{p}l_{1,t}\right) \end{aligned} \tag{C154}$$

where:

$$\omega_1^{oy} + \omega_1^{vy}\phi_1^k + \omega_1^{vy}\left(1-\phi_1^k\right) = 1$$

C.1.6 Calibrated Parameters

As we explained in the main body of the paper, some of the parameter values are taken from observed data means. In what follows we describe the relative expressions associated with these values.

The share of nominal oil demand on nominal gross output is:

$$shareoy_1 = \frac{(P_1^o)^{SS}(O_1)^{SS}}{\left(P_1^d\right)^{SS}\left(Y_1^d\right)^{SS}} = \frac{(O_1)^{SS}}{\left(Y_1^d\right)^{SS}} \tag{C155}$$

because the real price of oil is assumed to be 1 in steady state.

The ratio between oil used in production and oil used in consumption is:

$$ratiooyoc_1 = \frac{(P_1^o)^{SS}(O_1^y)^{SS}}{\left(P_1^d\right)^{SS}(O_1^c)^{SS}} = \frac{(O_1^y)^{SS}}{(O_1^c)^{SS}} \tag{C156}$$

The share of investment on gross output is:

$$shareiy_1 = \frac{\left(I_1^d\right)^{SS}}{\left(Y_1^d\right)^{SS}} \tag{C157}$$

The share of government spending on gross output is:

$$sharegy_1 = \frac{\left(G_1^d\right)^{SS}}{\left(Y_1^d\right)^{SS}} \tag{C158}$$

The ratio between oil production and oil demand is:

$$ratioyoo_1 = \frac{\left(Y_1^o\right)^{SS}}{\left(O_1\right)^{SS}} \tag{C159}$$

The share of imports on gross output is:

$$sharemy_1 = \frac{\left(M_1\right)^{SS}}{\left(Y_1^d\right)^{SS}} \tag{C160}$$

The ratio between imports of investment goods and imports of consumption goods is:

$$ratioyoo_1 = \frac{\left(M_1^i\right)^{SS}}{\left(M_1^c\right)^{SS}} \tag{C161}$$

Finally, we assume that the weight of labour in the value added production function is:

$$\omega_1^l = 1 \tag{C162}$$

C.1.7 Composite Parameters

Given the parameter values taken from observed data means and the expressions listed above, we can derive the remaining parameters as follows.

The share of hours worked is:

$$labshare_1 = \frac{L_1^{SS}}{1 - L_1^{SS}} \tag{C163}$$

The weight of oil input in the overall output production function is:

$$\omega_1^{oy} = \frac{\left(O_1^y\right)^{SS}}{\left(Y_1^d\right)^{SS}} = shareoyy_1 \tag{C164}$$

The weight of value added input in the overall output production function is:

$$\omega_1^{vy} = 1 - \omega_1^{oy} = \frac{(V_1)^{SS}}{\left(Y_1^d\right)^{SS}} = sharevy_1 \tag{C165}$$

The real rental rate in steady state is:

$$\left(r_1^k\right)^{SS} = \frac{1}{\beta_1} - 1 + \delta_1 \tag{C166}$$

The share of capital on gross output is:

$$\frac{(K_1)^{SS}}{\left(Y_1^d\right)^{SS}} = \frac{1}{\delta_1} shareiy_1 = shareky_1 \tag{C167}$$

The weight of capital in the value added production function is:

$$\omega_1^k = \frac{1}{\delta_1}\left(\frac{1}{\beta_1} - 1 + \delta_1\right)^{\frac{1+\rho_1^v}{\rho_1^v}} \frac{shareiy_1}{sharevy_1} \tag{C168}$$

The share of labour on gross output is:

$$\frac{(L_1)^{SS}}{\left(Y_1^d\right)^{SS}} = sharevy_1 \left(1 - \omega_1^k \left(\left(r_1^k\right)^{SS}\right)^{-\frac{1}{\rho_1^v}}\right)^{1+\rho_1^v} = sharely_1 \tag{C169}$$

The share of nominal consumption on nominal gross output is:

$$\begin{aligned} \frac{(P_1^c)^{SS}(C_1)^{SS}}{\left(P_1^d\right)^{SS}\left(Y_1^d\right)^{SS}} &= 1 - \frac{\left(P_1^d\right)^{SS}(I_1)^{SS}}{\left(P_1^d\right)^{SS}\left(Y_1^d\right)^{SS}} - \frac{\left(P_1^d\right)^{SS}(G_1)^{SS}}{\left(P_1^d\right)^{SS}\left(Y_1^d\right)^{SS}} \\ &\quad + \frac{(P_1^o)^{SS}(Y_1^o)^{SS}}{\left(P_1^d\right)^{SS}\left(Y_1^d\right)^{SS}} - \frac{(P_1^o)^{SS}(O_1^y)^{SS}}{\left(P_1^d\right)^{SS}\left(Y_1^d\right)^{SS}} \\ &= sharecy_1 \end{aligned} \tag{C170}$$

that is:

$$sharecy_1 = 1 - shareiy_1 - sharegy_1 + shareyoy_1 - shareoyy_1 \tag{C171}$$

The weights of oil in the production of consumption goods is:

$$\omega_1^{oc} = \frac{(O_1^c)^{SS}}{(C_1)^{SS}} = shareocc_1 \tag{C172}$$

where:

$$shareocc_1 = \frac{shareoy_1 - shareoyy_1}{sharecy_1} \tag{C173}$$

The weight of non-oil in the production of consumption goods is:

$$\omega_1^{cc} = 1 - \omega_1^{oc} = \frac{(C_1^{ne})^{SS}}{(C_1)^{SS}} \tag{C174}$$

The weight of domestic goods in the production of consumption goods is:

$$\omega_1^{c} = 1 - \omega_1^{mc} = \frac{\left(C_1^d\right)^{SS}}{(C_1^{ne})^{SS}} = sharecdcn_1 \tag{C175}$$

