Université de Montréal

Essays on Oil Price Fluctuations and Macroeconomic Activity

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(dédicace) *À mes parents à Diébougou*

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Résumé

Dans cette thèse, je me suis intéressé aux effets des fluctuations du prix de pétrole sur l'activité macroéconomique selon la cause sous-jacente ces fluctuations. Les modèles économiques utilisés dans cette thèse sont principalement les modèles d'équilibre général dynamique stochastique (de l'anglais Dynamic Stochastic General Equilibrium, DSGE) et les modèles Vecteurs Autorégressifs, VAR.

Plusieurs études ont examiné les effets des fluctuations du prix de pétrole sur les principaux variables macroéconomiques, mais très peu d'entre elles ont fait spécifiquement le lien entre les effets des fluctuations du prix du pétrole et la l'origine de ces fluctuations. Pourtant, il est largement admis dans les études plus récentes que les augmentations du prix du pétrole peuvent avoir des effets très différents en fonction de la cause sous-jacente de cette augmentation. Ma thèse, structurée en trois chapitres, porte une attention particulière aux sources de fluctuations du prix de pétrole et leurs impacts sur l'activité macroéconomique en général, et en particulier sur l'économie du Canada.

Le premier chapitre examine comment les chocs d'offre de pétrole, de demande agrégée, et de demande de précaution de pétrole affectent l'économie du Canada, dans un Modèle d'équilibre Général Dynamique Stochastique estimé. L'estimation est réalisée par la méthode Bayésienne, en utilisant des données trimestrielles canadiennes sur la période 1983Q1 à 2010Q4. Les résultats montrent que les effets dynamiques des fluctuations du prix du pétrole

sur les principaux agrégats macro-économiques canadiens varient en fonction de leurs sources. En particulier, une augmentation de 10% du prix réel du pétrole causée par des chocs positifs sur la demande globale étrangère a un effet positif significatif de l'ordre de 0,4% sur le PIB réel du Canada au moment de l'impact et l'effet reste positif sur tous les horizons. En revanche, une augmentation du prix réel du pétrole causée par des chocs négatifs sur l'offre de pétrole ou par des chocs positifs de la demande de pétrole de précaution a un effet négligeable sur le PIB réel du Canada au moment de l'impact, mais provoque une baisse légèrement significative après l'impact. En outre, parmi les chocs pétroliers identifiés, les chocs sur la demande globale étrangère ont été relativement plus important pour expliquer la fluctuation des principaux agrégats macroéconomiques du Canada au cours de la période d'estimation.

Le deuxième chapitre utilise un modèle Structurel VAR en Panel pour examiner les liens entre les chocs de demande et d'offre de pétrole et les ajustements de la demande de travail et des salaires dans les industries manufacturières au Canada. Le modèle est estimé sur des données annuelles désagrégées au niveau industriel sur la période de 1975 à 2008. Les principaux résultats suggèrent qu'un choc positif de demande globale a un effet positif sur la demande de travail et les salaires, à court terme et à long terme. Un choc négatif sur l'offre de pétrole a un effet négatif relativement faible au moment de l'impact, mais l'effet devient positif après la première année. En revanche, un choc positif sur la demande précaution de pétrole a un impact négatif à tous les horizons. Les estimations industrie-par-industrie confirment les précédents résultats en panel. En outre, le papier examine comment les effets des différents chocs pétroliers sur la demande travail et les salaires varient en fonction du degré d'exposition commerciale et de l'intensité en énergie dans la production. Il ressort que les industries fortement exposées au commerce international et les industries fortement intensives en énergie sont plus vulnérables aux fluctuations du prix du pétrole causées par des chocs d'offre de pétrole ou des chocs de demande globale.

Le dernier chapitre examine les implications en terme de bien-être social de l'introduction des inventaires en pétrole sur le marché mondial à l'aide d'un modèle DSGE de trois pays dont deux pays importateurs de pétrole et un pays exportateur de pétrole. Les gains de bien-être sont mesurés par la variation compensatoire de la consommation sous deux règles de politique monétaire. Les principaux résultats montrent que l'introduction des inventaires en pétrole a des effets négatifs sur le bien-être des consommateurs dans chacun des deux pays importateurs de pétrole, alors qu'il a des effets positifs sur le bien-être des consommateurs dans le pays exportateur de pétrole, quelle que soit la règle de politique monétaire. Par ailleurs, l'inclusion de la dépréciation du taux de change dans les règles de politique monétaire permet de réduire les coûts sociaux pour les pays importateurs de pétrole. Enfin, l'ampleur des effets de bien-être dépend du niveau d'inventaire en pétrole à l'état stationnaire et est principalement expliquée par les chocs sur les inventaires en pétrole.

Mots-clés : Estimation Bayésienne, modèles d'équilibre général dynamique stochastique, modèles vecteurs autorégressifs en panel, chocs de demande et d'offre de pétroliers, bien-être social, emploi, industries manufacturières, économie ouverte, Canada.

Abstract

In this thesis, I am interested in the effects of fluctuations in oil prices on macroeconomic activity depending on the underlying cause of these fluctuations. The economic models used in this thesis include the Dynamic Stochastic General Equilibrium (DSGE) Models and Vector Autoregressive (VAR) Models.

Several studies have examined the effects of fluctuations in oil price on the main macroeconomic variables, but very few of theses studies have specifically made the link between the effects of fluctuations in oil prices and the origin of these fluctuations. However, it is widely accepted in more recent studies that oil price increases may have very different effects depending on the underlying cause of that increase. My thesis, structured in three chapters, is focused on the sources of fluctuations in oil price and their impacts on the macroeconomic activity in general, and in particular on the canadian economy.

The first chapter of the thesis investigates how oil supply shocks, aggregate demand shocks, and precautionary oil demand shocks affect Canada's economy, within an estimated Dynamic Stochastic General Equilibrium (DSGE) model. The estimation is conducted using Bayesian methods, with Canadian quarterly data from 1983Q1 to 2010Q4. The results suggest that the dynamic effects of oil price shocks on Canadian macroeconomic variables vary according to their sources. In particular, a 10% increase in the real price of oil driven by positive foreign aggregate demand shocks has a significant

positive effect of about 0.4% on Canada's real GDP upon impact and the effect remains positive over time. In contrast, an increase in the real price of oil driven by negative foreign oil supply shocks or by positive precautionary oil demand shocks causes an insignificant effect on Canada's real GDP upon impact but causes a slightly significant decline afterwards. The intuition is that a positive innovation in aggregate demand tends to increase the demand for Canada's overall exports. Oil supply disruptions in foreign countries or positive precautionary oil demand shocks increase the uncertainty about future oil prices, which leads firms to postpone irreversible investment expenditures, and tends to reduce Canada's real GDP. Furthermore, among the identified oil shocks, foreign aggregate demand shocks have been relatively more important in explaining the variations of most of Canadian macroeconomic variables over the estimation period.

The second chapter examines the links between oil demand and supply shocks and labor market adjustments in Canadian manufacturing industries using a panel structural VAR model. The model is estimated with disaggregated annual data at the industry level from 1975 to 2008. The results show that a positive aggregate demand shock increases both labor and the price of labor over a 20-year period. A negative oil supply shock has a relatively small negative effect upon impact but the effect turns positive after the first year. In contrast, a positive precautionary oil demand shock has a negative impact over all horizons. The paper also examines how the responses to different types of oil shocks vary from industry to industry. The results suggest that industries with higher net trade exposure/oil-intensity are more vulnerable to oil price increases driven by oil supply shocks and aggregate demand shocks.

The third chapter examines the welfare implications of introducing competitive storage on the global oil market using a three country DSGE model characterized by two oil-importing countries and one oil-exporting country. The welfare gains are measured by consumption compensating variation un-

der two alternative monetary policy rules. The main results indicate that the introduction of oil storage has negative welfare effects for each of the two oil importing countries, while it has positive welfare effects for the oil exporting country, whatever the monetary policy rule. I also found that including the exchange rate depreciation in the monetary policy rules allows to slightly reduce the welfare costs for both oil importing countries. Finally, the magnitude of the welfare effects depends on the steady state level of oil storage and is mainly driven by oil storage shocks.

Keywords: Bayesian estimation, DSGE models, panel VAR models, oil demand and supply shocks, welfare, employment, manufacturing industries, open economy, Canada.

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List of abbreviations

CAD	Canadian Dollar
CES	Constant Elasticity of Substitution
CSD	Cross-Section Dependence
DSGE	Dynamic Stochastic General Equilibrium
GDP	Gross Domestic Product
LCP	Local Currency Pricing
LOP	Low of One Price
ML	Maximum Likelihood
NAICS	North American Industry Classification System
OLS	Ordinary Least Squares
S.D.	Standard Deviation
SMM	Simulated Method of Moments
U.S.	United States
USD	United States Dollar
VAR	Vector Autoregressive

Chapter 1

Oil Demand and Supply Shocks in Canada's Economy

1.1 Introduction

Oil is one of the most important commodities to the modern economy. It fuels our cars and manufacturing, and has been known to spark political conflicts. Thus, it's not surprising that oil plays an important role in determining macroeconomic outcomes, particularly for oil-exporting countries. However, are all changes to oil prices created equal? This paper examines whether the cause of an oil price change affects the impact that change has on the Canada's macroeconomic activity.

There is a fairly extensive literature on the macroeconomic impact of oil shocks since the seminal work of Hamilton (1983), which finds that seven of the eight recessions in the U.S between 1948-1981 were preceded by a large increase in the price of crude oil. The standard approach in the literature, including Kim and Loungani (1992), Mork et al. (1994a), Brown and Yucel (1999), Jiménez-Rodríguez and Sanchez (2005), and Kilian (2008b), among many others, is to focus on the impact of exogenous oil shocks on macroeconomic activity. This approach does not allow one to explicitly examine the effects of world aggregate demand shocks on oil price movements, nor does it allow one to distinguish between demand and supply shocks to the global crude oil market. The role of speculative oil demand on oil price movements has also been generally neglected in the literature. Other authors have disentangled the various oil demand and supply shocks, but find that these different oil shocks have similar macroeconomic effects. In particular, Bodenstein et al. (2007), find that a rise in foreign oil demand that induces a comparable rise in the price of oil as an adverse supply shock has similar effects on the trade balance and the terms of trade of the U.S. economy.

More recent empirical literature has challenged the standard approach, claiming that oil supply shock measures alone do not explain the bulk of oil price fluctuations and that all oil price shocks are not alike. First, there is significant evidence of macroeconomic aggregates influencing oil prices, as opposed to the reverse. A significant part of oil price volatility has historically been driven by world macroeconomic aggregates. Indeed, Barsky and Kilian (2004) find that while oil price shocks were caused by supply disruptions in the 1970s, aggregate demand shocks have accounted for the largest share of oil price fluctuations in the 2000s. According to Juvenal and Petrella (2011), from 2004 to 2008, aggregate demand shocks accounted for the largest share of oil price fluctuations, and speculative shocks have been the second most important driver. Second, Kilian (2008a) finds that the effect of oil supply shocks on the U.S. economy is smaller than previous estimates in the literature, which treated major oil price increases as exogenous to the global economy. Kilian's result suggests that the standard approach overestimates the macroeconomic impact of oil supply shocks. Finally, and more importantly, Kilian (2009) finds that the price of crude oil is driven by different types of oil shocks, which have very different macroeconomic effects. Indeed, using a structural vector autoregression (VAR) model, Kilian (2009) shows that the price of crude oil has historically been driven by distinct oil demand and oil supply shocks, and each of these shocks have different dynamic effects on U.S. GDP and inflation, in terms of timing, magnitude and sign. According to Kilian (2009), since the start of the 21st century, oil price increases have been driven less by oil supply shocks and more by a combination of aggregate demand and speculative oil demand shocks. These speculative oil demand shocks in particular have played a much larger role in driving oil price fluctuations than acknowledged in most of the literature. The findings of Kilian (2009) highlight the need to disentangle demand and supply shocks when studying the impact of oil price shocks on macroeconomic aggregates. The reason is that understanding the sources of oil price shocks is crucial in order to design and implement macroeconomic policies to mitigate the shocks' adverse effects.

Recently, there has been increased interest in exploring the sources of oil price fluctuations and their effects on macroeconomic variables. For instance, Hamilton (2009) explores the fundamental determinants of petroleum demand and supply. His results suggest that the role of speculation in driving oil price dynamics cannot be neglected. This has been confirmed by Kaufmann and Ullman (2009), who find that speculation exacerbates an initial increase in oil prices related to oil market fundamentals. Based on the work of Kilian (2009), Kilian et al. (2009) examine several different oil demand and supply shocks, and show that each has a different effect on external balances of the aggregates of major oil exporting countries, including Canada. Peersman and Van Robays (2009) find that the effects on the Euro area vary considerably depending on the source of oil price movements. These authors use a structural VAR framework and sign restriction to identify different types of oil shocks. In a similar study, Baumeister et al. (2010) investigate the economic consequences of oil shocks across countries and time. They find that economies which improved their net energy position the most over time became relatively less vulnerable to the various oil shocks identified in Kilian (2009). All of these studies find that there are important differences between oil demand and supply shocks, consistent with Kilian (2009).

Based on the empirical work of Kilian (2009), this paper develops a structural dynamic stochastic general equilibrium (DSGE) model for a small open oil-exporting economy. The model accounts for the three main components of oil price innovations, namely oil supply shocks, aggregate demand shocks, and precautionary oil demand shocks. Oil supply shocks refer to exogenous changes in current oil production, aggregate demand shocks refer to fluctuations in the price of oil driven by innovations to global real economic activity, and speculative oil demand shocks refer to shifts in the price of oil driven by innovations in inventories of crude oil.[1] The model is estimated using a Bayesian approach described in An and Schorfheide (2007), using quarterly Canadian data for real GDP, real consumption, real investment, the real exchange rate, real price of oil, crude oil production in Canada, and crude oil production in the rest of world, for the period 1983Q1 to 2010Q4. I use the estimated model to investigate the dynamic effects and relative importance of the different types of oil shocks on key Canadian macroeconomic variables.

I find that a 10% increase in the real price of oil driven by a positive foreign aggregate demand shock significantly increases Canada's real GDP by about 0.4% in the first quarter following the shock, and the effect remains positive over the long run. In contrast, a 10% increase in the real price of oil driven by a negative foreign oil supply shock or by a positive precautionary oil demand shock initially causes an insignificant effect. The effect turns significantly negative before returning to its steady-state level.

These results suggest that the effect of an oil price increase on Canada's economy depends on what is causing the higher oil price. An increase in oil prices is more beneficial to Canada's economy when it is driven by innovations in global real economic activity. Such shocks tend to increase the demand for Canadian exports. In contrast, if higher oil prices are the result of uncertainty about future oil prices in the crude oil market, investment slows, and tends to

1. Kilian (2009) uses the term "oil-specific demand shock" to reflect the fluctuations in precautionary demand for oil driven by uncertainty about future oil supply shortfalls.

reduce Canada's real GDP. Finally, the variance decomposition of Canada's real GDP indicates that, among the identified oil shocks, aggregate demand shocks play a dominant role in real GDP fluctuations. Oil supply shocks and precautionary oil demand shocks account for negligible shares of the variance in Canadian macroeconomic aggregates, in the short run as well as in the long run. Overall, the results in this paper strongly support the idea that not all oil price shocks are alike, consistent with the findings of Kilian (2009).

This paper is unique in several respects. It is one of very few studies that disentangle the effects of oil demand and supply shocks using an estimated structural DSGE model; most studies in the literature employ a VAR model. In addition, this study focuses on a major oil producer and net oil-exporting economy, Canada. This is in contrast with most studies in the literature, which tend to focus on oil-importing countries, such as the U.S. Canada is a notable case study, as it was the world's sixth-largest oil producer in 2010, and crude oil represents a significant share of Canada's total exports. Furthermore, this paper differs from others by modelling the oil production sector in a manner that recognizes the importance of this sector in Canada's economy. The inclusion of a cash market and storage market for crude oil in my model is also a notable contribution. Finally, this paper provides a comprehensive discussion of Bayesian estimation of DSGE models.

The rest of the paper is organized as follows. In Section 1.2, I present the details of the model. Section 1.3 discusses estimation issues, including the Bayesian estimation strategy, the data used, and parameter estimates. Section 1.4 analyzes the implications of oil demand and supply shocks for the Canadian economy. Section 1.5 examines the robustness of my findings. Finally, Section 1.6 concludes.

1.2 Model Economy

In this section, I develop a DSGE model for a small open oil-producing economy. The economy is small in the sense that changes in domestic variables have insignificant effects on foreign variables. In the model, there is a representative household, an oil producer, producers of an intermediate domestic good, and a producer of a final good. The inclusion of an oil producer is meant to account for the importance of oil reserves, as well as account for the relative capital-intensive technology used in the process of oil extraction in Canada. The model allows for crude oil storage, such that one can formally model precautionary and speculative oil demand shocks. In order to capture the persistence in the data, the model allows for real rigidities, including capital adjustment costs and habit formation in consumption preferences, as in Christiano et al. (2005). The indexes of variables in the oil production sector and the sector producing the domestic good are denoted by o and d, respectively.