The weight of imported goods in the production of consumption goods is:

$$\omega_1^{mc} = \frac{(M_1^c)^{SS}}{(C_1^{ne})^{SS}} = sharemccn_1 \tag{C176}$$

where:

$$sharemccn_1 = \frac{sharemy_1}{sharecy_1 \cdot sharecnc_1} \frac{1}{1 + ratiomimc_1} \tag{C177}$$

The weight of domestic goods in the production of investment goods is:

$$\omega_1^{i} = 1 - \omega_1^{mi} = \frac{\left(I_1^d\right)^{SS}}{(I_1)^{SS}} \tag{C178}$$

The weight of imported goods in the production of investment goods is:

$$\omega_1^{mi} = \frac{(M_1^i)^{SS}}{(I_1)^{SS}} = sharemii_1 \tag{C179}$$

where:

$$sharemii_1 = \frac{sharemy_1}{shareiy_1} \frac{ratiomimc_1}{1 + ratiomimc_1} \tag{C180}$$

The share of exports on gross output of country 1 is:

$$\begin{aligned}
\frac{\left(P_1^d\right)^{SS}\left(X_1\right)^{SS}}{\left(P_1^d\right)^{SS}\left(Y_1^d\right)^{SS}} &= \frac{\left(P_1^d\right)^{SS}\left(M_1\right)^{SS}}{\left(P_1^d\right)^{SS}\left(Y_1^d\right)^{SS}} \\
&\quad + \frac{\left(P_1^o\right)^{SS}\left(O_1\right)^{SS}}{\left(P_1^d\right)^{SS}\left(Y_1^d\right)^{SS}} \\
&\quad - \frac{\left(P_1^o\right)^{SS}\left(Y_1^o\right)^{SS}}{\left(P_1^d\right)^{SS}\left(Y_1^d\right)^{SS}} \\
&= sharexy_1
\end{aligned} \tag{C181}$$

or:

$$sharexy_1 = sharemy_1 + shareoy_1 - shareyoy_1 \tag{C182}$$

The share of exports on gross output of country 2 is:

$$\frac{\left(X_2\right)^{SS}}{\left(Y_2^d\right)^{SS}} = \frac{\left(M_2\right)^{SS}}{\left(Y_2^d\right)^{SS}} - \left(\frac{\left(O_1\right)^{SS}}{\left(Y_1^d\right)^{SS}} + \frac{\left(Y_1^o\right)^{SS}}{\left(Y_1^d\right)^{SS}}\right)\frac{\left(Y_1^d\right)^{SS}}{\left(Y_2^d\right)^{SS}}\frac{1}{\zeta_2} \tag{C183}$$

or:

$$sharexy_2 = sharemy_2 - \left(shareoy_1 - shareyoy_1\right)\frac{\left(Y_1^d\right)^{SS}}{\left(Y_2^d\right)^{SS}}\frac{1}{\zeta_2} \tag{C184}$$

The share of imports on gross output of country 2 is:

$$\begin{aligned}
&\frac{\left(P_1^d\right)^{SS}\left(M_1\right)^{SS}}{\left(P_1^d\right)^{SS}\left(Y_1^d\right)^{SS}} + \frac{\left(P_1^o\right)^{SS}\left(O_1 - Y_1^o\right)^{SS}}{\left(P_1^d\right)^{SS}\left(Y_1^d\right)^{SS}} \\
= \; & \frac{\left(e_1\right)^{SS}\left(P_2^d\right)^{SS}\left(M_2\right)^{SS}}{\left(P_2^d\right)^{SS}\left(Y_2^d\right)^{SS}}\frac{\left(P_2^d\right)^{SS}}{\left(P_1^d\right)^{SS}}\frac{\left(Y_2^d\right)^{SS}}{\left(Y_1^d\right)^{SS}}\zeta_2 \\
= \; & sharemy_2
\end{aligned} \tag{C185}$$

or:

$$sharemy_2 = \left(sharemy_1 + \left(shareoy_1 - shareyoy_1\right)\right)\frac{\left(Y_1^d\right)^{SS}}{\left(Y_2^d\right)^{SS}}\frac{1}{\zeta_2} \tag{C186}$$

The ratio between nominal GDP and nominal gross output is:

$$\frac{(NGDP_1)^{SS}}{\left(P_1^d\right)^{SS}\left(Y_1^d\right)^{SS}} = 1 - \frac{\left(P_1^o\right)^{SS}\left(O_1^y\right)^{SS}}{\left(P_1^d\right)^{SS}\left(Y_1^d\right)^{SS}} + \frac{\left(P_1^o\right)^{SS}\left(Y_1^o\right)^{SS}}{\left(P_1^d\right)^{SS}\left(Y_1^d\right)^{SS}} \tag{C187}$$

or:

$$sharengdpny_1 = 1 - shareoyy_1 + shareyoy_1 \tag{C188}$$

The ratio between gross outputs of country 1 and 2 is:

$$\frac{\left(Y_1^d\right)^{SS}}{\left(Y_2^d\right)^{SS}} = \frac{sharely_2}{sharely_1}\frac{(L_1)^{SS}}{(L_2)^{SS}} \tag{C189}$$

The share in world oil production for country 2 is:

$$\begin{aligned} & \frac{\left(Y_2^o\right)^{SS}}{\frac{\zeta_1}{\zeta_2}\left(Y_1^o\right)^{SS} + \left(Y_2^o\right)^{SS}} \qquad \text{(C190)} \\ = \; & \frac{\frac{\left(Y_2^o\right)^{SS}}{\left(Y_2^d\right)^{SS}}}{\frac{\zeta_1}{\zeta_2}\frac{\left(Y_1^o\right)^{SS}}{\left(Y_1^d\right)^{SS}}\frac{\left(Y_1^d\right)^{SS}}{\left(Y_2^d\right)^{SS}} + \frac{\left(Y_2^o\right)^{SS}}{\left(Y_2^d\right)^{SS}}} \\ = \; & shareoprod_2 \end{aligned}$$

or:

$$shareoprod_2 = \frac{shareyoy_2}{\frac{\zeta_1}{\zeta_2} shareyoy_1 \frac{\left(Y_1^d\right)^{SS}}{\left(Y_2^d\right)^{SS}} + shareyoy_2} \tag{C191}$$