1.2.1 Households

I consider an economy with an infinitely lived representative household, deriving utility from consumption and leisure, with separable preferences. The present value of the expected utility of the household is given by:

$$U^0 = E_0 \sum_{t=0}^{\infty} \beta^t \left\{ \log(C_t - \hbar C_{t-1}) + \chi \log(1 - N_t) \right\} \tag{1.1}$$

where $\beta \in (0,1)$ is a constant discount factor, C_t is consumption in period t, N_t is the fraction of total available time devoted to a productive activity in period t. The parameter χ represents relative preferences for leisure. Consistent with Christiano et al. (2005), I allow for habit formation in consumption, governed by persistence parameter $\hbar \in (0,1)$, such that the household's marginal utility of consumption today is affected by the level of aggregate consumption in the last period, C_{t-1}.

The household has access to riskless discount one-period domestic and foreign bonds. The household enters period t with a quantity of nominal domestic bonds, B_{t-1}, and a quantity of nominal foreign bonds, $e_t B^{\star}_{t-1}$. The household then receives wages $W_t N_t$ and capital income $R^k_{s,t} K_{s,t}$ from each sector $s \in \{o, d\}$. The household also receives a factor payment of oil reserve resources, $P_{X,t} X_t$, where $P_{X,t}$ is the nominal price of the oil reserve input, X_t. These resources are used to finance consumption C_t, investment in new capital I_t (by assuming that the household owns the capital stock and rent it to firms), and the acquisition of domestic and foreign assets to be carried over to the next period. The flow budget constraint of the household is given by:

$$P_t C_t + P_t I_t + \frac{B_t}{R_t} + \frac{e_t B^{\star}_t}{\Phi_{B^{\star}_t} R^{\star}_t} = B_{t-1} + e_t B^{\star}_{t-1} + W_t N_t + \sum_{s=o,d} R^k_{s,t} K_{s,t} + P_{X,t} X_t \quad (1.2)$$

where P_t is the aggregate price index of consumption, and also represents the price of investment; e_t is the nominal exchange rate, defined as the price of one unit of foreign currency in Canadian dollars; and R_t and $R^{\star}_t$ are the domestic gross interest rate and foreign gross interest rate, respectively. W_t is the wage rate, and $R^k_{s,t}$ is the rental price of capital in sector s=o,d. $\Phi_{B^{\star}_t}$ is a premium that the household has to pay when it borrows from abroad. This risk premium is assumed to be a strictly increasing function of the country's level of net foreign debt, relative to GDP:[2]

$$\Phi_{B_t^\star} = \exp\left(-\phi_{b^\star}\left(\frac{e_t B_t^\star}{P_{Y,t} Y_t}\right)\right) \tag{1.3}$$

where $P_{Y,t}Y_t$ is the nominal GDP and $\phi_{b^\star} > 0$ is a parameter that determines the debt-elasticity of interest-rate premium. As demonstrated by Schmitt-Grohe and Uribe (2003), a debt-elastic interest-rate premium is a technical term that ensures the stationarity of a dynamic equilibrium model of an open economy. If the country has a net lender position internationally, then the household will earn a lower return on any holdings of foreign bonds. By contrast, if the country has a net debtor position, the household will pay a higher return on any foreign debt.

The household faces an investment adjustment cost. Consistent with Christiano et al. (2005), the function of adjustment costs depends on current and lagged investment, and the stock of capital is accumulated according to

$$K_{s,t+1} = (1-\delta)K_{s,t} + A_{I,t}\left(1 - S(I_{s,t}/I_{s,t-1})\right) I_{s,t} \tag{1.4}$$

where $S(1) = S'(1) = 0$ and $S''(1) = \kappa_s > 0$ for $s \in \{o, d\}$. It is costly to change the level of investment out of the steady state. Parameter δ represents the capital depreciation rate common to both sectors, but parameter κ_s for capital adjustment costs can be different across sectors. To simplify notation, I do not index the function S. Variables $I_{o,t}$ and $I_{d,t}$ are the level of investment in the oil and domestic goods sectors, respectively, such that the total investment $I_t = I_{o,t} + I_{d,t}$. The variable $A_{I,t}$ is an investment-specific technology shock, or the marginal efficiency of investment. This shock captures the rate of transformation of investment into installed capital to be used in production.

2. The specification of the risk premium, in this paper, is taken from Bodenstein et al. (2007).

In each period t, the household chooses consumption C_t, labor N_t, nominal domestic bonds B_t, nominal foreign bonds $B_t^\star$, capital stocks $K_{o,t+1}$ and $K_{d,t+1}$, and investments $I_{o,t}$ and $I_{d,t}$, in order to maximize 1.1 subject to 1.2 and 1.4. The resulting first-order conditions are :

$$(C_t - \hbar C_{t-1})^{-1} - \hbar\beta\left(C_{t+1} - \hbar C_t\right)^{-1} = \Lambda_t \tag{1.5}$$

$$\frac{\chi(1-N_t)^{-1}}{\Lambda_t} = w_t \tag{1.6}$$

$$\Lambda_t = \beta R_t E_t\left[\frac{P_t}{P_{t+1}}\Lambda_{t+1}\right] \tag{1.7}$$

$$\Lambda_t = \beta\Phi_{B_t^\star} R_t^\star E_t\left[\frac{P_t}{P_{t+1}}\frac{e_{t+1}}{e_t}\Lambda_{t+1}\right] \tag{1.8}$$

$$q_{s,t} = \beta E_t\left[\left(\frac{\Lambda_{t+1}}{\Lambda_t}\right)\left(r_{s,t+1}^k + (1-\delta)q_{s,t+1}\right)\right] \tag{1.9}$$

$$\begin{aligned} 1 = \quad & q_{s,t}A_{I,t}\left[1 - S\left(\tfrac{I_{s,t}}{I_{s,t-1}}\right) - S'\left(\tfrac{I_{s,t}}{I_{s,t-1}}\right)\left(\tfrac{I_{s,t}}{I_{s,t-1}}\right)\right] \\ & + \beta E_t\left[\left(\tfrac{\Lambda_{t+1}}{\Lambda_t}\right) q_{s,t+1}A_{I,t+1}S'\left(\tfrac{I_{s,t+1}}{I_{s,t}}\right)\left(\tfrac{I_{s,t+1}}{I_{s,t}}\right)^2\right] \end{aligned} \tag{1.10}$$

$$q_{s,t} = \frac{\Xi_{s,t}}{\Lambda_t} \tag{1.11}$$

where Λ_t is the Lagrange multiplier associated with the real budget constraint and $\Xi_{s,t}$ is the Lagrange multiplier associated with 1.4. $w_t = W_t/P_t$ is the real wage rate and $r_{s,t}^k = R_{s,t}^k/P_t$ is the real capital return in sector $s \in \{o, d\}$. The variable $q_{s,t}$, known as the Tobin's q, is the relative price or shadow price of installed capital $K_{s,t+1}$ in period t available for production in period t+1, in terms of consumption units.

Equations (1.6) to (1.9) can be interpreted as follows. Equation (1.6) implies that marginal rate of substitution between leisure and consumption is equal to the wage rate. Equation (1.7) implies that the marginal cost of foregoing one unit of consumption for additional savings in the domestic asset (the left side) is equal to the discounted future marginal benefit in terms of consumption units derived from this additional unit of asset (the right side). This is a no-arbitrage condition between consuming and saving in domestic bonds. Equation (1.8) is a no-arbitrage condition between consuming and saving in foreign bonds. The decision to invest in the foreign asset takes into account the expected change in the exchange rate. Equation (1.9) implies that the marginal of cost foregoing one unit of consumption for additional investment in new capital is equal to the discounted future marginal benefit in terms of the utility derived from this additional investment in capital. The no-arbitrage conditions imply that the expected return on the bond markets must be the same as the expected return that the household gets by renting their capital to firms producing the domestic good.

In order to capture the sectoral volatility, the model allows heterogeneity in wages and labor across sectors as in Horvath (2000) and Bouakez et al. (2009). Specifically, households are willing to work a positive number of hours in each sector, even if wages are not equal in the two sectors. That is,

$$N_t = \left(N_{o,t}^{\frac{\varsigma+1}{\varsigma}} + N_{d,t}^{\frac{\varsigma+1}{\varsigma}} \right)^{\frac{\varsigma}{\varsigma+1}} \tag{1.12}$$

where $\varsigma > 0$ is the labor elasticity of substitution across sectors and $N_{s,t}$ is the number of hours worked in sector s=o,d at time t. N_t can be regarded as an index of hours worked, and its corresponding wage index is given by

$$W_t/P_t = \left((W_{o,t}/P_t)^{1+\varsigma} + (W_{d,t}/P_t)^{1+\varsigma} \right)^{1/(1+\varsigma)} \tag{1.13}$$

where $W_{o,t}$ and $W_{d,t}$ correspond to the nominal wage rate in oil and domestic good sectors. This index has the property that $\sum_{s=o,d} W_{s,t}N_{s,t} = W_tN_t$, thereby preserving the representative household setup.

1.2.2 Crude oil production

The economy is endowed with crude oil reserves. There is a competitive firm producing refined crude oil using capital and the crude oil reserves with a constant elasticity of substitution (CES) technology of the form:

$$Y_{o,t} = A_{o,t}\left(\alpha_{K_o}^{\frac{1}{\mu}}K_{o,t}^{\frac{\mu-1}{\mu}} + \alpha_{N_o}^{\frac{1}{\mu}}N_{o,t}^{\frac{\mu-1}{\mu}} + \alpha_X^{\frac{1}{\mu}}X_t^{\frac{\mu-1}{\mu}}\right)^{\frac{\mu}{\mu-1}} \tag{1.14}$$

where $Y_{o,t}$, is the level of crude oil extracted at time t, $K_{o,t}$ is capital, $N_{o,t}$ is labor, and X_t, is the level of oil reserves available. Parameters α_{K_o}, α_{N_o} , and α_X are the shares of capital, labor, and oil reserve inputs in the production of crude oil, respectively, and $\alpha_{K_o} + \alpha_{N_o} + \alpha_X = 1$. Variable $A_{o,t}$ is a technology shock that only affects the oil sector. The parameter μ is the elasticity of substitution among factors used in oil production. I treat available oil reserves as a fixed factor, and do not attempt to model new oil discoveries.[3] This input in the production process for oil extraction captures the importance of this natural resource to Canada's economy. The price of crude oil, $P^{\star}_{o,t}$, is in U.S. dollars and is determined by the international oil market.

3. The model has been designed to explain the macroeconomic effects of increases in oil prices driven by exogenous shocks that originate from abroad. It is not meant to explain the effects of oil price fluctuations due to new oil reserve discoveries in Canada.

At each period, given the price of crude oil, $P^\star_{o,t}$; the rental price of capital, $R^k_{o,t}$; the wage, $W_{o,t}$; and the price of crude oil reserves, $P_{X,t}$; the oil-producing firm chooses the level of capital, labor, and crude oil reserves, $\{K_{o,t}, N_{o,t}, X_t\}$, to maximize its profit:

$$\Pi_{o,t} = \max_{\{K_{o,t},N_{o,t},X_t\}} \left\{ e_t P^\star_{o,t} Y_{o,t} - R^k_{o,t} K_{o,t} - W_{o,t} N_{o,t} - P_{X,t} X_t \right\} \quad \text{subject to (1.14)} \tag{1.15}$$

From the first-order conditions with respect to $K_{o,t}$, $N_{o,t}$, and X_t, the demand curves for capital, labor and crude oil reserves, respectively, are given by:

$$r^k_{o,t} = s_t p^\star_{o,t} \times A_{o,t}^{\frac{\xi_o - 1}{\mu}} \left(\frac{1}{\alpha_{K_o}} \frac{K_{o,t}}{Y_{o,t})} \right)^{-\frac{1}{\mu}} \tag{1.16}$$

$$w_{o,t} = s_t p^\star_{o,t} \times A_{o,t}^{\frac{\xi_o - 1}{\mu}} \left(\frac{1}{\alpha_{N_o}} \frac{N_{o,t}}{Y_{o,t}} \right)^{-\frac{1}{\mu}} \tag{1.17}$$

$$p_{X,t} = s_t p^\star_{o,t} \times A_{o,t}^{\frac{\xi_o - 1}{\mu}} \left(\frac{1}{\alpha_X} \frac{X_t}{Y_{o,t}} \right)^{-\frac{1}{\mu}} \tag{1.18}$$

where $p_{X,t} = P_{X,t}/P_t$, $p^\star_{o,t} = P^\star_{o,t}/P^\star_t$ and $s_t = e_t P^\star_t / P_t$ are the real price of crude oil reserves, the real price of crude oil in international oil market, and the real exchange rate, respectively. Equations (1.16), (1.17) and (1.18) represent the demand for the inputs $K_{o,t}$, $N_{o,t}$, and X_t, respectively. These equations stipulate that the marginal cost of each input is equal to its marginal productivity. Finally, oil output is used as an input into the production of the domestic good, or exported abroad.

1.2.3 Domestic good production

In the economy, there is a single domestic intermediate good produced by perfectly competitive identical firms. The production technology for a typical firm is given by a nested constant elasticity of substitution function of the form:

$$Y_{d,t} = A_{d,t}\left(\alpha_{K_d}^{\frac{1}{\nu}} K_{d,t}^{\frac{\nu-1}{\nu}} + \alpha_{N_d}^{\frac{1}{\nu}} N_{d,t}^{\frac{\nu-1}{\nu}} + \alpha_{O}^{\frac{1}{\nu}} O_{t}^{\frac{\nu-1}{\nu}}\right)^{\frac{\nu}{\nu-1}} \tag{1.19}$$

where $K_{d,t}$, $N_{d,t}$, and O_t are, respectively, the level of capital, labor, and oil used to produce the level $Y_{d,t}$ of domestic good. Parameters α_{K_d}, α_{N_d} , and α_O, such that their sum is equal to 1, define the weights of capital, labor, and oil inputs, respectively, in the production of domestic good. $A_{d,t}$ is a technology shock specific to the domestic good sector. ν determines the degree of substitution between oil and the other factors of production. I assume the Law of One Price holds for oil, implying that its price in the domestic economy is given by $P_{o,t} = e_t P^{\star}_{o,t}$.

At each period t, and given the prices $R^k_{d,t}$, $W_{d,t}$, and $P_{o,t}$, a typical producing firm optimally chooses the levels of physical capital, $K_{d,t}$, labor, $N_{d,t}$, and oil, O_t that maximizes its profits:

$$\Pi_{d,t} = \max_{\{K_{d,t},N_{d,t},O_t\}} \left\{P_{d,t}Y_{d,t} - R^k_{d,t}K_{d,t} - W_{d,t}N_{d,t} - P_{o,t}O_t\right\} \tag{1.20}$$
$$\text{subject } to \ (1.19)$$

From the first-order condition, it follows that the demand curves for capital, labor and oil, respectively, are given by:

$$r^k_{d,t} = p_{d,t} \times A_{d,t}^{\frac{\xi d-1}{\nu}} \left(\frac{1}{\alpha_{K_d}} \frac{K_{d,t}}{Y_{d,t}}\right)^{-\frac{1}{\nu}} \tag{1.21}$$

$$w_{d,t} = p_{d,t} \times A_{d,t}^{\frac{\xi d-1}{\nu}} \left(\frac{1}{\alpha_{N_d}} \frac{N_{d,t}}{Y_{d,t}}\right)^{-\frac{1}{\nu}} \tag{1.22}$$

$$p_{o,t} = p_{d,t} \times A_{d,t}^{\frac{\xi d-1}{\nu}} \left(\frac{1}{\alpha_O} \frac{O_t}{Y_{d,t}} \right)^{-\frac{1}{\nu}} \tag{1.23}$$

where $p_{o,t} = P_{o,t}/P_t$ and $p_{d,t} = P_{d,t}/P_t$ are the real domestic price of oil and the real price of the domestic good, respectively. Equations 1.21-1.23 imply that the price of each input is equal to its marginal productivity.

The domestic good can be used to produce the final good or exported abroad. The foreign demand for the domestic good depends on its relative price and the foreign output, $Y_t^\star$, and is given by:

$$Y_{d,t}^x = \omega_{d,x} \left(\frac{P_{d,t}}{e_t P_t^\star} \right)^{-\vartheta_x} Y_t^\star \tag{1.24}$$

where $\omega_{d,x}$ is a non-negative parameter determining the fraction of foreign spending that is spent on purchasing the domestic good. Parameter ϑ_x represents the price elasticity of demand for the domestic good in foreign countries. $P_t^\star$ is the foreign price index. Variables $Y_t^\star$ and $P_t^\star$ are both exogenously given. I assume that the relationship between foreign output and foreign real interest rate is $\hat{r}_t^\star = E_t \hat{Y}_{t+1}^\star - \hat{Y}_t^\star$, where the circumflex denotes that a variable is expressed as a log deviation from its steady state.

1.2.4 Final good production

There is a final good produced by a perfectly competitive firm using domestic and imported goods according to a constant-elasticity-of-substitution (C.E.S.) technology:

$$Z_t = \left(\omega_d^{\frac{1}{\vartheta}} {Y_{d,t}^z}^{\frac{\vartheta-1}{\vartheta}} + (1-\omega_d)^{\frac{1}{\vartheta}} Y_{m,t}^{\frac{\vartheta-1}{\vartheta}} \right)^{\frac{\vartheta}{\vartheta-1}} \tag{1.25}$$

where the parameter ω_d is the importance of the domestic intermediate good in the production of final good. The parameter $\vartheta > 0$ is the elasticity of substitution between domestic and imported goods. The demand functions, derived from the profit maximization function for the firm producing the final good, are given by:

$$Y^z_{d,t} = \omega_d \left(\frac{P_{d,t}}{P_t}\right)^{-\vartheta} Z_t \quad and \quad Y_{m,t} = (1-\omega_d)\left(\frac{P_{m,t}}{P_t}\right)^{-\vartheta} Z_t \tag{1.26}$$

The zero-profit condition implies that the price of the final good, P_t, is given by:

$$P_t = \left(\omega_d P_{d,t}^{1-\vartheta} + (1-\omega_d) P_{m,t}^{1-\vartheta}\right)^{\frac{1}{1-\vartheta}} \tag{1.27}$$

The final good is then split between consumption C_t and investment I_t. For simplicity, I assume that $P_{m,t} = \zeta_t e P^\star_t$, where ζ_t is a shock to the price of imports that reflects the deviations from the Law of One Price in the imports price. Throughout this assumption, I allow for incomplete exchange-rate pass-through in imports. In the rest of the paper, $p_{m,t} = P_{m,t}/P_t$ will refer to the real price of imports.

1.2.5 Oil markets

To reflect the oil market behavior, I introduce two interrelated markets for crude oil, as in Pindyck (2004): the *cash market* for immediate (or "spot") purchases and sales, and the *storage market* for inventory. This distinction allows holding crude oil inventories for speculative purposes. Oil inventories help satisfy demand in the oil market when there are oil supply disruptions, and also help to smooth the production process. [4]

4. There are several reasons for carrying inventories for oil, including uncertainty about the size of future demand, uncertainty about the amount of lead time for deliveries, provision for greater assurance of continuing production, and speculation on future prices of oil.

1.2.5.1 Storage market for crude oil

Following Hamilton (2009), I consider a competitive representative speculator who purchases and stores crude oil today (denoted as date t) and expects to sell it tomorrow at a higher price. Let OS_t denote the inventory level of oil that the speculator wants to hold at period t. The profits earned by storing OS_t units of oil is the difference between the speculator's revenue in period $t+1$, and the cost of purchasing OS_t in the spot market in period t plus the storage costs. The speculator's profit maximization function is:

$$\max_{OS_t} \left\{ R_t^{\star\,-1}\, E_t(P^\star_{o,t+1})OS_t - P^\star_{o,t}OS_t - \Omega(OS_t, Z_{os,t}) - \kappa_{os}OS_t \right\} \tag{1.28}$$

where $\Omega(OS_t, Z_{os,t})$ is the marketing cost i.e the cost of delivery scheduling and avoidance of stockouts, and $\kappa_{os} > 0$ is the per-unit storage cost, which is assumed to be constant. $Z_{os,t}$ is an exogenous storage demand shock. The value of the marginal unit of inventory, defined as the *marginal convenience yield*, is given by $\psi_t = -\partial\Omega/\partial OS_t$. In the commodity pricing literature, the marginal convenience yield is generally assumed to be decreasing, such that $\partial\psi_t/\partial OS_t < 0$ (see Pindyck (2004), for example).[5]

Given the spot price of oil, the first-order condition with respect to OS_t gives the demand function for crude oil inventories:

$$\psi_t - \kappa_{os} = P^\star_{o,t} - E_t(P^\star_{o,t+1})/R^\star_t \tag{1.29}$$

The log-linearized version of the storage demand function is:

$$\hat{OS}_t = \theta \left[\beta(E_t\hat{p}^\star_{o,t+1} - \hat{r}^\star_t) - \hat{p}^\star_{o,t}\right] + \hat{Z}_{os,t} \tag{1.30}$$

5. Additionally, it's assumed that $\partial\psi_t/\partial Z_{os,t} > 0$, i.e an increase in uncertainty about the future oil price is more likely to result in scarcity in the oil market.

where $\theta^{-1} = -\frac{OS}{P_o^\star}\frac{\partial \psi_t}{\partial OS} > 0$. Equation (1.29) implies that profit-maximizing competitive storage will set the expected marginal revenue from storing a barrel of crude oil equal to the marginal storage cost. I assume that the percentage deviation of $Z_{os,t}$ from its steady state level evolves according to an AR(1) process.

1.2.5.2 Cash markets of crude oil

In the cash market for crude oil, oil is sold or purchased at spot price $P_{o,t}^\star$. The equilibrium condition on the cash market of oil at each period t is given by:

$$\Delta OS_t = (Y_{o,t} + Y_{o,t}^\star) - (O_t + O_t^\star) \tag{1.31}$$

where $Y_{o,t}^\star$ and $O_t^\star$ represent foreign oil production and consumption, respectively. The total new oil production is $Y_{o,t} + Y_{o,t}^\star$, while the total oil demand for immediate use is the sum of the domestic oil demand and the foreign oil demand, given by $O_t + O_t^\star$. The consumption demand function for crude oil in the foreign economy is assumed to have the following form:

$$O_t^\star = \phi_o^\star \left(\frac{P_{o,t}^\star}{P_t^\star}\right)^{-\varphi} Y_t^\star \tag{1.32}$$

where φ represents the price-elasticity of oil demand in the foreign economy. Parameter $\phi_o^\star$ is a non-negative scaling parameter. A positive innovation in global real economic activity implies a positive innovation in foreign oil demand. I assume assume that foreign oil production is given by an exogenous AR(1) process. The price of oil is determined endogenously in the world oil market to satisfy equation (1.31). Because the level of oil inventories can change from period to period, the price of oil in any period need not be equal to the total new production and total consumption of oil. In other words, the price of oil that clears the world crude oil market is not only determined by current oil production and consumption, but also by changes in oil inventories. Oil inventories are included in the model to explain short-run variations in oil prices induced by the uncertainty about shortfalls of expected oil supply relative to expected oil demand (see Kilian (2009) and Alquist and Kilian (2010)).

1.2.6 Exogenous processes

There are seven exogenous driving forces in the model. These are a foreign oil supply shock ($Y^{\star}_{o,t}$), speculative oil demand shock ($Z_{os,t}$), shock on foreign output ($Y^{\star}_{t}$), technological shock on the oil sector ($A_{o,t}$), technological shock on the domestic good sector ($A_{d,t}$), investment-specific technology shock ($A_{I,t}$), and shock to the price of imports (ζ_t). I assume that the percentage deviations from the steady-state [6] of each of the exogenous processes evolve according to an $AR(1)$ process:

$$\hat{\lambda}_t = \rho_\lambda \hat{\lambda}^{\star}_{t-1} + \epsilon_{\lambda,t} \tag{1.33}$$

where $\lambda = \{Y^{\star}_o, Y^{\star}, Z_{os}, A_o, A_d, A_I, \zeta\}$. The persistence parameters, ρ_λ, are strictly bounded between -1 and 1, and the innovations, $\epsilon_{\lambda,t}$, are mutually independent, serially uncorrelated and normally distributed with a mean of 0 and a variance σ^2_λ. Note that the process that drives the foreign oil supply is specified such that a positive innovation tends to lower the oil supply and increase the real price of oil.

1.2.7 Market-clearing conditions

An equilibrium for this economy is a collection of sequences $\{C_t$, N_t, $N_{o,t}$, $N_{d,t}$, I_t, $I_{o,t}$, $I_{d,t}$, $B^{\star}_t$, B_t, $Y_{o,t}$, $K_{o,t}$, $Y_{d,t}$, $K_{d,t}$, $Y_{m,t}$, Z_t, O_t, $Y^z_{d,t}$, $Y^x_{d,t}$, r_t, w_t, $w_{o,t}$, $w_{d,t}$, $r^k_{o,t}$, $r^k_{d,t}$, $q_{o,t}$, $q_{d,t}$, $p_{o,t}$, $p_{d,t}$, $p_{m,t}$, $s_t\}^{\infty}_{t=0}$, and a collection of $\{O^{\star}_t$, $p^{\star}_{o,t}$, $r^{\star}_t\}^{\infty}_{t=0}$ satisfying the household and producers' first-order conditions, given

6. I define $\hat{x}_t = (x_t - x)/x$ as the percentage deviation from its steady state x. Around x and when x_t is positive, it is assumed that the approximation $\log(x_t) - \log(x) = (x_t - x)/x$.

the set of exogenous stochastic processes $\{Y^{\star}_{o,t}, Y^{\star}_{t}, Z_{os,t}, A_{o,t}, A_{d,t}, A_{I,t}, \zeta_t\}_{t=0}^{\infty}$. Without a loss of generality, the domestic debt is assumed to be in zero net supply in each period. The market-clearing conditions for the domestic and final good require: $Y_{d,t} = Y^{z}_{d,t} + Y^{x}_{d,t}$ and $Z_t = C_t + I_t$.

Using the equilibrium conditions in the goods, labor and capital markets, and imposing the budget constraint of the household, I obtain the following equation that describes the evolution of the net foreign asset position (the current account equation):

$$\frac{e_t B^{\star}_t}{\Phi_{B^{\star}_t} R^{\star}_t} = e_t B^{\star}_{t-1} + e_t P^{\star}_{o,t}(Y_o - O_t) + P_{d,t} Y^{x}_{d,t} - P_{m,t} Y_{m,t} \tag{1.34}$$

The nominal gross domestic (GDP) product measured from the demand side, at current domestic prices, is such that:

$$P_{Y,t} Y_t = P_t C_t + P_t I_t + P_{o,t}(Y_{o,t} - O_t) + P_{d,t} Y^{x}_{d,t} - P_{m,t} Y_{m,t} \tag{1.35}$$

where Y_t demotes real GDP and $P_{Y,t}$ the implicit GDP deflator.

1.3 Estimation Issues

For a given set of parameters, the model is log-linearized around its deterministic steady state. Appendix $A.2$ presents the full log-linearized equations. In order to accurately represent the Canadian economy's response to shocks, the key parameters in the log-linearized model are estimated applying Bayesian methods, as described in An and Schorfheide (2007) and Adolfson et al. (2007). There are several advantages of using Bayesian methods to estimate a DSGE model, but two in particular justify my estimation strategy. First, there are parameter restrictions that are more difficult to enforce using standard maximum likelihood (ML) estimation or simulated method of moments (SMM) estimation. Second, Bayesian methods are more suitable for estimating models with weak identification than ML or SMM.

1.3.1 Bayesian estimation strategy

The Bayesian estimation is based on the likelihood function generated by the solution of the log-linear version of the model. The set of the log-linearized equilibrium equations of the model can be expressed in a linear rational expectation system so that the solution to this system, in reduced form, can be rewritten as follows:

$$\hat{\mathbf{x}}_t = F(\Theta)\hat{\mathbf{x}}_{t-1} + G(\Theta)\varepsilon_{\xi,t} \tag{1.36}$$

where Θ is the vector of model parameters, and matrices $F(.)$ and $G(.)$ are non-linear functions of the structural parameters contained in vectors. The variable $\hat{\mathbf{x}}_t$ is a vector containing the model variables expressed as log-deviation from their steady-state values. It collects the endogenous variables of the model and the exogenous variables. Vector $\varepsilon_{\xi,t}$ contains white noise innovations to the exogenous shocks of the model. The vector of observable variables $\hat{\mathbf{y}}_t$ is related to variables in the model through a measurement equation:

$$\hat{\mathbf{y}}_t = H\hat{\mathbf{x}}_t \tag{1.37}$$

where H is a matrix that selects elements from $\hat{\mathbf{x}}_t$. Given the observable variables collected in $\mathcal{Y}_T = \{\hat{\mathbf{y}}_1, ..., \hat{\mathbf{y}}_T\}$, the likelihood function $L(\Theta, \mathcal{Y}_T)$, and the prior distribution $f(\Theta)$, the joint posterior density $f(\Theta|\mathcal{Y}_T)$ of model parameters is computed using Bayes' theorem:

$$f(\Theta|\mathcal{Y}_T) = \frac{L(\mathcal{Y}_T|\Theta)f(\Theta)}{\int_\Theta L(\mathcal{Y}_T|\Theta)f(\Theta)d\Theta} \tag{1.38}$$

Since $\int_\Theta L(\mathcal{Y}_T|\Theta;)f(\vartheta)d\Theta$ is constant, I only need to be able to evaluate the posterior density up to a proportionate constant using the following relationship:

$$f(\Theta|\mathcal{Y}_T) \propto L(\mathcal{Y}_T|\Theta)f(\Theta) \tag{1.39}$$

Assuming that the state innovations $\varepsilon_{\xi,t}$ are normally distributed with mean zero and variance-covariance matrix Σ, the conditional likelihood function of the model, $L(\mathcal{Y}_T|\Theta)$, is given by:

$$\ln L(\mathcal{Y}_T|\Theta) = -\frac{T}{2}\ln(2\pi) - \frac{1}{2}\sum_{t=1}^{T}\ln\left|HP_{t|t}H'\right| - \frac{1}{2}\sum_{t=1}^{T}(\hat{\mathbf{y}}_t - H\hat{\mathbf{x}}_{t|t-1})'(HP_{t|t}H')^{-1}(\hat{\mathbf{y}}_t - H\hat{\mathbf{x}}_{t|t-1}) \tag{1.40}$$

where $\hat{\mathbf{x}}_{t+1|t} = E(\hat{\mathbf{x}}_{t+1}|\hat{\mathbf{y}}_1, \ldots \hat{\mathbf{y}}_t)$ and $P_{t+1|t} = E[(\hat{\mathbf{x}}_{t+1} - \hat{\mathbf{x}}_{t+1|t})'(\hat{\mathbf{x}}_{t+1} - \hat{\mathbf{x}}_{t+1|t})]$. A technique known as the Kalman filter is used to evaluate the prediction of the the value $\hat{\mathbf{x}}_{t+1|t}$.[7] Then, the mode of the posterior distribution of all estimated parameters is obtained by maximizing the log posterior kernel $\ln\kappa(\Theta|\mathcal{Y}_T) = \ln L(\mathcal{Y}_T|\Theta) + \ln f(\Theta)$ with respect to Θ. The Metropolis-Hastings numerical algorithm is used to simulate the posterior distribution for the model parameters.[8]

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7. The procedure of the Kalman filter is summarized as follows:
- **Step 1:** Initialize the state estimate and its covariance matrix: $\hat{\mathbf{x}}_{0|0} = \hat{\mathbf{x}}_0$ and $P_{0|0} = P_0$.
- **Step 2:** For $t = 1 ... T$, evaluate recursively the following equations:
  1. Predicted (a priori) state estimate $\hat{\mathbf{x}}_{t|t-1} = F\hat{\mathbf{x}}_{t-1|t-1}$,
  2. Predicted (a priori) estimate covariance $P_{t|t-1} = FP_{t-1|t-1}F' + \Sigma$,
  3. Updated (a posteriori) state estimate $\hat{\mathbf{x}}_{t|t} = \hat{\mathbf{x}}_{t|t-1} + P_{t|t-1}H'(HP_{t|t}H')^{-1}(\hat{\mathbf{y}}_t - H\hat{\mathbf{x}}_{t|t-1})$,
  4. Updated (a posteriori) estimate covariance $P_{t|t} = P_{t|t-1} - P_{t|t-1}H'(HP_{t|t-1}H')^{-1}HP_{t|t-1}$.

8. Further details on Bayesian estimation of DSGE models are provided in An and Schorfheide (2007). In my study, the estimation is conducted using the *Dynare* toolbox for *Matlab* developed by Adjemian et al. (2012).

1.3.2 Calibration and prior specifications

Finding the steady state of the model requires solving a large system of nonlinear equations. I use the properties of the model and various data to calibrate some steady state ratios — implicitly related to some parameters that determine these steady state ratios — in the log-linearized version of the model. Then, with these ratios values fixed, I estimate a set of parameters that are crucial to the model's dynamics using Bayesian methods.

I estimate the vector of parameters ϑ, μ, ν, ς, φ, κ_o, κ_d, θ, $\rho_{Y_o^\star}$, $\rho_{Y^\star}$, $\rho_{Z_{os}}$, ρ_{A_o}, ρ_{A_d}, ρ_{A_I}, ρ_ζ, $\sigma_{Y_o^\star}$, $\sigma_{Y^\star}$, $\sigma_{Z_{os}}$, σ_{A_o}, σ_{A_d}, σ_{A_I}, σ_ζ, conditional on prior information concerning the values of these parameters. The choice of the appropriate prior information is tricky, because it requires finding the appropriate domain of prior information for each parameter, as well as the shape of the prior distribution.[9] In general, I assume an inverse-gamma distribution for parameters bounded to be positive, a gamma distribution for parameters bounded to be non-negative, and a beta distribution for parameters bounded between 0 and 1.

Table 1.2 presents the prior distributions on the parameters to be estimated in detail. These prior distributions are assumed to be independent of each other. The AR(1) processes have beta distributions for autocorrelation coefficients, while standard errors of shocks have prior inverse gamma distributions. Following Bouakez and Rebei (2008a), I set the prior mean for the elasticity of substitution between domestic and imported goods, ϑ, equal to 1.5. Consistent with Elekdag et al. (2008), the prior mean for the elasticity of substitution among factors used in oil production, μ, and the prior mean of the elasticity of substitution among factors used in domestic good production, ν, are set equal to 0.6 and 0.7, respectively. I impose an inverse-gamma distribution with a prior mean of $\varphi = 0.44$ for the price-elasticity of oil de-

9. The strategy to choose appropriate values for prior information is to start with given values in the prior domains and adjust these according to whether the optimizer indicates upper-bound constraints or lower-bound constraints for the particular parameter.

mand in the foreign economy. This prior mean is consistent with the estimate of the price-elasticity of oil demand reported in Kilian and Murphy (2013). Following Horvath (2000), I set the prior mean for labor supply elasticity at 1. Finally, the prior mean for parameter θ is set at 5.