The share in world oil consumption for country 2 is:

$$\begin{aligned} & \frac{(O_2)^{SS}}{\frac{\zeta_1}{\zeta_2}(O_1)^{SS} + (O_2)^{SS}} \qquad \text{(C192)} \\ = \; & \frac{\frac{(O_2)^{SS}}{\left(Y_2^d\right)^{SS}}}{\frac{\zeta_1}{\zeta_2}\frac{(O_1)^{SS}}{\left(Y_1^d\right)^{SS}}\frac{\left(Y_1^d\right)^{SS}}{\left(Y_2^d\right)^{SS}} + \frac{(O_2)^{SS}}{\left(Y_2^d\right)^{SS}}} \\ = \; & shareocons_2 \end{aligned}$$

or:

$$shareocons_2 = \frac{shareoy_2}{\frac{\zeta_1}{\zeta_2} shareoy_1 \frac{\left(Y_1^d\right)^{SS}}{\left(Y_2^d\right)^{SS}} + shareoy_2} \tag{C193}$$

The overall oil production as share of gross output is:

$$\frac{\left(Y_1^o\right)^{SS}}{\left(Y_1^d\right)^{SS}} = \frac{\left(Y_1^o\right)^{SS}}{\left(O_1\right)^{SS}} \frac{\left(O_1\right)^{SS}}{\left(Y_1^d\right)^{SS}} = shareyoy_1 \tag{C194}$$

or:

$$shareyoy_1 = ratioyoo_1 \cdot shareoy_1 \tag{C195}$$

The real wage in steady state is:

$$(w_1)^{SS} = \frac{1}{1 + \left(\tau_1^{wf}\right)^{SS}} \frac{\left(MC_1\right)^{SS}}{\left(P_1^d\right)^{SS}} \left[\left(\omega_1^{vy} \omega_1^{vy}\right)^{\frac{\rho_1^o}{1+\rho_1^o}} \left(\omega_1^{vy} \left(\phi_1^l\right)^{1+\rho_1^w}\right) \right] \tag{C196}$$

The ratio between real dividends and gross output is:

$$\frac{\left(d_1\right)^{SS}}{\left(Y_1^d\right)^{SS}} = 1 - \frac{\left(MC_1\right)^{SS}}{\left(P_1^d\right)^{SS}} \tag{C197}$$

where:

$$\left(MC_1\right)^{SS} = \frac{1}{1 + \left(\theta_1^p\right)^{SS}} \tag{C198}$$

C.2 Data Construction

As we described in the main body of the paper, the data is quarterly and the model is estimated for the sample period 1990:Q1-2005:Q4 with a pre-sample from 1988:Q1 to 1989:Q4. In this appendix we provide the numerous sources and construction methods of the observed series. Unless otherwise noted, all original series are seasonally adjusted.

UK GDP. The UK GDP is the log of real UK GDP (code ABMI in ONS Quarterly National Accounts).

Foreign GDP. The foreign GDP is the log of trade-weighted foreign GDP. The data series for real GDPs of the foreign countries are taken from the OECD - Quarterly National Accounts[82]. The countries are: the Euro area, the United States, Japan, Norway, Switzerland, Sweden, Canada, Denmark, Australia and India. These are the most important trading partners of the United Kingdom for the period considered. We follow the paper of Loretan (2005) in order to construct the relative imports/exports weights.

UK crude oil production. The UK crude oil production is the log of the UK crude oil production taken from US Energy Information Administration[83] - Monthly Energy Review - Table 11.1b.

Foreign crude oil production. The foreign crude oil production is the log of foreign crude oil production (calculated as world production net of UK production) taken from US Energy Information Administration[84] - Monthly Energy Review - Table 11.1b.

Real oil price. The real oil price is the log of the Europe Brent Spot Price FOB from the US Energy Information Administration[85] converted from US dollars to Sterling Pounds using the Quarterly Average Forward Exchange Rate, 3 months, US$ into Sterling (code XUQADS3 in Bank of England Statistical Interactive

[82] http://dx.doi.org/10.5257/oecd/na/2012-06.
[83] http://www.eia.gov/totalenergy/data/monthly/#petroleum.
[84] http://www.eia.gov/totalenergy/data/monthly/#petroleum.
[85] http://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=PET&s=RBRTE&f=M.

Database[86]) and deflated by the UK GDP deflator (code YBGB in ONS Quarterly National Accounts).

UK real effective exchange rate. The UK real effective exchange rate is the log of the Quarterly Average Broad Effective Exchange Rate Index, (code XUQABK82 in the Bank of England Statistical Interactive Database[87]).

UK private consumption expenditure. The UK private consumption expenditure is the Household Final Consumption Expenditure at market prices (code ABJQ in ONS Quarterly National Accounts) and it is expressed as a share of UK GDP at Market Prices (code YBHA in ONS Quarterly National Accounts).

UK total gross fixed capital formation. The UK total gross fixed capital formation is the total gross fixed capital formation at market prices (code NPQS in ONS Quarterly National Accounts) and it is expressed as a share of UK GDP at Market Prices (code YBHA in ONS Quarterly National Accounts).

UK oil imports. The UK oil imports are the total oil gross imports (Petroleum - Imports) taken from the US Energy Information Administration[88] - International Energy Statistics, expressed as a share of UK GDP using the Europe Brent Spot Price FOB (British Sterling per Barrel) and the UK GDP at Market Prices (code YBHA in ONS Quarterly National Accounts).

UK non-oil goods imports. The UK non-oil goods imports are the Goods Imports at market prices (code BOKH in ONS Quarterly National Accounts) minus the UK oil imports, expressed as a share of UK GDP using the UK GDP at Market Prices (code YBHA in ONS Quarterly National Accounts).