The following parameters are calibrated and kept constant over the estimation exercise. I set $\beta = 0.99$, which implies a steady-state annualized real interest rate of 4%. I set $\delta = 0.025$, which implies an annual depreciation rate of capital of 10%. Total labor is set at one-third of the household's available time. The share of the domestic good in the final-good, ω_d, is fixed at 0.68, which implies that imports represent 32% of GDP in the steady state, matching its sample mean. I calibrate a small value for the risk premium parameter, $\phi_{b^\star} = 0.001$. This value, combined with the calibrated value of the net-foreign-debt-to-GDP ratio, implies an average annual risk premium of about 10 basis points. The domestic and foreign gross inflation rates are normalized to 1. Parameter ϑ_x is set to equal ϑ because the two parameters cannot be identified separately given the set of observed variables. I set the steady-state ratio of speculative demand for oil to quarterly foreign oil production, $OS/Y_o^\star$, equal to 0.66. This value is obtained by dividing the U.S. ending stocks of crude oil to the U.S. total crude oil supply. The robustness of the results to alternative calibrations of this parameter is explored later. The remaining parameters, χ, α_{K_o}, α_{N_o} α_{K_d}, α_{N_d}, $\omega_{d,x}$, κ_{os} and $\phi_o^\star$, can be related to the key steady state ratios in the log-linearized version of the model, and are therefore set so as to match their sample mean. Table 1.1 reports the calibrated parameters along with the implied steady-state ratios. [10]

The estimation uses seven quarterly series of Canadian data for the period 1983Q1 to 2010Q4. The starting date corresponds to the year when Canada switched from being a net oil importer to being a net oil exporter. The data includes real GDP, real consumption, real investment, real exchange rate,

10. One does not need calibrate parameters that do not show up in the log-linearized model, since these parameters are a function of steady-state ratios and parameters calibrated previously.

Table 1.1: Calibrated parameters and implied steady states

Description	Parameter	Value
(a) Calibrated parameters		
Discount factor	β	0.99
Depreciation rate of capital	δ	0.025
Share of imports in the final good	ω_d	0.68
Debt-elasticity of interest-rate premium	$\phi_{b^\star}$	0.001
(b) Implied steady state relationships (in percent)		
Labor share in total available time	N	33.3
Ratio of consumption to GDP	$PC/P_Y Y$	80
Ratio of Net Foreign Assets to GDP	$eB^\star/P_Y Y$	- 26.7
Ratio of oil output to GDP	$P_o Y_o/P_Y Y$	4.50
Ratio of Net oil exports to GDP	$P_o O^{\mathrm{x}}/P_Y Y$	0.50
Capital income share in oil output	$R_o^k K_o/P_o Y_o$	30.0
Labor income share in oil output	$W_o N_o/P_o Y_o$	11.0
Ratio of Canada's oil production to foreign oil production	$Y_o/Y_o^\star$	3.10
Ratio of oil stock to foreign oil production	$OS/Y_o^\star$	66.0

Note: Capital and labor income shares in oil output have been calibrated following Elekdag et al. (2008). These ratios are set in order to capture the relative capital-intensive technology used in the process of oil extraction in Canada, in particular, for Athabasca oil sands in Alberta or the offshore oil-rigs of Hibernia. The series for Net Foreign Assets are from the External Wealth of Nations Mark II database. A detailed description of these series can be found in of Lane and Milesi-Ferretti (2007).

real price of oil, and crude oil production in Canada and in the rest of world. The data is from Statistics Canada and the U.S. Energy Information Agency (EIA). Real GDP, real consumption, real investment, and Canada's and foreign oil production are expressed in per capita terms by dividing them by the civilian labor force in Canada. Real consumption and investment are measured by personal consumption expenditures and gross private domestic investment, respectively. The real exchange rate is obtained by multiplying the nominal exchange rate, defined as the price of one U.S. dollar in terms of Canadian dollars, by the ratio of the U.S. Personal Consumption Expenditures Deflator (PCED) to the Canadian PCED. The real price of oil is

Table 1.2: Prior distributions

Description	Param.	Shape	Domain	Mean	S.D.
Elasticity Domestic-Foreign goods	ϑ	I	$\mathbb{R}^{++}$	1.50	0.75
Substitution between factors in oil production	μ	I	$\mathbb{R}^{++}$	0.60	0.50
Substitution between factors in D.G. production	ν	I	$\mathbb{R}^{++}$	0.70	0.50
Elasticity of Foreign oil demand	φ	I	$\mathbb{R}^{++}$	0.44	0.30
Labor elasticity of substitution across sectors	ς	I	$\mathbb{R}^{++}$	1.00	0.75
Elasticity of oil storage demand	θ	I	$\mathbb{R}^{++}$	5.00	5.00
Investment adjustment costs oil sector	κ_o	G	$\mathbb{R}^{+}$	20.0	20.0
Investment adjustment costs D.G.	κ_d	G	$\mathbb{R}^{+}$	2.00	4.00
Degree of habit formation	$\hbar$	B	$[0,1)$	0.50	0.20
Persistence of oil supply	$\rho_{Y_o^\star}$	B	$[0,1)$	0.60	0.20
Persistence of aggregate demand	$\rho_{Y^\star}$	B	$[0,1)$	0.60	0.20
Persistence of precautionary oil demand	$\rho_{Z_{os}}$	B	$[0,1)$	0.60	0.20
Persistence of technology oil sector	ρ_{A_o}	B	$[0,1)$	0.60	0.20
Persistence of technology D.G.	ρ_{A_d}	B	$[0,1)$	0.60	0.20
Persistence of investment technology	ρ_{A_I}	B	$[0,1)$	0.10	0.05
Persistence of price of imports gap	ρ_ζ	B	$[0,1)$	0.60	0.20
Sd of oil supply	$\sigma_{Y_o^\star}$	I	$\mathbb{R}^{++}$	2.00	1.50
Sd of aggregate demand	$\sigma_{Y^\star}$	I	$\mathbb{R}^{++}$	2.00	1.50
Sd of precautionary oil demand	$\sigma_{Z_{os}}$	I	$\mathbb{R}^{++}$	25.0	20.0
Sd of technology oil sector	σ_{A_o}	I	$\mathbb{R}^{++}$	2.00	1.50
Sd of technology D.G.	σ_{A_d}	I	$\mathbb{R}^{++}$	1.00	0.75
Sd of Investment technology	σ_{A_I}	I	$\mathbb{R}^{++}$	4.00	3.00
Sd of price of imports gap	σ_ζ	I	$\mathbb{R}^{++}$	2.00	1.50

Note: N stands for Normal, B Beta, G Gamma, U Uniform, and I Inverted-Gamma1. S.D. stands for Standard Deviation. $\mathbb{R}^{+} = \{\text{x} \mid \text{x is a nonnegative real number}\}$, $\mathbb{R}^{++} = \{\text{x} \mid \text{x is a strictly positive real number}\}$.

the spot price of oil deflated by the U.S. PCED. The spot price of oil is the West Texas Intermediate price in U.S. dollars per barrel. Note that oil production in the foreign economy is treated as an observed variable because it enables identification of parameters governing oil supply shocks. Appendix A provides more detailed about the data used in the estimation of the model. All the observable variables are transformed into percent log deviations from their Hodrick-Prescott trend (with a smoothing parameter of 1600) in order to be consistent with the theoretical log-linearized model. The vector of observable variables is then given by $\hat{\mathbf{y}}_t = 100 * [\hat{Y}_t, \hat{C}_t, \hat{I}_t, \hat{s}_t, \hat{Y}_{o,t}, \hat{Y}^\star_{o,t}, \hat{p}^\star_{o,t}]'$.

The estimation requires that the number of shocks must be greater or equal to the number of observed variables; otherwise, the likelihood would be undefined due to a stochastic singularity (for more detail, see, for example, Ruge-Murcia (2007)).

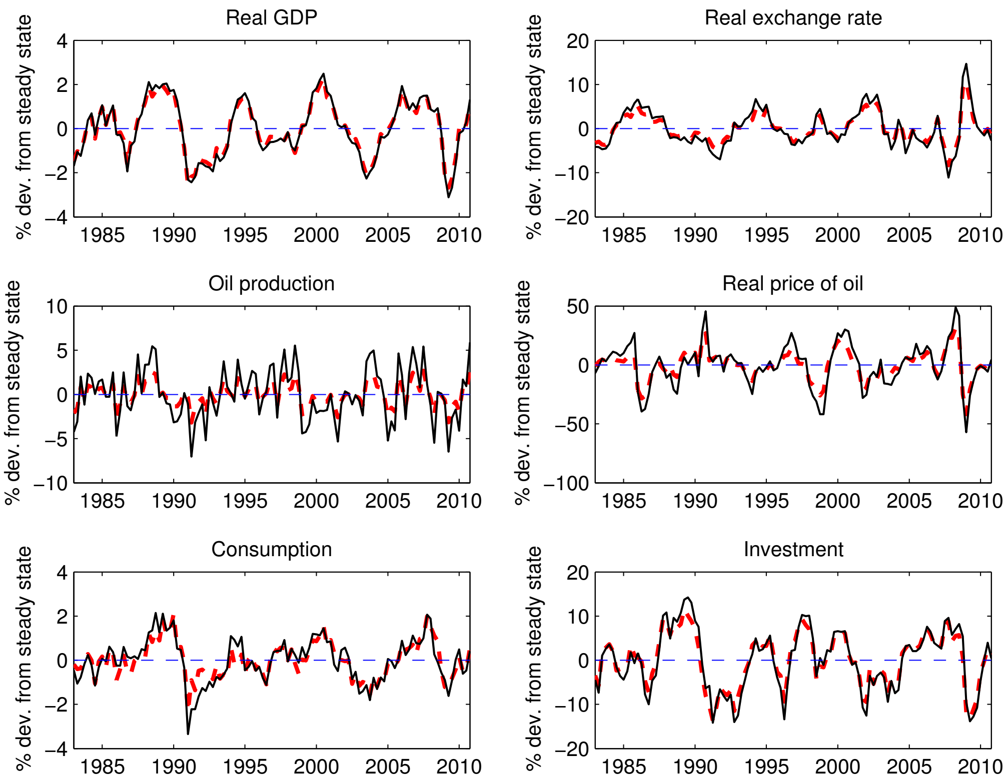
1.3.3 Posterior parameter estimates

Table 1.3 displays the prior means, the posterior means and medians, as well as the fifth and 95th percentiles of the posterior distributions for the estimated parameters.[11] All the posterior means lie in their corresponding 90% probability interval. Using the information in the data results in a substantial shift in the posterior distribution relative to the prior distribution for most of the estimated parameters. Figure 1.1 depicts the in-sample fit of the model, by plotting the data and the model's Kalman-filtered one-sided estimates of the observed variables, computed at the posterior mean of the estimated parameters. The estimated model seems to replicate reasonably well the behaviors of each observable. In what follows, I examine the posterior means of the estimated parameters.

First, I look at the parameters related to exogenous processes. The oil supply shock is weakly persistent. The precautionary oil demand shock is persistent and highly volatile. The autocorrelation coefficients of technology shocks in the oil and domestic good sectors, ρ_{A_d} and ρ_{A_o}, respectively, are estimated at 0.47 and 0.83, respectively, while the estimates of their standard

11. I used *Dynare* version *4.3.3* and *Matlab* version *R2011a*. A posterior sample of 500,000 draws was generated. The posterior distributions were computed by Christopher Sims' optimizer csminwel, a standard numerical optimization routine of *Dynare*. The convergence diagnostics of estimates are satisfactory after 500,000 draws. These diagnostics are based on the convergence of the Markov chain generated by Metropolis-Hastings algorithms to the posterior distribution of interest and convergence of empirical averages to posterior moments.

Figure 1.1: In-sample one step ahead predictions
(Data are black lines and model predictions are red lines)



deviations, σ_{A_d} and σ_{A_o}, are 2.67 and 0.66, respectively. Thus, technology shocks in the domestic good sector are more persistent, but less volatile than technology shocks in oil sector. Investment-specific shocks are slightly persistent and volatile.

Turning to the structural parameters of the model, the posterior mean for labor supply elasticity is equal to 0.73, lower than its prior value of unity and implying higher heterogeneity in wages across the two sectors of the economy. The posterior mean for the elasticity of substitution between domestic and foreign good, ϑ, is estimated to be 0.61. This number is substantially lower than the value of 1.5 that is typically used in calibration studies, but

Table 1.3: Prior moments and posterior estimates

Parameter	Shape	Prior			Posterior		
		Mean	S.D.	90% Prob. interval	Mean	Median	90% HPD.
ϑ	Inv. gamma	1.50	0.75	[0.71, 2.87]	0.61	0.61	[0.55, 0.67]
μ	Inv. gamma	0.60	0.50	[0.21, 1.39]	0.43	0.37	[0.19, 0.65]
ν	Inv. gamma	0.70	0.50	[0.27, 1.54]	0.44	0.43	[0.30, 0.57]
φ	Inv. gamma	0.44	0.30	[0.17, 0.95]	0.31	0.30	[0.21, 0.41]
ς	Inv. gamma	1.00	0.75	[0.37, 2.24]	0.75	0.65	[0.32, 1.18]
θ	Inv. gamma	5.00	5.00	[1.59, 12.2]	4.27	3.96	[2.14, 6.40]
κ_o	Gamma	20.0	20.0	[1.03, 59.9]	26.7	20.8	[1.00, 56.0]
κ_d	Gamma	2.00	4.00	[0.00, 9.68]	0.78	0.74	[0.46, 1.10]
$\hbar$	Beta	0.50	0.20	[0.17, 0.83]	0.36	0.36	[0.29, 0.42]
$\rho_{Y_o^\star}$	Beta	0.60	0.20	[0.25, 0.90]	0.57	0.57	[0.45, 0.69]
$\rho_{Y^\star}$	Beta	0.60	0.20	[0.25, 0.90]	0.70	0.71	[0.62, 0.79]
$\rho_{Z_{os}}$	Beta	0.60	0.20	[0.25, 0.90]	0.78	0.78	[0.68, 0.88]
ρ_{A_o}	Beta	0.60	0.20	[0.25, 0.90]	0.47	0.47	[0.33, 0.61]
ρ_{A_d}	Beta	0.60	0.20	[0.25, 0.90]	0.83	0.83	[0.74, 0.93]
ρ_{A_I}	Beta	0.10	0.05	[0.03, 0.19]	0.08	0.07	[0.02, 0.13]
ρ_ζ	Beta	0.60	0.20	[0.25, 0.90]	0.66	0.66	[0.55, 0.77]
$\sigma_{Y_o^\star}$	Inv. gamma	2.00	1.50	[0.75, 4.48]	1.48	1.47	[1.32, 1.64]
$\sigma_{Y^\star}$	Inv. gamma	2.00	1.50	[0.75, 4.48]	2.64	2.63	[2.30, 2.98]
$\sigma_{Z_{os}}$	Inv. gamma	25.0	20.0	[9.00, 57.3]	29.2	27.6	[17.5, 41.1]
σ_{A_o}	Inv. gamma	2.00	1.50	[0.75, 4.48]	2.67	2.66	[2.37, 2.95]
σ_{A_d}	Inv. gamma	1.00	0.75	[0.37, 2.24]	0.66	0.65	[0.58, 0.73]
σ_{A_I}	Inv. gamma	4.00	3.00	[1.49, 8.97]	3.94	3.79	[2.52, 5.37]
σ_ζ	Inv. gamma	2.00	1.50	[0.75, 4.48]	2.27	2.26	[2.00, 2.54]

Note: For the description of the parameters, see Table 1.2. Posteriors are obtained from 2 chains of 500,000 draws generated using a random walk Metropolis-Hasting algorithm, where I discard the initial 250,000. The 90% probability interval for prior is [5% quantile and 95% quantile]. The HPD stands for the highest posterior density. S.D. stands for Standard Deviation.

is consistent with previous estimates of other small open-economy DSGE models for Canada. In particular, the parameter ϑ is estimated at around 0.6 in Ambler et al. (2004), and 0.86 in Justiniano and Preston (2010). The estimates for the elasticity of substitution between the inputs for crude oil output, μ, is equal to 0.43, indicating a small substitution among factors of production. The degree of habit formation in consumption, $\hbar$, is estimated at 0.36, lower than the value of 0.64 of external habit persistence for Canada reported in Justiniano and Preston (2010), but is close to the estimates of 0.4 for the U.S. in Lubik and Schorfheide (2006). The posterior mean for the price elasticity of oil demand in the foreign economy, φ, is equal to 0.31, lower than its prior value. Finally, the estimates of investment-adjustment cost parameters in oil's sector, κ_o, and domestic good sector, κ_d, are equal to 26.7 and 0.78, respectively. These estimates imply that the elasticity of investment with respect to a 1% temporary increase in the current price of installed capital in the oil sector is equal to $\kappa_o^{-1} = 0.04$, while this elasticity in domestic good sector is equal to $\kappa_d^{-1} = 1.3$. The posterior means for investment-adjustment cost parameters confirm the theory that it is more costly to adjust capital in the oil sector than in domestic good sector. The high value associated with the investment adjustment costs in the oil sector suggests that the production of oil does not respond slowly to changes in demand.

1.4 Oil Shocks and Canadian Economic Fluctuations

This section assess the differences between the dynamic effects of the three types of oil shocks and their relative importance on key Canadian macroeconomic variables. In particular, I use the estimated model to analyze the impulse response functions and the variance decomposition.

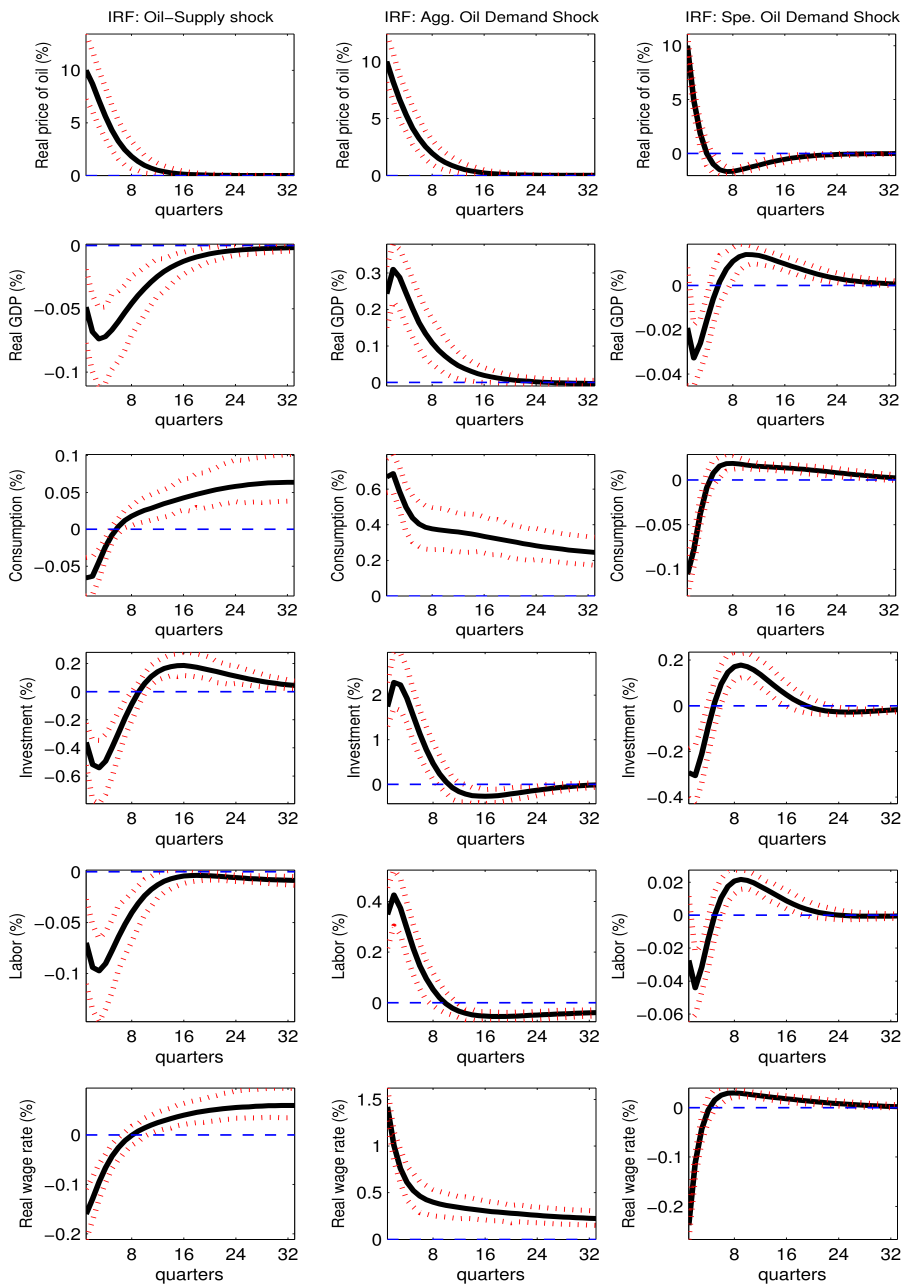
1.4.1 Impulse-response analysis

Impulse response functions are the expected future path of the endogenous variables, conditional on each shock occurring in the initial period. Figures 1.2 to 1.4 in Appendix C summarize the responses of some selected variables to an oil supply shock, an aggregate demand shock and a speculative oil demand shock, so that, in each case, the real world price of oil rises 10% upon impact. The median impulse responses are represented by solid blue lines, and the dotted lines represent the fifth and 95th percentile bands.

The first column of Figures 1.2 to 1.4 shows the responses to an oil supply disruption in the foreign economy. There is an insignificant negative effect on real GDP upon impact. The corresponding response of consumption is significantly negative. There a significant increase in the real interest rate, causing a significant reduction in investment. As expected, there is an immediate increase in the production of crude oil in Canada as well as in oil exports. The Canadian real exchange rate appreciates, and there is a reduction in Canadian exports of the domestic good. The opposite effect occurs for imports. An oil supply disruption in the foreign economy provides an incentive for Canada's oil sector to increase its production, leading to a higher demand for labor and investment in this sector. At the same time, the increase in the oil price causes an increase in the marginal cost of producing the domestic good, thereby reducing the demand for labor in the domestic good sector. A negative innovation in oil supply initially causes a small decrease in the foreign debt.

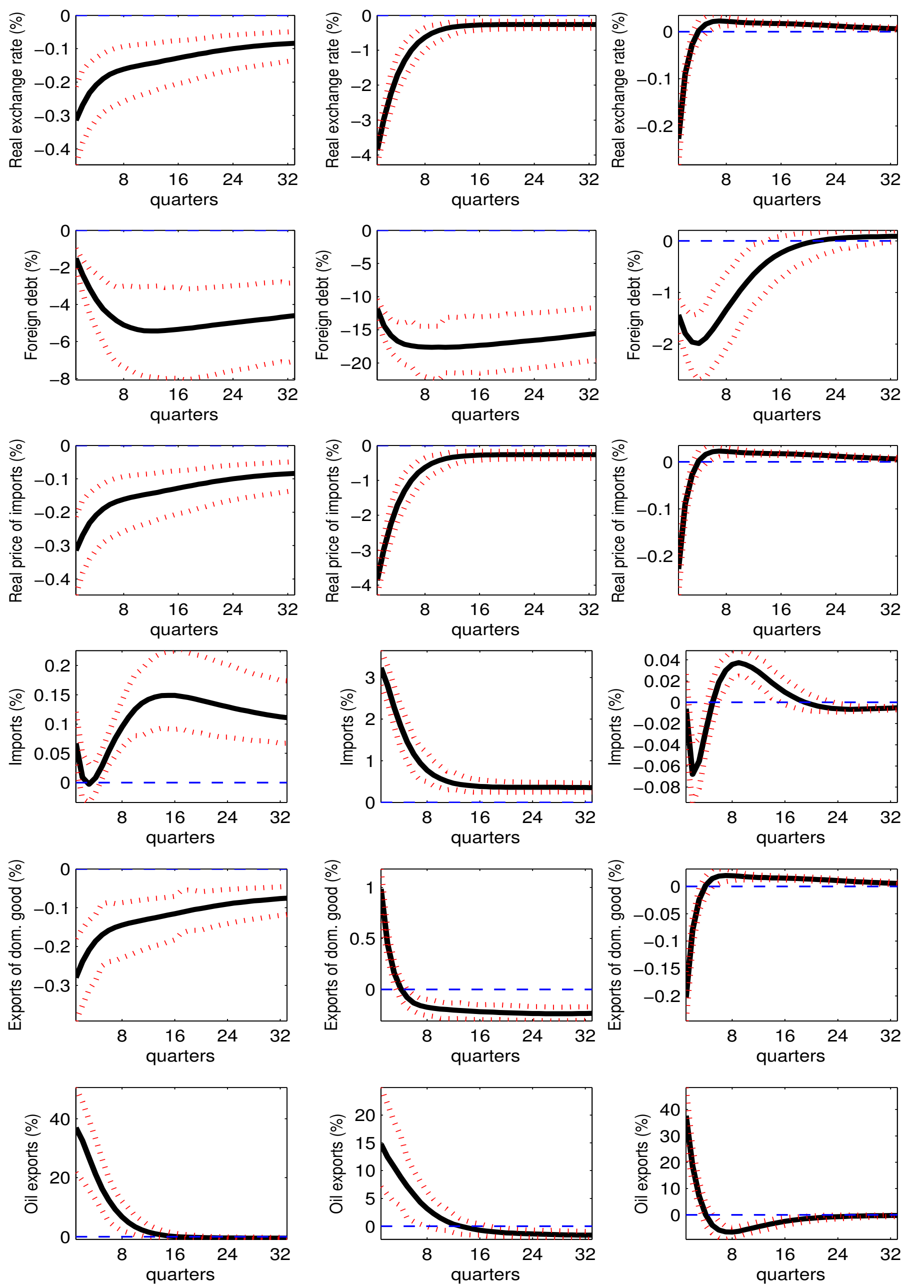
The second column of Figures 1.2 to 1.4 shows the effects of a positive shock to oil demand caused by a positive foreign aggregate demand shock, such that the real price of oil increases by 10%. An unanticipated aggregate demand expansion leads to a significant increase of about 0.4% in real GDP in the first quarter. The response remains positive and statistically significant over all horizons. The corresponding shock significantly increases real consumption by approximately 2% upon impact, and the effect also re-

Figure 1.2: Impulse Response Functions



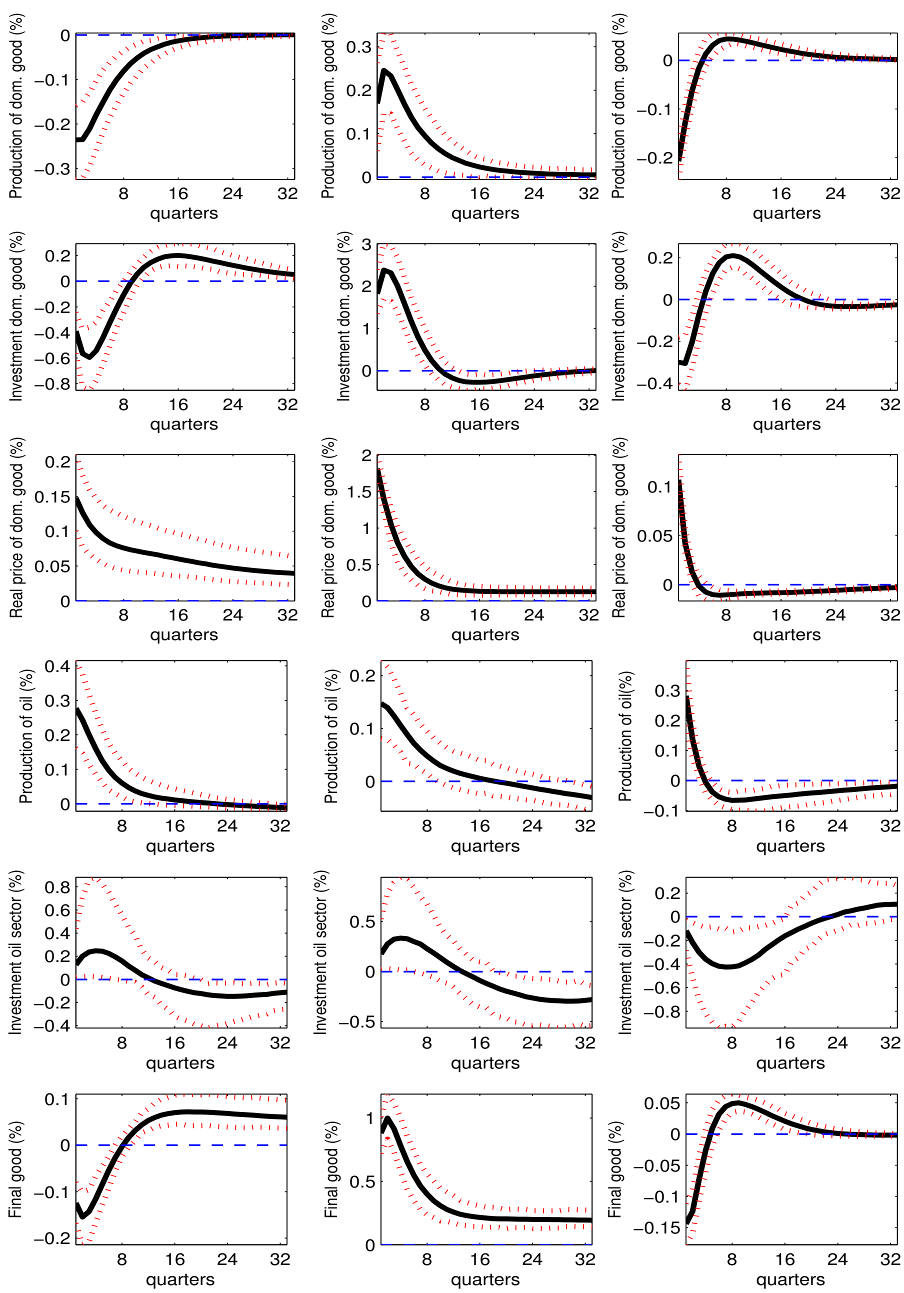
Note: All shocks have been normalized such that an innovation will tend to increase the price of oil.

Figure 1.3: Impulse Response Functions



Note: All shocks have been normalized such that an innovation will tend to increase the price of oil.

Figure 1.4: Impulse Response Functions



Note: All shocks have been normalized such that an innovation will tend to increase the price of oil.

mains positive over the long run. A positive aggregate shock initially causes a significant appreciation in the Canadian dollar. At the same time, there is initially a relatively small decrease in the real interest rate, and and the effect on total investment is positive. There is an increase in exports of the domestic good, as well as in exports of crude oil, resulting in an increase in overall exports. The rest of variables show responses that are consistent with the theory.

The third column of Figures 1.2 to 1.4 shows the effects of a positive speculative oil demand shock that creates a 10% increase in the real price of oil. An unanticipated speculative oil demand increase has an insignificant effect on real GDP upon impact. The effect on GDP turns significantly negative before returning to its steady state. The corresponding shock significantly reduces consumption by about 0.2%. At the same time, the shock causes a temporary increase in the real interest rate and reduces investment in both sectors. There is an initial appreciation in the Canadian dollar, followed by a depreciation. The shock leads to a significant increase in oil exports but causes a reduction in exports of the domestic good and in imports. The combined effects lead to an increase in foreign debt of about 4% upon impact. The effect of an oil supply shock and a precautionary oil demand shock are qualitatively similar in terms of dynamics for most of variables, except that the magnitudes of these effects are different and the negative effect of an oil price increase driven by a positive precautionary oil demand shock are more persistent.

The impulse response functions show important differences in how oil demand and supply shocks affect Canada's economy. An increase oil prices driven by an aggregate demand shock tends to boost Canada's economy. Indeed, a positive innovation in aggregate demand increases investment and Canada's overall exports. Since Canada is a net oil-exporting economy, an increase in oil prices driven by a reduction in foreign oil supply or by an increase in precautionary oil demand provides a larger incentive for Canada's oil sector to produce more, resulting in an increase in oil exports. Consequently, this increases demand for labor and investment in this sector. However, these positive effects on oil sector do not offset the negative impact on non-oil sector activities. A foreign oil supply disruption and a rise in precautionary oil demand leads to increased uncertainty about future oil prices, which in turn leads to a reduction in investment, labor and Canada's real GDP. These latter effects are in line with Bernanke (1983), which claims that industries prefer to delay irreversible investment expenditures when there is increased uncertainty about future oil prices. Overall, impulse response functions in this paper clearly indicate that all oil price shocks are not alike, in line with the findings of Kilian (2009).

1.4.2 Variance Decomposition

Table 1.4 reports the posterior means of the one-step-ahead conditional variance and the unconditional variance of some selected variables using the estimated model. Variance decomposition is computed relative to the sum of the contribution of each shock driving the model. The one-step-ahead conditional variance decomposition provides the decomposition of the effects of shocks upon impact, while the unconditional variance decomposition provides the decomposition of the effects of shocks in the long run.

I first focus my analysis on the relative contribution of the different oil shocks. According to the estimated model, in the short run, precautionary oil demand shocks have accounted for the largest share (about 75%) of fluctuations in the world oil price. Aggregate demand shocks are the second most important driver, accounting for about 22% of the fluctuations. Oil supply shocks explain a relatively small share of variation in the world oil price, with about 5% of the contribution in the short run, as well as in the long run. In the long run, the contribution of precautionary oil demand shocks declines to about 60%, while that of aggregate demand shocks increases to approximately 36%.

These results of variance decomposition of the real price of oil are in line with those in Kilian and Murphy (2012). Indeed, they show that oil supply shocks have a minor impact on the real price of oil because the oil supply elasticity is near zero. Approximatively 5% of conditional variance and 7% of unconditional variance in real GDP is explained by aggregate demand shocks. Oil supply shocks and precautionary oil demand shocks account for negligible shares of the variance in real GDP, both in the short run and in the long run. Aggregate demand shocks explain the largest share of the variations in most of the Canadian macroeconomic aggregates in the short run. Among oil shocks, aggregate demand shocks are by far the most important source of fluctuations in most Canadian macroeconomic aggregates, in the short run as well as in the long run.