UK non-oil goods exports. The UK non-oil goods exports are the Goods Exports at market prices (code BOKG in ONS Quarterly National Accounts) minus the UK oil exports, expressed as share of UK GDP using the UK GDP at

[86] http://www.bankofengland.co.uk/boeapps/iadb/index.asp?first=yes&SectionRequired=I&HideNums=-1&ExtraInfo=true&Travel=NIxIRx.

[87] http://www.bankofengland.co.uk/boeapps/iadb/index.asp?first=yes&SectionRequired=I&HideNums=-1&ExtraInfo=true&Travel=NIxIRx.

[88] http://www.eia.gov/cfapps/ipdbproject/iedindex3.cfm?tid=50&pid=76&aid=3&cid=UK, &syid=1988&eyid=2005&freq=Q&unit=TBPD.

Market Prices (code YBHA in ONS Quarterly National Accounts).

UK core inflation. The UK core inflation is the log change in the Consumer Price Index: All Items Excluding Food and Energy, Index 2010=100 and NSA (Organisation for Economic Co-operation and Development, Code: GBRCPICORMINMEI, retrieved from FRED, Federal Reserve Bank of St. Louis[89]). The series is seasonally adjusted with Eviews.

UK wage inflation. The UK wage inflation obtained from the log change in UK Total Compensation of Employees at Current Prices (Code DTWM in ONS - UK Output, Income and Expenditure Tables; and LF2G in ONS - LFS).

UK nominal interest rate. The UK nominal interest rate is the Quarterly Average Rate of Discount - 3 Month Treasury Bills (Code IUQAAJNB in Bank of England Statistical Interactive Database[90]).

UK government debt. The UK government debt is Public Sector Finances - Net Debt at Current Prices and NSA (code RUTN in ONS Public Sector Finances). This series is seasonally adjusted with Eviews and expressed as share of UK GDP at Market Prices (code YBHA in ONS Quarterly National Accounts).

[89] https://research.stlouisfed.org/fred2/series/GBRCPICORMINMEI/.

[90] http://www.bankofengland.co.uk/boeapps/iadb/index.asp?first=yes&SectionRequired=I&HideNums=-1&ExtraInfo=true&Travel=NIxIRx.

C.3 Construction of the Tax Rates for the UK Economy

This appendix describes the data sources and the construction of the tax rates for the UK economy. Due to data availability, we consider the sample period 1997:Q1-2005:Q4. Moreover, we collect all data series in nominal values.

Consumption Tax Revenues. The consumption tax revenues, T_1^c, are VAT revenues (code NZGF in ONS Public Sector Finances - Table PSF3D).

Consumption Tax Rate. The average consumption tax rate is defined as:

$$(\tau_1^c)^{SS} = \frac{T_1^c}{C_1 - T_1^c} \tag{C199}$$

Labour Income Tax Revenues. The labour income tax revenues, T_1^l, include self assessed income tax, paye IT, other income tax and miscellaneous revenues (codes LIBS, MS6W, MF6X, and MF6Z in ONS Public Sector Finances - Table PSF3D).

Labour Income Tax Rate. The average labour income tax rate is defined as:

$$\left(\tau_1^l\right)^{SS} = \frac{T_1^l}{TCE_1} \tag{C200}$$

where TCE_1 is the total compensation of employees (code DWTM in ONS UK Economic Accounts).

National Insurance Contributions (of Households and Firms) Tax Revenues. The National Insurance Contributions (of households and firms) tax revenues, T_1^w, are NICs revenues (code AIIH in ONS Public Sector Finances - Table PSF3D).

National Insurance Contributions (Households and Firms) Tax Rates. As described in Section 3.3, we assume the same tax rates for National Insurance Contribution paid by households, $\left(\tau_1^{wh}\right)^{SS}$, and firms, $\left(\tau_1^{wf}\right)^{SS}$. The average NIC tax rates paid by households and firms are defined as:

$$\left(\tau_1^{wh}\right)^{SS} = \left(\tau_1^{wf}\right)^{SS} = \frac{T_1^w}{TCE_1} \tag{C201}$$

Fuel Duty Tax Revenues. The fuel duty tax revenues, T_1^{oc}, are Fuel Duty revenues (code CUDG in ONS Public Sector Finances - Table PSF3D).

Fuel Duty Tax Rate. The average fuel duty tax rate is defined as:

$$(\tau_1^{oc})^{SS} = \frac{T_1^{oc}/2}{AFR_1} \tag{C202}$$

where AFR_1 is the series of total retail sales of automotive fuel (code IZ57 in ONS Retail Sales - Table ValSAT). As we can observe in the numerator of (C202), we consider the share of the automotive sector fuel consumption as share of total petroleum refined products (that is roughly the 50%).

Corporation Tax Revenues. The corporation tax revenues, T_1^d, are Corporation Tax revenues (code ACCD in ONS Public Sector Finances - Table PSF3D).

Corporation Tax Rate. The average corporation tax rate is defined as:

$$\left(\tau_1^d\right)^{SS} = \frac{T_1^d - T_1^{dyo}}{GOSC_1} \tag{C203}$$

where T_1^{dyo} is the series of Total Corporation Tax coming from UK oil production (in ONS Statistics of Government Revenues from UK Oil and Gas Production - Table T11.11) and $GOSC_1$ is the series of gross operating surplus of corporations (code CGBY in ONS UK Economic Accounts) excluding the share of gross operating surplus of corporations involved in oil production.

Petroleum Revenue Tax Revenues. The petroleum revenue tax revenues, T_1^{yo}, are Petroleum Revenue Tax revenues (code ACCJ in ONS Public Sector Finances - Table PSF3D).

Petroleum Revenue Tax Rate. The average petroleum revenue tax rate is defined as:

$$(\tau_1^{yo})^{SS} = \frac{T_1^{yo} + T_1^{dyo} + R_1^{yo}}{RCOS_1} \tag{C204}$$

where R_1^{yo} is the series of Royalties coming from UK oil production (in ONS Statistics of Government Revenues from UK Oil and Gas Production - Table

T11.11) and $RCOS_1$ is the series of revenue from crude oil sales (Table 4 in Scottish National Account Project - Oil and Gas Statistics).