Now, I examine the contributions of other shocks using variance decomposition. Shocks that originate from the domestic economy in explain almost none the variance of the real (world) price of oil, which is what would be expected for a small open economy. Investment shocks account for about 14% of the fluctuations in real GDP, 67% of those in labor and more than 78% of those in investment in the short run. These shocks has been identified by Justiniano et al. (2010) as the main drivers of movements in labor, investment, and output. Meanwhile, investment shocks are responsible for only a small fraction of the fluctuation in consumption, which is instead driven largely by the combination of aggregate demand shocks and shocks to the price of imports. Shocks to the price of imports are the second driving force behind fluctuations in the real interest rate and real wage. Technology shocks specific to the domestic good sector are by far the biggest driving force behind changes to real GDP. Technology shocks in the oil sector are responsible for only a small fraction of the fluctuations of my selected variables.

Table 1.4: Variance decomposition (in percent)

	Oil supply shocks	Aggregate demand shocks	Prec. oil demand shocks	Techn. shocks oil prod.	Techn. shocks D.G. prod.	Investment shocks	Price of imports shocks
			Conditional 1-step ahead variance				
Real price of oil	03.1	22.3	74.5	00.0	00.0	00.0	00.0
Real GDP	00.0	04.9	00.1	03.6	77.3	14.0	00.1
Consomption	00.1	39.8	03.4	00.0	18.1	04.1	34.5
Investment	00.0	07.9	00.8	00.0	04.5	78.3	08.5
Real interest rate	00.0	29.2	09.0	00.0	09.5	10.4	41.8
Labor	00.1	23.2	00.5	00.0	08.7	66.9	00.5
Real wage rate	00.1	47.0	04.4	00.0	12.2	00.7	35.6
Real exchange rate	00.1	84.3	01.0	00.0	06.6	00.9	07.2
Foreign debt to GDP	00.2	91.4	04.5	00.6	01.1	00.0	02.1
			Unconditional variance				
Real price of oil	05.2	35.5	59.3	00.0	00.0	00.0	00.0
Real GDP	00.1	07.0	00.2	00.9	79.4	09.0	03.4
Consomption	00.4	68.7	00.7	00.2	13.7	02.9	13.4
Investment	00.2	17.5	01.2	00.0	18.0	46.6	16.6
Real interest rate	00.1	28.2	08.5	00.0	10.9	11.9	40.4
Labor	00.5	43.1	01.5	00.0	06.1	35.6	13.2
Real wage rate	00.3	62.6	01.7	00.1	13.4	01.8	20.0
Real exchange rate	00.3	82.8	00.4	00.1	11.1	01.6	03.7
Foreign debt to GDP	01.0	84.7	00.3	00.4	10.7	01.2	01.6

1.5 Robustness Analysis

In this section, I check the robustness of the previous results with respect to alternative specifications of the production function of the domestic good, and with respect to changes in some parameters that have been calibrated.

1.5.1 Alternative calibration

It is important to verify that the main findings from my estimation hold, even if the baseline estimates of exogenous variables change. I examine sensitivity of the baseline estimates with respect to the steady-state ratio of oil stock to foreign oil production, $OS/Y_o^\star$, and capital's share in oil output, $R_o^k K_o/P_o Y_o$. Table 1.5 presents the posterior means obtained with the same priors but with different parameters $OS/Y_o^\star \in \{0.5, 1, 1.5, 2\}$, and $R_o^k K_o/P_o Y_o \in \{0.10, 0.5\}$. A comparison with the first column, which replicates the baseline calibration, shows that the estimated values of the parameters are very similar, with the exception of the variance of the precautionary oil demand shock, which decreases with respect to $OS/Y_o^\star$. The impulse responses of the real price of oil, real GDP, investment, consumption and labor (not presented here), are robust to changes in $OS/Y_o^\star$, whereas variance decomposition results vary slightly. In particular, the relative contribution of precautionary oil demand shocks to changes in the selected variables decreases with respect to the ratio $OS/Y_o^\star$.

1.5.2 Alternative Specification

The production process can vary depending on the good. To test the robustness of my findings to different assumptions about the production process for the domestic good, I consider two alternative specifications of the production function for the domestic good, where I differ the role that tech-

Table 1.5: Posterior means for alternative calibrations

Param.	Baseline calibr.	$R_o^k K_o/P_oY_o = 0.10$				$R_o^k K_o/P_oY_o = 0.50$			
		$\frac{OS}{Y_o^\star} = 0.5$	$\frac{OS}{Y_o^\star} = 1$	$\frac{OS}{Y_o^\star} = 1.5$	$\frac{OS}{Y_o^\star} = 2$	$\frac{OS}{Y_o^\star} = 0.5$	$\frac{OS}{Y_o^\star} = 1$	$\frac{OS}{Y_o^\star} = 1.5$	$\frac{OS}{Y_o^\star} = 2$
ϑ	0.61	0.61	0.61	0.61	0.61	0.61	0.61	0.61	0.62
μ	0.43	0.42	0.41	0.41	0.41	0.46	0.42	0.41	0.41
ν	0.44	0.44	0.44	0.44	0.44	0.45	0.45	0.45	0.45
φ	0.31	0.31	0.32	0.32	0.32	0.31	0.32	0.32	0.33
ς	0.75	0.74	0.76	0.73	0.85	0.73	0.73	0.76	0.75
θ	4.27	4.92	3.72	3.37	3.19	4.86	3.68	3.36	3.12
κ_o	26.7	22.6	22.5	21.2	23.8	29.4	28.9	30.1	30.9
κ_d	0.78	0.79	0.80	0.81	0.81	0.75	0.76	0.77	0.77
$\hbar$	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36
$\rho_{Y_o^\star}$	0.57	0.57	0.57	0.58	0.58	0.57	0.57	0.58	0.58
$\rho_{Y^\star}$	0.70	0.71	0.71	0.71	0.71	0.70	0.71	0.71	0.71
$\rho_{Z_{os}}$	0.78	0.79	0.76	0.73	0.71	0.79	0.75	0.73	0.71
ρ_{A_o}	0.47	0.46	0.46	0.46	0.46	0.48	0.48	0.48	0.48
ρ_{A_d}	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83
ρ_{A_I}	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08
ρ_ζ	0.66	0.66	0.66	0.66	0.66	0.66	0.66	0.66	0.66
$\sigma_{Y_o^\star}$	1.48	1.48	1.48	1.48	1.48	1.48	1.48	1.48	1.48
$\sigma_{Y^\star}$	2.64	2.62	2.63	2.63	2.63	2.63	2.63	2.63	2.63
$\sigma_{Z_{os}}$	29.2	34.7	24.1	20.8	19.2	34.7	24.0	20.9	19.0
σ_{A_o}	2.67	2.66	2.66	2.66	2.66	2.67	2.67	2.67	2.67
σ_{A_d}	0.66	0.65	0.65	0.66	0.66	0.66	0.66	0.66	0.66
σ_{A_I}	3.94	3.88	3.93	3.98	3.97	3.91	4.00	4.00	4.03
σ_ζ	2.27	2.27	2.27	2.27	2.27	2.27	2.27	2.26	2.27
$\log \kappa(\Theta \vert \mathcal{Y}_T)$	-1668	-1668	-1666	-1666	-1666	-1669	-1668	-1668	-1668

nology plays. In particular, I consider a model (b), as in Kim and Loungani (1992) and Backus and Crucini (2000), where the technology has capital and oil in a constant elasticity of substitution function within a Cobb-Douglas production function:

$$Y_{d,t} = A_{d,t} N_{d,t}^{\alpha} \left((1-\omega_o)^{\frac{1}{\nu}} K_{d,t}^{1-\frac{1}{\nu}} + \omega_o^{\frac{1}{\nu}} O_t^{1-\frac{1}{\nu}} \right)^{\frac{\nu(1-\alpha)}{\nu-1}} . \tag{1.41}$$

I also consider a model (c), as in Atkeson and Kehoe (1999), where the technology has capital and oil as a CES function within a CES production function:

$$Y_{d,t} = A_{d,t} \left(\alpha^{\frac{1}{\eta}} N_{d,t}^{1-\frac{1}{\nu}} + (1-\alpha)^{\frac{1}{\eta}} V_t^{1-\frac{1}{\eta}} \right)^{\frac{\eta}{\eta-1}} \tag{1.42}$$

with

$$V_t = \left((1-\omega_o)^{\frac{1}{\nu}} K_{d,t}^{1-\frac{1}{\nu}} + \omega_o^{\frac{1}{\nu}} O_t^{1-\frac{1}{\nu}} \right)^{\frac{\nu}{\nu-1}} \tag{1.43}$$

where parameter α is labor's share in the production of the domestic good. The form of the production technology implies that oil and capital are used to produce capital services, which are combined with labor to produce goods. Parameter ω_o is the bias towards oil in producing capital services, while ν represents the elasticity of substitution between capital and oil. In model (c), η is the elasticity of substitution between labor and capital services. Note that model (b) is a particular case of model (c) where $\eta = 1$.

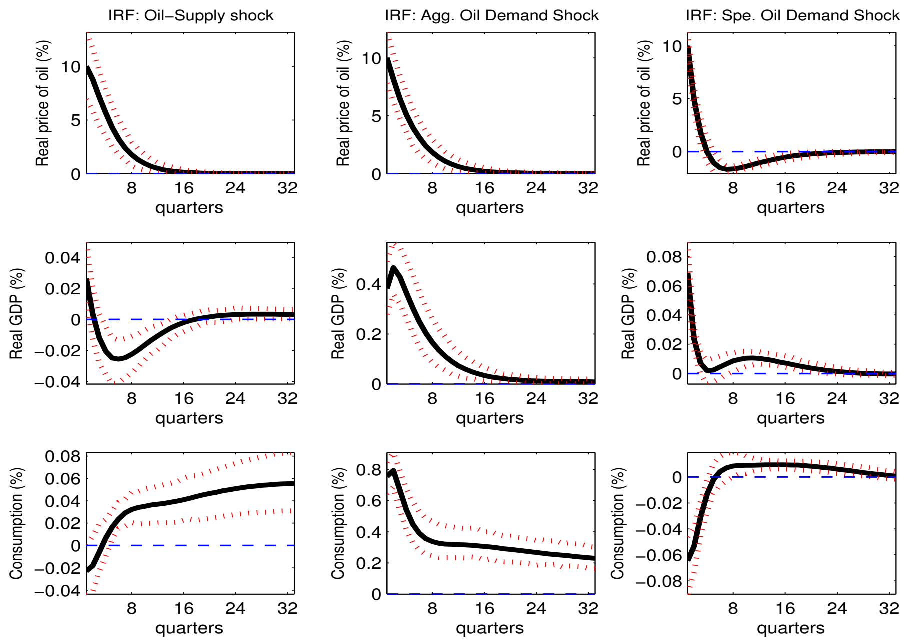
Table 1.6 presents the estimates of posterior means of the different models using the baseline calibration. The estimated values of the same parameters in model (c) are very similar to those of baseline model. In addition, Figure 1.5 shows very similar patterns of impulse response from model (c) to those from the baseline model for the same variables. The posterior density is higher in the case of the baseline model and model (c) relative, to model (b).

Table 1.6: Posterior means for alternative specification

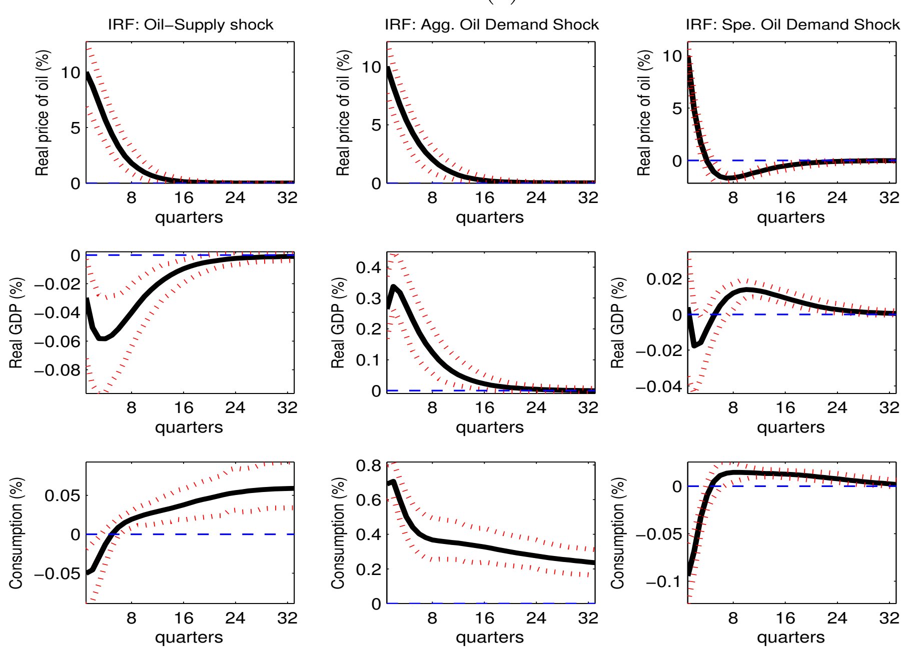
Description	Parameter	Baseline model	Model (b)	Model (c)
Elasticity Domestic-Foreign goods	ϑ	0.61	0.60	0.62
Substitution between factors in oil production	μ	0.43	0.39	0.42
Substitution between K-O in D.G. production	ν	0.44	0.42	0.54
Substitution between N-KO in D.G. production	η	-	-	0.40
Elasticity of Foreign oil demand	φ	0.31	0.31	0.31
Labor elasticity of substitution across sectors	ς	0.75	0.77	0.74
Elasticity of oil storage demand	θ	4.27	4.32	4.27
Investment adjustment costs oil sector	κ_o	26.7	27.0	25.4
Investment adjustment costs D.G.	κ_d	0.78	1.03	0.79
Degree of habit formation	$\hbar$	0.36	0.38	0.36
Persistence of oil supply	$\rho_{Y_o^\star}$	0.57	0.57	0.57
Persistence of aggregate demand	$\rho_{Y^\star}$	0.70	0.70	0.71
Persistence of precautionary oil demand	$\rho_{Z_{os}}$	0.78	0.78	0.78
Persistence of technology oil sector	ρ_{A_o}	0.47	0.47	0.47
Persistence of technology D.G.	ρ_{A_d}	0.83	0.80	0.83
Persistence of investment technology	ρ_{A_I}	0.08	0.07	0.08
Persistence of price of imports gap	ρ_ζ	0.66	0.65	0.66
Sd of oil supply	$\sigma_{Y_o^\star}$	1.48	1.48	1.47
Sd of aggregate demand	$\sigma_{Y^\star}$	2.64	2.70	2.64
Sd of precautionary oil demand	$\sigma_{Z_{os}}$	29.2	29.5	29.2
Sd of technology oil sector	σ_{A_o}	2.67	2.67	2.67
Sd of technology D.G.	σ_{A_d}	0.66	0.69	0.66
Sd of Investment technology	σ_{A_I}	3.94	4.92	3.97
Sd of price of imports gap	σ_ζ	2.27	2.09	2.26
(log) Posterior kernel	$\log \kappa(\Theta\|\mathcal{Y}_T)$	-1668	-1670	-1668

Figure 1.5: Impulse Response Functions for alternative specification

Model (b)



Model (c)



Note: All shocks have been normalized such that an innovation will tend to increase the price of oil.

1.6 Conclusion

This paper uses a structural DSGE model to investigate the dynamic effects and the relative importance of oil supply shocks, aggregate demand shocks, and precautionary oil demand shocks on Canada's economy. The model is estimated using Canadian quarterly data for the period 1983Q1 to 2010Q4, and using Bayesian methods. The in-sample fit of the estimated model is satisfactory. The analysis of impulse response functions and variance decomposition shows important differences in how oil demand and supply shocks affect Canadian macroeconomic variables. According to the results from the estimated model, an oil price increase is more beneficial to the Canada's economy when that increase is caused by increased innovation in global economic activity. On the other hand, an increase in the real price of oil driven by negative innovations in foreign oil supply or by positive precautionary oil demand shocks has little negative effect on Canada's real GDP. Finally, the variance decomposition over the estimation period indicates that, among the different oil shocks, foreign aggregate demand shocks have been relatively more important in explaining the variance of most of Canadian macroeconomic variables. Oil supply shocks and precautionary oil demand shocks have a negligible effect on the variance of real GDP and most other macroeconomic variables.

This paper makes a unique contribution to the literature by disentangling the effects of the three main type of oil price shocks in an estimated structural DSGE model for an oil-exporting economy. Furthermore, this paper differs from others by explicitly modelling the oil production sector, which allows the model to take into account the importance of this sector to Canada's economy. The introduction of cash market and storage market for crude oil is also a notable distinction. Finally, this paper provides a comprehensive discussion of Bayesian estimation of DSGE models.

There has been a perception that Canada, as a net oil-exporting country, enjoys a net economic benefit when crude oil prices increase and suffers when prices decline. According to the results of this paper, this perception should be reconsidered.

Future research could focus on relaxing some of the model's restrictions. For example, the model could be extended to allow for nominal rigidities in prices, or to allow for central bank or government intervention.