C.4 Parameters Values

C.4.1 Average Ratios for the UK Economy

Unless otherwise noted, the average ratios are computed for the period 1990-2005.

The UK oil share on nominal gross output is defined as:

$$shareoy = \frac{GVA - GVA\ excl\ Oil\ and\ Gas}{GVA} \tag{C205}$$

where GVA is the total gross value added at basic prices (Code ABMM in ONS) and $GVA\ excl\ Oil\ and\ Gas$ is the gross value added excluding oil and gas at basic prices (Code KLS2 in ONS). Due to data availability for these two series we consider the sample period 1997-2005.

The ratio between oil used in production and oil used in consumption is defined as:

$$ratiooyoc = \frac{O^y}{O^c} \tag{C206}$$

where O^y is the total supply of products at purchasers' prices of coke and refined petroleum products (taken from ONS Input-Output Tables). O^c is the households final consumption expenditure of coke and refined petroleum products (taken ONS Input-Output Tables). Due to data availability for these two series we consider the sample period 1992-2004.

The share of investment on GDP is defined as:

$$shareiy = \frac{I}{Y} \tag{C207}$$

where I is the real total gross fixed capital formation (Code NPQT in ONS) and Y is the real gross domestic product (Code ABMI in ONS).

The share of government spending on GDP is defined as:

$$sharegy = \frac{G}{Y} \tag{C208}$$

where G is the general government final consumption expenditure (Code NMRY in ONS).

The ratio between oil production and oil demand is defined as:

$$ratioyoo = \frac{Y^o}{O} \tag{C209}$$

where Y^o is the crude oil production of the United Kingdom (taken from the US Energy Information Administration - Monthly Energy Review - Table 11.1b) and O is the petroleum consumption of United Kingdom (taken from the US Energy Information Administration - Monthly Energy Review - Table 11.2).

The share of imports on GDP is defined as:

$$sharemy = \frac{M}{Y} \tag{C210}$$

where M are the real imports of goods and services (Code IKBL in ONS).

The ratio between imports of investment goods and imports of consumption goods is defined as:

$$ratioyoo = \frac{M^i}{M^c} \tag{C211}$$

where M^i are total imports of services (Code IKBC in ONS) and M^c are total imports of goods (Code IKBI in ONS).

Finally, ζ_1 is the sum of total population of the United Kingdom (taken from the OECD - Quarterly National Accounts).

C.4.2 Average Ratios for the Foreign Bloc

In order to aggregate data for the foreign countries we use the Loretan (2005) technique. In particular, we proceed as follows. Firstly, from the Direction of Trade Statistics database of the International Monetary Fund we compute the average of imports/exports between the UK and foreign countries for the period 1990-2005. Secondly, we select the major UK trading partners. Specifically, they are the Euro Area, the United States, China, Japan, Sweden, Switzerland, Norway, Canada, Denmark, Australia, India, Saudi Arabia and United Arab Emirates. The average of imports/exports of the UK with this group of countries corresponds to the 80% of total UK trade. Thirdly, we compute the average ratios for the foreign bloc by aggregating their data series through the weighted average for the period 1990-2005.

Unless otherwise noted, the average ratios are computed for the period 1990-2005.

Due to data availability in order to construct foreign oil share we only consider the Euro Area and the United States. The Euro Area and the US oil shares on their nominal gross outputs are defined as:

$$shareoy = \frac{Petroleum\ Items\ Exp}{GDP} \tag{C212}$$

For the Euro Area, *Petroleum Items Exp* is the sum of crude petroleum and natural gas expenditures and coke, refined petroleum products and nuclear fuels expenditures (taken from Eurostat Input-Output Tables). GDP is the nominal gross domestic product (taken from the Eurostat interactive database). Due to data availability the sample period is 2000-2008.

For the US, *Petroleum Items Exp* is the sum of natural gas expenditures and petroleum expenditures (taken from the Annual Energy Outlook of US EIA). GDP is the nominal gross domestic product (taken from FRED).

Due to data availability, in order to construct foreign oil share we only consider the Euro Area and the United States. The ratio between oil used in production and oil used in consumption is defined as:

$$ratiooyoc = \frac{O^y}{O^c} \tag{C213}$$

For the Euro Area, O^y is the total use at basic price of coke, refined petroleum products and nuclear fuel (taken from the Eurostat Input-Output Tables). O^c is the final consumption expenditure at basic price of coke, refined petroleum products and nuclear fuel (taken from the Eurostat Input-Output Tables). Due to the availability of these two series we consider the sample period 2000-2005.

For the US, O^y is the total commodity output of petroleum and coal products (taken from the Bureau of Economic Analysis Input-Output Tables). O^c is the personal consumption expenditures of petroleum and coal products (taken from Bureau of Economic Analysis Input-Output Tables). Due to the availability of these two series we consider the sample period 1998-2005.

The share of investment on GDP for foreign countries is defined as:

$$shareiy = \frac{I}{Y} \tag{C214}$$

For the Euro Area, the United States, Japan, Sweden, Switzerland, Norway, Canada, Denmark, Australia and India, I is the gross fixed capital formation (taken from OECD - Quarterly National Accounts) whereas Y is the gross domestic product (taken from OECD - Quarterly National Accounts).

For China (sample period 1998-2005), Saudi Arabia and the United Arab Emirates, I is the gross fixed capital formation (Code 93E.ZF in International Financial Statistics - IMF) whereas Y is the gross domestic product (Code 99B.ZF in International Financial Statistics - IMF).

The share of government spending on GDP for foreign countries is defined as:

$$sharegy = \frac{G}{Y} \tag{C215}$$

For the Euro Area, the United States, Japan, Sweden, Switzerland, Norway, Canada, Denmark, Australia and India, G is the general government final consumption expenditure (taken from OECD - Quarterly National Accounts) whereas Y is the gross domestic product (taken from OECD - Quarterly National Accounts).