Chapter 2

Oil Shocks and Labor Adjustments in Canadian Manufacturing Industries

2.1 Introduction

Oil price fluctuations have important effects on many industries. Canadian manufacturing industries are no exception, as they depend on oil to fuel the production process. In 2008, manufacturing accounted for 51% of all industrial energy demand.[1]

Manufacturing is more vulnerable to oil price shocks because it is more energy intensive than other sectors. Moreover, since manufacturing is affected by international trade, it is also exposed to the effects of exchange rate fluctuations. Oil price fluctuations affect manufacturing industries through revenue and cost channels. Greater export orientation increases the revenue arising from a dollar depreciation and vice versa. An increase in the oil price

1. Energy from electricity, hydro, nuclear and steam are excluded. When including these types of energy, manufacturing accounted for 62 per cent of all industrial energy demand in 2008.

leads to an appreciation of the Canadian dollar, all else equal, which, in turn, causes a decrease in the export volume and revenue of manufacturing companies. In contrast, for industries that are net importers, an appreciation of the Canadian dollar could improve the industry's competitiveness and expand its labor demand. Therefore, oil price increases that lead to the Canadian dollar appreciating positively affect manufacturing industries by reducing their cost of imported non-oil inputs. An increase in the oil price also leads to an increase in production costs for manufacturing companies, since energy is an essential input into production.

This paper is motivated by two main reasons. First, most of studies examining the macroeconomic consequences of oil price shocks in Canada focus on aggregate data. Unfortunately, no study has disentangled the effects of oil demand and supply shocks on labor market activity using disaggregated data at the industry level. Second, recent findings by Somé (2012), using a dynamic stochastic general equilibrium model, show that oil demand and supply shocks have different effects on most Canadian macroeconomic aggregates.

This paper analyzes how oil demand and supply shocks affect the labor market in Canadian manufacturing industries. In addition, I examine how the degree of companies' net trade exposure and energy intensity affect the magnitude of the impulse responses of labor market variables to the different types of oil price shocks.

I model the labor market in a similar fashion to Campa and Goldberg (2001). However, I adopt a panel structural vector autoregressive (VAR) approach instead of equation-by-equation regressions. I conduct estimations using disaggregated annual data for Canada at the three-digit industry level under the North American Industry Classification System (NAICS) from 1975 to 2008.[2] Industries are classified in high and low net trade exposure groups using a methodology developed by Dion (2000). Industries are clas-

2. The starting date, 1975, is dictated by the availability of data.

sified in energy-intense and low-energy groups. Since the measure of labor demand is central in this empirical work, I use two measures of labor demand to ensure robustness: the labor input index and the total number of hours worked.

I have two key findings. First, the responses of labor demand and real wages (the relative price of labor) to the different types of oil shocks are all significant on impact. Second, the oil price fluctuations have significantly different effects on labor in Canada's manufacturing industries depending on what cause the oil price fluctuations. A positive aggregate demand shock has a positive effect on labor market variables over all horizons. A negative oil supply shock has a relatively small negative effect on labor only upon impact. The effect turns positive one year after the shock, and remains negative over all future horizons. A positive precautionary oil demand shock has a negative impact over all horizons. In addition, I find that Industries with higher net trade exposure/oil-intensity are more vulnerable to oil supply shock and aggregate demand shock.. These results are still robust when I use total number of jobs instead of the labor input index as an alternative measure of labor activity.

The rest of the paper is organized as follows. In section 2.2, I present a brief review of the literature. Section 2.3 presents my econometric model. Section 2.4 describes the data. In section 2.5, I present the estimation methodology, including preliminary econometric tests and the identification strategy of the model. Section 2.6 presents the estimation results and their interpretation; the section also analyzes the result sfor the full panel as well as for the sub-panels of high and low trade-exposed industries and the sub-panels of energy-intense and low-energy industries. Finally, section 2.7 concludes.

2.2 Relevant literature

The effect of oil shocks on labor market adjustments is a significant issue that has been widely studied in the literature. Loungani (1986) finds that the dispersion of employment growth across industries is substantially due to the varying impact of oil shocks across industries. Hamilton (1988) extends the work of Loungani (1986) and shows that volatility in the prices of primary commodities could lead to a reduction in aggregate employment. Hamilton (1988) argues that workers of adversely affected sectors remain unemployed while waiting for conditions to improve in their own sector, rather than move to positively affected sectors. Davis and Haltiwanger (2001) find that oil shocks account for about one quarter of the variance of U.S. manufacturing employment growth from 1972 to 1988. They also show that oil shocks generate important job reallocation within the manufacturing sector. Papapetrou (2001) finds that oil shocks have adverse effects on industrial production and employment in Greece's economy. Bernanke (1983) suggests that oil price volatility also affects employment in manufacturing industries through uncertainty in investments as suggested. This implies that when a firm faces increased uncertainty about the price of oil as a result of high oil price volatility, it is optimal for the firm to delay irreversible projects if the returns are closely related to oil prices; firms should wait for new information that will help them estimate the project's return. Finally, recent studies, such as Kilian (2009) and Somé (2012), indicate that different oil price shocks can have different dynamic effects on real macroeconomic variables.

Empirical studies of Canada's economy have focused attention on the link between oil price fluctuations and their effects on real GDP (e.g., Mork et al. (1994a)) and the Canada-U.S. exchange rate (e.g., Leung and Yuen (2005), Ferraro et al. (2012)). However, these studies do not consider the possibility that oil shocks may affect the manufacturing sector different than other industries. Manufacturing could be more sensitive to changes in oil prices, due to the fact that it is more energy-intensive.

The main contribution of this paper is an estimation of the impact of oil demand and oil supply shocks on labor demand and the price of labor in Canadian manufacturing industries using a panel VAR model.

2.3 Model of the labor market

To study the dynamic adjustment of labor to oil price shocks, I use a theoretical framework similar to the one in Campa and Goldberg (2001). The model assumes that manufacturing industries have three inputs: labor (L_t), capital, and energy (oil, in this case). The respective prices of the inputs are denoted by W_t, Z_t and $e_t P_{o,t}$, where e_t is the exchange rate and $P_{o,t}$ is the international price of oil. Within an industry, the demand for labor is subject to adjustment costs, and the demand for the industry's output is assumed to be a function of aggregate demand ($Y_{w,t}$) and the exchange rate. Assuming that labor supply is an increasing function of wages and a decreasing function of aggregate demand, Campa and Goldberg (2001) show that, for a given industry i, the solution of the labor market equilibrium conditions is given by the two following equations in reduced-form:

$$L_{i,t} = \alpha_{0,i} + \alpha_{i,1} L_{i,t-1} + \alpha_{i,2} Z_{i,t} + \alpha_{i,3} Y_{w,t} + \alpha_{i,4} e_t + \alpha_{i,5} P_{o,t} + \epsilon_{i,t} \quad (2.1)$$

$$W_{i,t} = \beta_{i,0} + \beta_{i,1} L_{i,t-1} + \beta_{i,2} Z_{i,t} + \beta_{i,3} Y_{w,t} + \beta_{i,4} e_t + \beta_{i,5} P_{o,t} + \epsilon_{i,t} \quad (2.2)$$

where all variables are logarithms. Equations 2.1 and 2.2 are commonly used in the literature, such as by by Revenga (1992) and Leung and Yuen (2005). An alternative specification used by Dekle (1998) is based only on the structural form of the labor demand equation, including the industry-specific price of labor. Delke takes this approach because specification errors in the labor supply lead to specification errors in equilibrium equations 2.1 and 2.2.

In this paper, I follow a panel VAR approach, which is a one-stage approach for identifying the impact of the different types of oil shocks on labor activity. This one-stage approach is desirable, because any two-stage approach would involve a generated regressor problem.

2.4 Data

I use annual data from 20 Canadian manufacturing industries at the 3-digit industry level under the NAICS classification, and aggregate-level data from 1975 to 2008. The data comes from Statistics Canada and the Federal Reserve Bank of St. Louis.

There are six baseline variables: the labor input index ($L_{i,t}$), [3] the relative price of capital ($Z_{i,t}$), the relative price of labor ($W_{i,t}$), the real price of oil ($P_{o,t}$), the aggregate demands, and global crude oil production. I use the Federal Reserve Bank of St. Louis's Industrial Production Index as a proxy for aggregate demand for manufacturing goods. The data on global crude oil production comes from the U.S. Energy Information Administration. The real price of oil is given by the U.S.-dollar spot price for a barrel of West Texas Intermediate oil, deflated by the U.S. Consumer Price Index. The labor input in manufacturing industries is a chained-Fisher aggregation of hours worked for all workers, classified by education, work experience, and class of workers. The relative price of labor is the ratio of labor compensation to the Fisher volume index of labor input, deflated by the Consumer Price Index. The relative price of capital is the ratio of the capital cost index to the Fisher volume index of capital input, deflated by the Consumer Price

3. An alternative measure of labor demand is the number of jobs ($E_{i;t}$). I use this measure later in the paper in robustness checks.

Index. Because the real CAD-USD exchange rate and the international real price of oil are highly correlated, the real exchange rate is not included in the VAR model to avoid issues related to oil shock identification. Additional details about the data are presented in Appendix C.

I split the full panel into high and low trade-exposed industries based on a measure of net international trade exposure for each manufacturing industry, using a methodology developed by Dion (2000). This measure is defined as the ratio of exports to production, less the ratio of imported inputs used in production, plus competing imports as a share of the domestic market.[4] For this study, the classification is based on the industry average between 1992 and 2007. Industries with a net international trade exposure below the manufacturing sector average are placed in the low trade exposure group. The full panel of manufacturing industries is also split into a sub-panel of energy intensive manufacturing industries, and a sub-panel of low-energy manufacturing industries. Energy intensity is defined as energy consumption relative to GDP for a given industry. Table 2.1 presents the classifications according to the degree of trade exposure and according to energy intensity.

2.5 Estimation methodology

This section discusses the identification strategy for my panel VAR model, as well as preliminary econometric tests, including cross-sectional dependence (CSD) tests, unit root tests, and cointegration tests.

4. Apparent Domestic Market = Manufacturing Revenues + Total Imports - Total Exports.
Net trade exposure = Exports/Revenues - Imports/Revenues + Imports/Apparent Domestic Market.

Table 2.1: List of manufacturing industries by degree of trade exposure and by energy intensity

NAICS	Industries	Trade exposure	Energy intensity
311	Food	High	High
312	Beverage and tobacco products	Low	Low
313-314	Textile and textile product mills	Low	High
315	Clothing	Low	Low
316	Leather and allied products	Low	Low
321	Wood products	High	High
322	Paper	High	High
323	Printing and related support activities	Low	Low
324	Petroleum and coal products	High	High
325	Chemicals	High	High
326	Plastics and rubber products	High	High
327	Non-metallic mineral products	Low	High
331	Primary metals	High	High
332	Fabricated metal products	Low	High
333	Machinery	High	Low
334	Computers and electronic products	Low	Low
335	Electrical equipment, appliances and components	Low	Low
336	Transportation equipment	High	Low
337	Furniture and related products	High	Low
339	Miscellaneous	Low	Low

Note: The classification according the degree of net trade exposure is based on the industry net trade exposure average between 1992 and 2008. The classification according the energy intensity is based on the industry energy intensiveness average between 1975 and 2008.

2.5.1 Preliminary tests

I conduct unit root tests for variables common to all industries ($Q_{o,t}$, $Y_{w,t}$, $P_{o,t}$) using the augmented Dickey-Fuller and the Phillips-Perron unit root tests. The null hypothesis for both tests is the presence of a unit root, and the alternative hypothesis is that the variable in question is stationary. The Phillips-Perron test uses Newey-West standard errors to account for potential serial correlation, whereas the augmented Dickey-Fuller test uses additional lags of the first-difference variable. Table 2.2 shows that both types of unit root test clearly reject the null hypothesis of non-stationarity for any industry-specific variable. But first-difference variables are stationary at the 5% significance level.

Table 2.2: Unit root tests for aggregated variables

	p-value: Augmented Dickey-Fuller		p-value: Levin-Lin	
Variable	No trend	With trend	No trend	With trend
World oil production	0.932	0.083	0.772	0.569
World oil production (first difference)	0.036	0.085	0.000	0.002
Industrial Production Index (IPI)	0.792	0.299	0.636	0.525
IPI (first difference)	0.008	0.044	0.003	0.018
Oil price	0.763	0.983	0.784	0.984
Oil price (first difference)	0.003	0.005	0.000	0.000

Note: The null hypothesis is the presence of a unit root. The optimal lag length for the test is chosen according the Akaike criterion.

Prior to the unit root tests for industry-specific variables, I test for the presence of Cross-Section Dependence (CSD) between industries for each industry-specific variable, using the parametric testing procedure proposed by Pesaran (2004). If there is CSD, it must be taken into account in the unit root test procedure. The CSD test employs the correlation coefficients between time periods for each panel unit. Under the null hypothesis, the cross-sectional dependence statistic has a standard normal distribution. The test is robust to nonstationarity, parameter heterogeneity and structural breaks, and performs well even in small samples.

The null hypothesis is rejected for all industry-specific variables. Therefore, the industry-specific dynamics must be taken into account by the unit root tests. As such, I conduct a unit root test proposed by Pesaran (2007) for each industry-specific variable with CSD. To eliminate CSD, the standard

Table 2.3: Cross-Section Dependence tests

Variable	CSD test	p-value
Labor index	6.86	0.000
Employment	7.84	0.000
Relative price of labor	23.76	0.000
Relative price of capital	21.22	0.000

Note: The null hypothesis is a standard normal distribution for the CSD test statistic.

Dickey-Fuller regressions are augmented with the cross-sectional averages of lagged levels and first-differences of the individual series. Under the null hypothesis of non-stationarity, the test statistic has a standard normal distribution.

The results from the unit root tests in Table 2.4 show that all industry-specific variables contain unit roots but are stationary in first difference at the 5% significance level. The results are robust to the inclusion of a trend.

Table 2.4: Panel unit root tests for industry-specific variables

	p-value, Pesaran (2007) unit root tests	
Variable	No trend	With trend
Labor	1.000	1.000
Labor (first difference)	0.000	0.000
Employment	1.000	1.000
Employment (first difference)	0.000	0.000
Relative price of labor	0.069	0.575
Relative price of labor (first difference)	0.000	0.000
Relative price of capital	0.727	0.730
Relative price of capital (first difference)	0.000	0.000

Note: The null hypothesis is the presence of a unit root. The optimal lag length for the test is chosen according the Akaike criterion.

All variables are transformed to growth rates by taking the first difference of the natural logarithms. I investigate the labor market response to the different type of oil price shocks using the following panel VAR(1) model:

$$\begin{bmatrix} N_{i,t} \\ X_{w,t} \end{bmatrix} = \mu_i + \Phi \begin{bmatrix} N_{i,t-1} \\ X_{w,t-1} \end{bmatrix} + B \begin{bmatrix} e_{i,t}^{N} \\ e_t^{X_w} \end{bmatrix} \tag{2.3}$$

where $N_{i,t} = \begin{bmatrix} L_{i,t}, W_{i,t}, Z_{i,t} \end{bmatrix}'$ and $X_{w,t} = \begin{bmatrix} Q_{o,t}, Y_{w,t}, P_{o,t} \end{bmatrix}'$.

The vector of endogenous variables is divided into two groups. The first block of variables, $N_{i,t}$, includes only industry-specific variables: the labor input ($L_{i,t}$), the relative price of labor ($W_{i,t}$), and the relative price of capital ($Z_{i,t}$). The second group, $X_{w,t}$, captures the supply and demand conditions in the crude oil market and includes world oil production ($Q_{o,t}$); a measure of world economic activity $Y_{w,t}$ which is approximate by the G-17 Industrial Production Index; and the real price of crude oil ($P_{o,t}$). The vectors $e_{i,t}^{N}$ and $e_t^{X_w}$ are structural innovations to $N_{i,t}$ and $X_{w,t}$. Letting $\mathbb{Y}_{i,t} = \begin{bmatrix} N_{i,t}, X_{w,t} \end{bmatrix}'$ and $e_{i,t} = \begin{bmatrix} e_{i,t}^{N}, e_t^{X_w} \end{bmatrix}'$, the panel VAR specification can be rewritten in first difference in the following general representation:

$$\Delta \mathbb{Y}_{i,t} = \Phi \Delta \mathbb{Y}_{i,t-1} + \Delta \epsilon_{i,t} \tag{2.4}$$

where the structural orthogonalized innovations are linear combinations of the reduced form innovations by $Be_{i,t} = \epsilon_{i,t}$, such that $BB' = \Omega_\epsilon$, where Ω_ϵ is the covariance matrix of the errors $\epsilon_{i,t}$. I further assume a near-panel structural VAR, where the three (foreign) oil market variables, $\mathbb{Y}_2 = X_w$, are assumed to stay unaffected by the other three industry-specific variables, $\mathbb{Y}_1 = N_i$. Because of the exogeneity of X_w, the lag parameter Φ is an upper block triangular matrix:

$$\Phi = \begin{pmatrix} \Phi_{\mathbb{Y}_1,\mathbb{Y}_1} & \Phi_{\mathbb{Y}_1,\mathbb{Y}_2} \\ 0 & \Phi_{\mathbb{Y}_2,\mathbb{Y}_2} \end{pmatrix} \tag{2.5}$$

The model parameters (Φ and Ω_ϵ) are estimated using a quasi-maximum likelihood method from Binder et al. (2005). These estimators are consistent irrespective of whether the underlying time series are stationary and cointegrated.