For China (sample period 1998-2005), Saudi Arabia and the United Arab Emirates, G is the government consumption expenditure (Code 91F.ZF in International Financial Statistics - IMF) whereas Y is the gross domestic product

(Code 99B.ZF in International Financial Statistics - IMF).

The ratio between oil production and oil demand for theforeign bloc is defined as:

$$ratioyoo = \frac{Y^o}{O} \tag{C216}$$

For the Euro Area, the United States, China, Japan, Sweden, Switzerland, Norway, Canada, Denmark, Australia, India, Saudi Arabia and the United Arab Emirates, Y^o is petroleum production (taken from the US Energy Information Administration - International Energy Statistics) whereas O is the petroleum consumption (taken from the US Energy Information Administration - International Energy Statistics).

The ratio between imports of investment goods and imports of consumption goods for the foreign bloc is defined as:

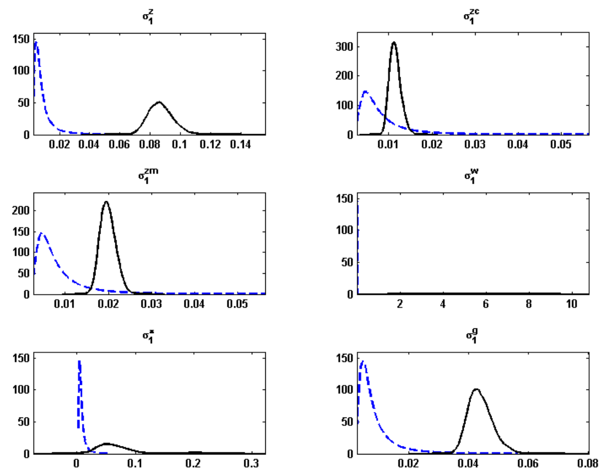
$$ratioyoo = \frac{M^i}{M^c} \tag{C217}$$

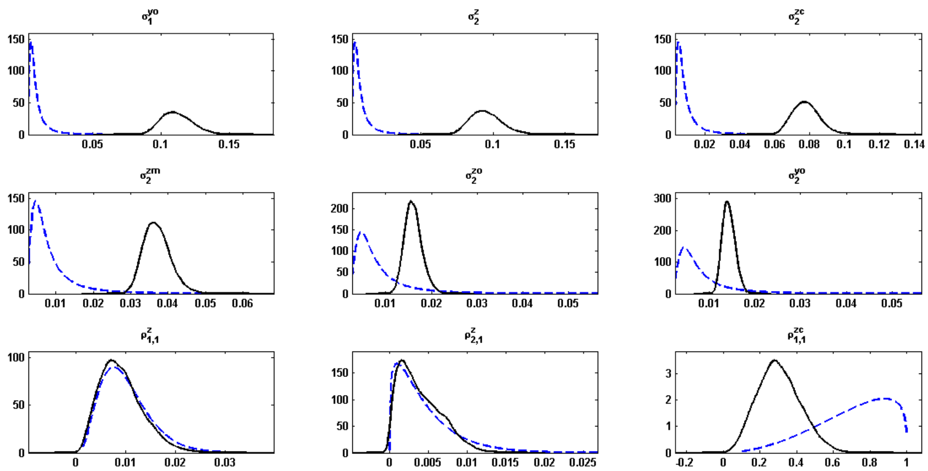
For the Euro Area, the United States, Japan, Sweden, Switzerland, Norway, Canada, Denmark, Australia and India, M^i is the series of imports of goods (taken from OECD - Quarterly National Accounts) whereas M^c is the series of imports of services (taken from OECD - Quarterly National Accounts).

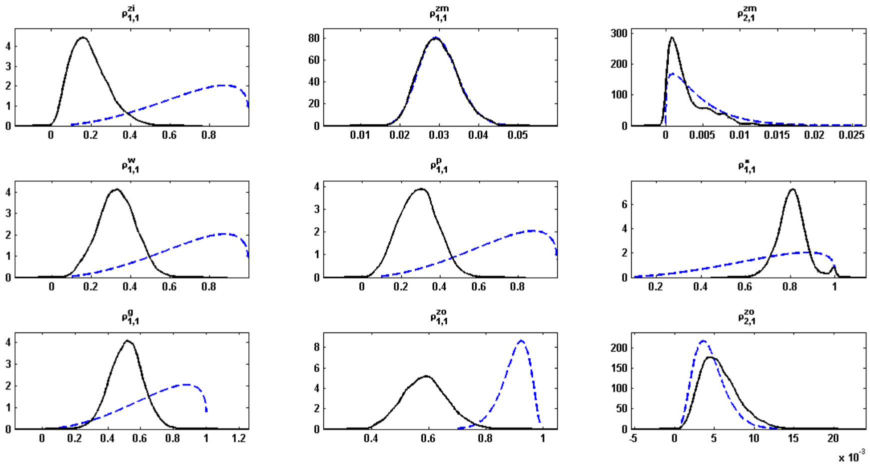
Finally, ζ_2 is the sum of the total population of the Euro Area, the United States, China, Japan, Sweden, Switzerland, Norway, Canada, Denmark, Australia, India, Saudi Arabia and the United Arab Emirates (taken from OECD - Quarterly National Accounts).

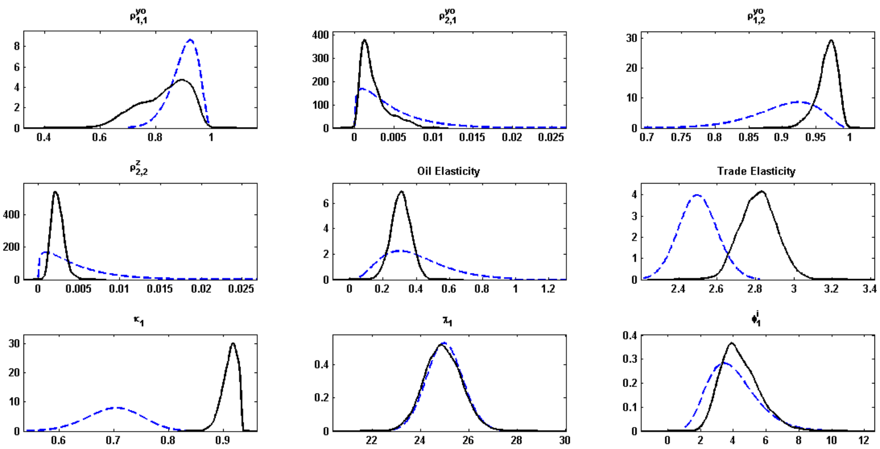
C.5 Prior and Posterior Parameters Distributions

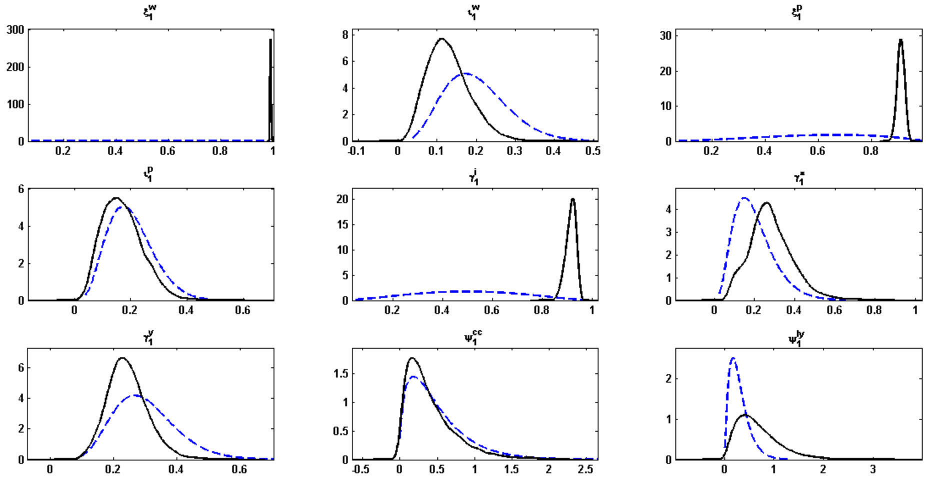
In the following figures, prior distributions correspond to dashed blue lines whereas posterior distributions correspond to solid blue black lines.



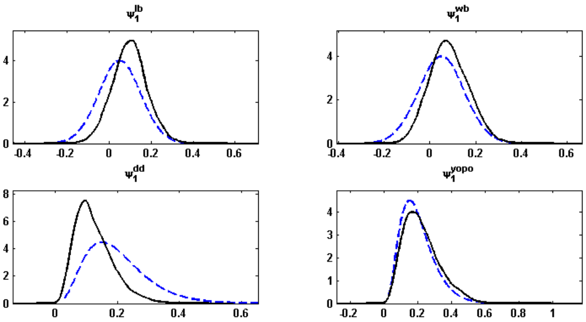





Oil Elasticity
Trade Elasticity



ξ1w
ι1w
ξ1p
ι1p
γ1i
γ1*
γ1y
ψ1cc
ψ1ly



ψ1lb
ψ1wb
ψ1ococ
ψ1dd
ψ1yopo

Conclusion

Large fluctuations in oil prices have been a recurrent feature of the macroeconomic environment since the 1970s. In this regard, media, policymakers and economists have paid close attention to changes in globally traded oil prices and worried about the potential impact of oil price shocks on economic performance. Most of the studies on oil price fluctuations have exclusively focused on the US case. Consequently, economists have furnished a clear picture of the relationship between oil price shocks and the US macroeconomy. On the other hand, previous economic literature did not focus extensively on the United Kingdom. However, the UK is an interesting case as it represents an advanced economy that was a net oil importer during the 1970s shifting to a net oil exporter in the 1980s and, finally, came back to be a net oil importer in the mid-2000s. Hence in this thesis, using different approaches, we examine the causes and the effects of oil price changes on the UK economy.

In the first chapter, we investigate how the impact of oil price changes on the UK economy differs depending on the underlying source of the shock, that is, whether oil price fluctuations are driven by shifts in oil demand or supply. In line with existing literature, our results indicate that oil demand shocks have been responsible for the major episodes of oil price increases from the mid-1970s until today. Moreover, we find that the specific source of the shock affects the size and nature of the responses of main UK macroeconomic aggregates. In particular, when a rise in oil prices is caused by an oil supply disruption the UK experiences a persistent decline in its GDP and an increase in its CPI inflation. In contrast, a rise in oil prices due to an expansion of global economic activity does not affect immediately UK real output whereas domestic inflation increases on impact. Our impulse response analysis also suggests that in response to a positive oil demand shock the Bank of England increases the nominal interest rate whereas a negative oil supply shock induces the BoE to reduce its policy rate. Finally, we find that the increase in the oil price induces a reduction of government deficit because the

UK benefits from the higher oil revenues coming from the North Sea.

In the second chapter, we develop an open economy two-bloc DSGE model in order to analyse the main transmission channels and the effects of oil price fluctuations on the UK economy. In particular, our theoretical framework: i) assumes the endogenous determination of the real oil price, ii) models the world economy, iii) has a new Keynesian structure, and iv) distinguishes between demand and supply channels of oil shocks. In order to estimate our model we use Bayesian methods over the sample 1990:Q1-2005:Q4 covering the period in which the UK was a net oil exporter. As observed data for our analysis, we consider data series of the UK economy and rest of the world. In particular, the data series for the foreign bloc are taken from the main UK trading partners and are aggregated using the Loretan (2005) method of trade weights.

Our results show that global oil shocks largely affect the UK economy. In particular, we find that foreign oil intensity shocks explain most of the UK oil price volatility. Moreover, our impulse response analysis suggests that a reduction in the real oil price induces an increase in domestic GDP and a fall in inflation. As a consequence, the Bank of England reduces the nominal interest rate. Our results also indicate that the UK exchange rate reacts differently depending on the source of oil price shocks. Thus, for example, increases in foreign oil intensity imply an appreciation of the Pound. Conversely, the British Sterling depreciates in response to positive shocks to foreign oil production and negative shocks to foreign technology. In general, we find that large reductions in the oil price worsen the UK trade balance. Finally, the results of our historical decompositions for the period 1990-2005 indicate that episodes of sharp increases in the oil price explain large reductions in domestic output and significant rises in inflation.

In third chapter, we set up an open economy DSGE model in order to investigate the effects of oil price shocks on the UK economy with a particular focus on its government sector. In particular, we evaluate how oil price changes affect the main UK tax receipts and, in turn, which is the effect on UK public finances. The theoretical framework of Chapter 3 extends the one of Chapter 2 considering a detailed fiscal bloc. Again, our model is estimated with Bayesian techniques over the sample 1990:Q1-2005:Q4.

Our results show that UK government debt volatility is largely explained by foreign oil intensity shocks as these shocks cause important fluctuations in government oil revenues. Moreover, in line with the results of Chapter 2, we find that foreign oil shocks are the main responsible of UK oil price variation. The estimates of our fiscal rules' parameters indicate that the fuel duty tax has a weak response to changes in the domestic oil demand. Conversely, the petroleum revenue tax has a stronger response to oil price changes.

Our impulse response analysis confirms the results of Chapter 2. In particular, we find that decreases in the oil price have positive effects on the domestic economy increasing GDP and lowering inflation. In such scenario the UK oil balance worsens causing a decrease in the UK overall trade balance. Differently from the second chapter, our results indicate that the Pound depreciates in response to positive foreign oil intensity shocks. The last effect is due to the reduction of the VAT in the UK which implies a lower price for domestic consumption goods. Finally, we quantify the effects of oil price changes on UK public finances. In particular, we find that, in response to a fall in the oil price, domestic government debt increases since total tax revenues diminish.

Given the promising results of this thesis, there are at least three research extensions that deserve to be analysed. Firstly, we aim to assess whether the Scotland and the rest of the UK react differently to oil price shocks. More specifically, our objective is to develop an open economy DSGE model that is able to disentangle the overall UK economy into two distinct regions (namely, Scotland and rest of UK) which, in turn, trade oil and non-oil goods with the rest of the world. Accordingly, this model will extend the theoretical frameworks of Chapter 2 and 3.

We believe that this analysis is particularly important because the oil industry significantly contributes to the Scottish economy. As reported by the Fiscal Commission Working Group (2013), the oil activity is the largest industrial sector in Scotland in terms of its contribution to GDP, acts as a major source of employment and investment, and provides the vast majority of Scotland's oil and gas needs. Moreover, the majority of UK oil production takes place off the coast of Scotland. In this regard, Scotland has been net oil exporter since the 1980s and it is still today. Therefore, our model will offer a careful distinction between the two UK regions considering an oil importer bloc (rest of UK) and an oil producer and exporter bloc (Scotland).

Our analysis will also address the future economic challenges that Scotland and rest of the UK may face. Recently, the main parties in the UK Parliament pledged to extend the powers of the Scottish Parliament. In this regard, an all-party commission was formed in order to discuss about a further devolution of taxes and expenditure to the Scottish Parliament. In particular, it may be that the responsibility for regulating UK oil production, which currently resides with the UK Government, will be transeferred to the Scottish Government. Accordingly, our model will provide a careful modelling of Scottish and rest of UK fiscal policies allowing for the analysis of monetary policy interactions with fiscal provisions for oil revenues. In this regard, our work will provide a clear understanding of the economic impact of oil price changes on the Scottish and rest of UK economies. In addition, our study will offer a useful tool for policy makers in order to respond to the several determinants underlying oil price shocks as well as wider aspects of fiscal devolution.

The second research extension that we have in mind concerns assessing the effects of oil price shocks when UK policy rates are at the zero lower bound. In particular, Bodenstein et al. (2013) have shown that, in the US case, the zero lower bound constraint tends to cushion rather than amplify the fall in GDP that occurs in response to higher oil prices in normal times when monetary policy is unconstrained by the zero lower bound. Bodenstein et al. (2013) have also shown that the mitigation of the output decline from the zero lower bound depends on the source of the shock and on the persistence that alternative shocks induce in the price of oil. Our idea is to extend the analysis of Bodenstein et al. (2013) to the UK economy starting from to 2008 until the current period. Accordingly, our analysis would consider the recent plunge of oil price below $50 a barrel. Thus, it would be extremely useful to analyse the behaviour of main UK macroeconomic fundamentals in a situation of very low oil price and policy rates at the zero lower bound.

Finally, as future research extension we aim to analyse the relationship between government debt structure and oil shocks for an emerging and small oil-exporter country. As Arellano and Ramanarayanan (2012) have argued, debt crises in emerging economies are often blamed on governments borrowing extensive quantities of short-term debt in international capital markets. Short-term borrowing leaves an economy with large amounts of debt to roll over, which becomes problematic when interest rates rise and access to external credit is restricted. In their paper Arellano and Ramanarayanan (2012) show that long-term debt provides a hedge against future fluctuations in spreads, whereas short-term debt is more effective at providing incentives to repay.

Our idea is develop a DSGE model in order to assess the behaviour of the fiscal sector in an emerging and small oil-exporter country in the presence of a plunge in the oil price. In particular, it would be extremely useful to analyse the effects of the different maturities of bonds issued by the government in the case of a fall in oil revenues. In particular, in a small oil-exporting country the public sector benefits from the revenues coming from oil sales. Thus, the government is able to balance its fiscal policy fixing a certain share of oil income in its budget constraint. Accordingly, in the case of a plunge in the oil price the government should hedge against the worsening of its finances issuing bonds with different maturities. Moreover, it would be interesting to analyse the interactions of fiscal policy and monetary policy in such scenario.

In conclusion, we believe that these proposal features are crucial in order to better understand the effects of oil global price changes and are important contributions with respect to the existing economic literature.

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