2.5.2 Identification of different types of oil shocks

Identifying oil demand and oil supply shocks has become very popular in the literature because it is widely accepted that oil price increases have very different effects depending on the underlying cause of that increase (see Kilian (2009)).

Many empirical methods have been proposed to identify oil demand and oil supply shocks in the global crude oil market. The first generation of methods, which includes the structural VAR model proposed by Kilian (2009), is based on the assumption of a short-run vertical oil supply curve. It is assumed that shifts in the demand for oil do not have contemporaneous effects on the level of oil production. In addition, Kilian postulates that economic activity is not immediately affected by oil-specific demand shocks. His identification scheme is, however, less appropriate for estimations with quarterly or annual data.

More recent methods have relaxed some of the identifying assumptions in Kilian (2009), with the help of sign restrictions on the implied impulse response functions.[5] For example, Baumeister and Peersman (2012a) propose a strategy to identify the different types of oil shocks by employing a sign restriction of time-varying impulse responses in a quarterly structural VAR model. Kilian and Murphy (2012) use a monthly structural VAR model to identify oil shocks. Both models only impose sign restrictions during the impact period, as they are « more agnostic about some of the dynamic responses of crude oil production and global real activity and do not wish to rule out that general equilibrium effects may cause a sign reversal. » In ad-

5. See Baumeister and Peersman (2012a) and Kilian and Murphy (2012), among others.

dition to the sign restrictions, they also impose an upper bound of 0.0258 on the elasticity of the supply of oil with respect to the real price of oil. Kilian and Murphy (2012) find that a positive aggregate demand shock tends to increase oil production, stimulate real activity and increase the real price of oil on impact. A positive oil-market-specific demand shock will raise the real price of oil on impact and stimulate oil production, but will lower real activity. An unexpected oil supply disruption will, by construction, lower oil production on impact. It also will lower real activity, while increasing the real price of oil.

To disentangle the three different types of shocks ($e_t^{X_w}$) on oil market variables, I impose zero and sign restrictions, combined with elasticity bounds as used by Kilian and Murphy (2012). However, since this study uses annual data, the sign restrictions are assumed to hold only for the first year after the shocks. The impulse responses of the other variables to oil shocks are left unconstrained in the estimation and their responses are fully determined by the data. In addition, the bounds imposed on the price elasticity of oil supply are adjusted accordingly. Data provided by the Energy Information Administration show that, between 1989 and 1990 and during the Gulf War, the production of crude oil increased by 1.2%, whereas the real price of crude oil jumped by 18.6%, implying an elasticity of 0.064 of the supply of oil with respect to the real price of oil. Table 2.5 shows the sign restrictions on the impulse response functions (see Appendix B.2) to disentangle the different oil shocks.

Identification of the different structural shocks requires an estimate of the $M \times M$ matrix $\tilde{B}$ in $\epsilon_t = \tilde{B} e_t$. Consider $\Omega_\epsilon = P \Lambda P'$ and $B = P \Lambda^{0.5}$, such that B satisfies $\Omega_\epsilon = BB'$. Then $\tilde{B} = BQ$ also satisfies $\tilde{B}\tilde{B}'$ for any orthogonal $M \times M$ matrix Q. The set of identifying matrices $\tilde{B}$ is constructed via the following steps:

Table 2.5: Sign restrictions on impact responses

Structural shocks	L_i	W_i	Z_i	Q_o	Y_w	P_o
1. Labor shock	+			0	0	0
2. Shock on wages		+		0	0	0
3. Shock on price of capital			+	0	0	0
4. Oil supply shock (disruption)				-	-	+
5. Aggregate demand shock				+	+	+
6. Oil-specific demand shock				+	-	+

Note: The sign restrictions are assumed to hold only for the first year after the shocks.

1. Compute $B = P\Lambda^{0.5}$, where Λ is a diagonal matrix of the eigenvalues of Ω_ϵ, and P is a matrix whose columns are the corresponding eigenvectors.
2. Draw an $M \times M$ random matrix Q from the set of orthogonal matrices, such that (BQ, Φ) satisfies the zero restrictions on the impulse response functions.
3. Keep Q if the sign restrictions of the impulse response functions are satisfied.
4. Repeat steps 2 and 3 a large number of times, recording each Q that satisfies the identifying restrictions.

2.6 Empirical results

In this section, I present the results of estimations for the full panel. I examine the dynamic effects and the relative importance of the three different types of oil shocks on labor demand and the relative price of labor, through the impulse response functions and the variance decomposition. I then analyze how the effects of the different oil shocks vary with respect to companies' energy intensity and net trade exposure. I compare the impulse responses for the two sub-panels of high- and low-trade industries, as well as the impulse responses for the two sub-panels of energy-intensive and low-energy industries.

2.6.1 Results for all manufacturing industries

For a VAR model, the correct lag length is critical to obtaining good estimates. Too short of a lag may produce serially correlated errors and bias the remaining coefficients. Too long of a lag leads to a loss of degrees of freedom and over-parameterization. In this study, the optimal lag length is determined using the likelihood ratio test. The result of the test indicates that a lag length of one is optimal. [6]

The estimates of coefficients in Φ of model 2.4 are reported in Table 2.6. Most of these coefficients are statistically significant at the 5% level and have the expected sign. The one-period lag of the oil price has a significant and negative impact on labor demand, but it has a positive impact on the real wage. The coefficient for the relative price of labor, $W_{i,t-1}$, is unexpectedly positive, but not statistically significant. Meanwhile, the coefficient for the one-period lag of the capital-price, Z_{t-1}, is significant and positively correlated with the labor input, suggesting that capital and labor are substitutes. As expected, the coefficient for global demand, $Y_{w,t-t}$, is positive and not significant. This means that labor demand in Canadian manufacturing industries is higher when world real economic activity increases. Finally, there is a negative relationship between changes in the oil price and economic growth.

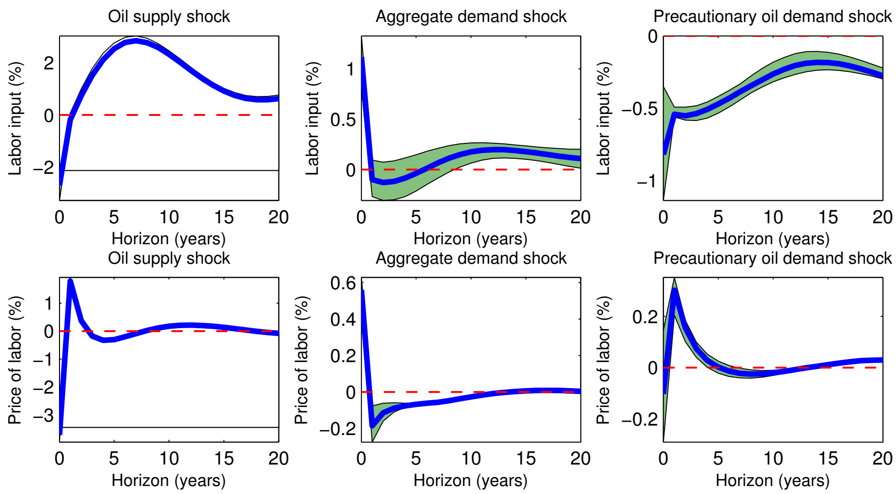
6. I have omitted the test results for brevity, but can provide them upon request.

Table 2.6: Results for all manufacturing industries

	$L_{i,t-1}$	$W_{i,t-1}$	$Z_{i,t-1}$	$Q_{o,t-1}$	$Y_{w,t-1}$	$P_{o,t-1}$
Labor input	1.034	0.030	0.017	-0.107	0.094	-0.033
	(0.000)	(0.318)	(0.002)	(0.123)	(0.181)	(0.000)
Real Price of Labor	-0.038	0.460	-0.003	0.064	-0.011	0.018
	(0.008)	(0.000)	(0.698)	(0.442)	(0.899)	(0.016)
Real Price of capital	0.267	0.173	0.678	-0.746	0.452	-0.100
	(0.000)	(0.328)	(0.000)	(0.071)	(0.313)	(0.006)
Oil Production	-	-	-	0.962	-0.077	-0.027
				(0.000)	(0.009)	(0.000)
Real Economic Activity	-	-	-	0.177	0.668	-0.039
				(0.000)	(0.000)	(0.000)
Real Price of Oil	-	-	-	3.018	-0.637	0.847
				(0.000)	(0.004)	(0.000)

Figure 2.1 shows the responses of labor and labor price to an oil supply shock, an aggregate demand shock, and a precautionary oil demand shock, such that the real price of oil rises 10% upon impact in each case. The median impulse responses are drawn in solid blue lines, and the area between the 16th and 84th percentiles is highlighted in green. The impulse responses for the three type of oil shocks differ greatly in their magnitude and signs. An increase in oil prices driven by precautionary oil demand shocks causes a decrease in labor activity over the entire 20-year span of the model. This shock increases the price of labor resulting from an increase in the costs of production. An oil supply disruption causes a negative effect only in the first year. A positive aggregate demand shock leads to a positive effect on labor over all time periods. This shock increases the price (cost) of labor upon impact, but the labor price subsequently decreases after the first year. These results are consistent with findings in Somé (2012). Indeed, a precautionary oil demand shock is not beneficial for Canadian manufacturing companies, while an aggregate demand shock has a larger positive impact.

Figure 2.1: Impulse responses for all industries



Note: The blue lines represent the median impulse responses to different types of oil shocks, and the green shading represents the area between the 16th and 84th percentiles.

The means of the variance decomposition at one horizon for labor market variables are displayed in Table 2.7. Each of the oil shocks explains less than 10% of the variance of labor and the variance of the relative price of labor. The contribution of aggregate demand shocks to labor variation is larger than that of the other two shocks. In particular, the aggregate demand shock explains 6.2% of variations in labor, while oil supply shocks and precautionary oil demand shocks explain 1.6% and 3.6%, respectively, of fluctuations in labor. Meanwhile, each of the oil shocks explains less than 2% of the variation in the relative price of labor. The labor shock, the age shock, and the capital price shock explain 30.3%, 32.0%, and 27.9%, respectively, of the variation in labor. These shocks explain 31.5%, 32.1%, and 33.2% of the variation in the price of labor.

Table 2.7: Conditional Variance Decomposition (in percent)

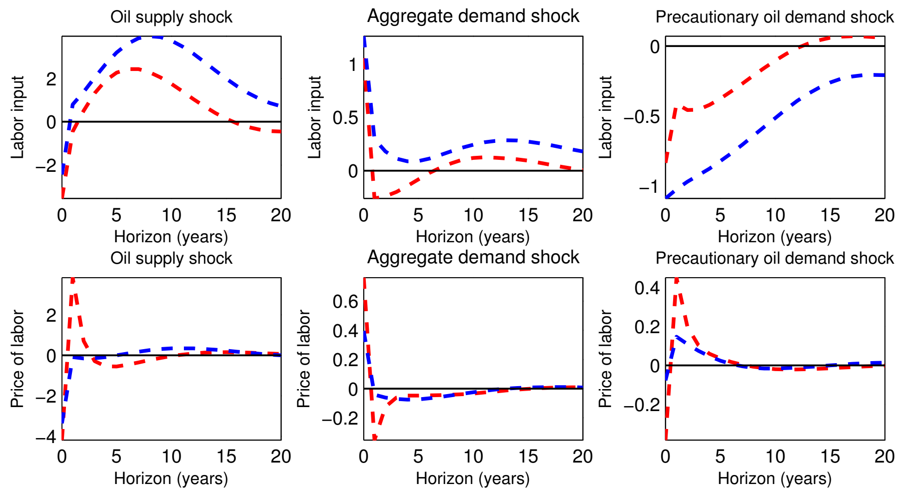
Variable	Labor shocks	Labor price shocks	Capital price shocks	Oil supply shocks	Aggregate demand shocks	Oil-specific demand shocks
Labor input	30.3	30.4	27.9	1.6	6.2	3.6
Price of labor	31.5	32.1	33.2	2.0	1.1	0.2

2.6.2 Results for sub-panel groups

Figures 2.2 and 2.3 show how the impulse responses of labor demand and the price of labor vary according to the degree of trade exposure and energy intensity. For each shock, the impulse responses are normalized such that the real price of oil rises 10% upon impact. The impulse responses in Figure 2.2 for the different sub-panels of industries have similar paths to those obtained using the full panel of industries. However, they differ in terms of magnitude. The response of labor to a precautionary oil demand shock for the sub-panel of high trade-exposed industries is greater than the response for the sub-panel of low trade exposed industries over all time horizons. This shock causes a larger negative effect on labor for lower trade exposed industries.

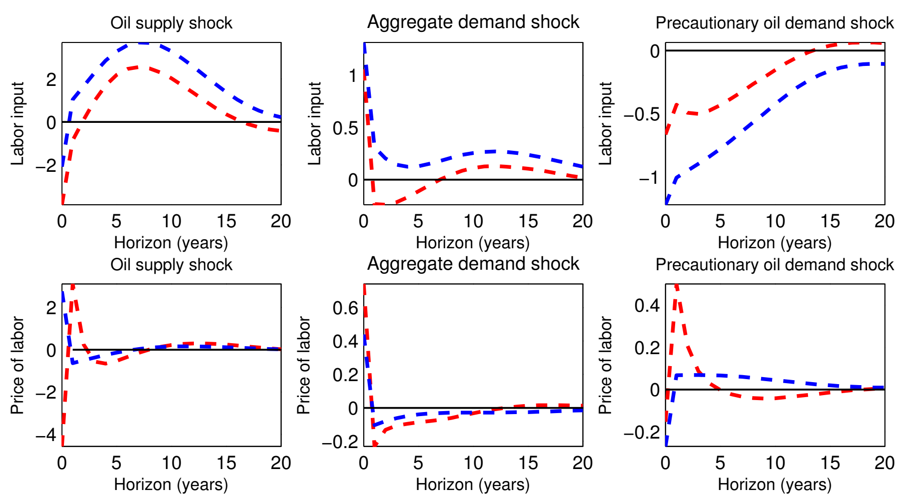
Meanwhile, the response of labor to an aggregate demand shock (or to an oil supply shock) for the sub-panel of low trade-exposed industries is larger than the response for the sub-panel of high trade-exposed industries over all time horizons, which implies that oil shocks have less effect on more trade-exposed industries. It should be noted that an aggregate demand shock causes, at the medium run, a negative effect on labor for the sub-panel of high trade-exposed industries. The same path is observed between energy-intensive and low-energy industries. There is no clear relationship between the degree of trade exposure (or energy intensity) and the response of relative price of labor to the different types of oil shocks.

Figure 2.2: Impulse responses for high and low trade-exposed industries



Note: The blue line represents the impulse response to different types of oil shocks for low trade-exposed industries; the red line is for high trade-exposed industries.

Figure 2.3: Impulse responses for high and low energy-intensive industries



Note: The blue line represents the impulse response to different types of oil shocks for low-energy industries; the red line is for energy-intensive industries.

2.6.3 Robustness Analysis

I check the robustness of the previous results with respect to alternative measure of labor input. I use the total jobs instead of the labor input index as an alternative measure of labor activity to obtain the estimates and impulse responses from analogous regressions of equation 2.4 for the full panel and the sub-panel using the total number of jobs. Using total jobs as a measure of labor activity allows to assess the effect on the pure number of jobs, without any other considerations (e.g. full- or part-time, age, skills, or education).

The estimates in tables 2.8 and 2.9 are similar in format to those of tables 2.8 and 2.9 and the impulse responses in figures 2.4, 2.5, and 2.6, are similar in path to those of figures 2.1, 2.2, and 2.3, suggesting that results still robust to the use of total job as alternative measure of labor input index.

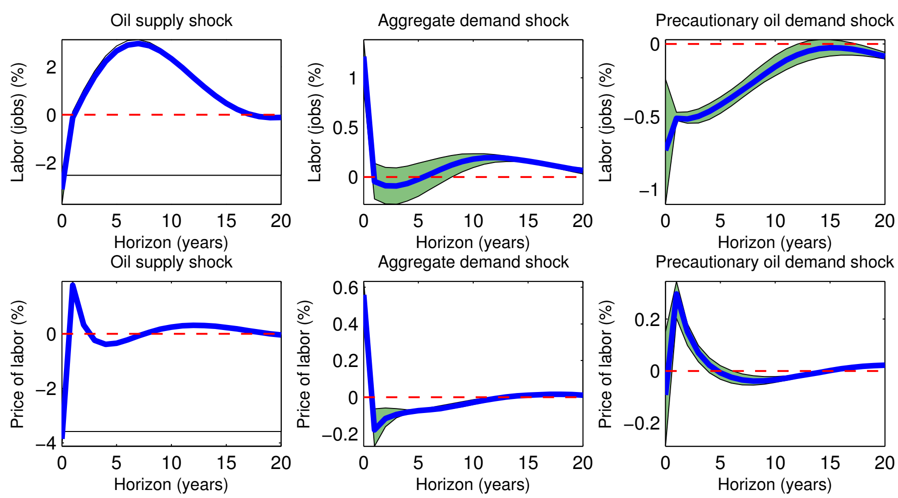
Table 2.8: Results for all manufacturing industries using total jobs as alternative measure of labor input

	$L_{i,t-1}$	$W_{i,t-1}$	$Z_{i,t-1}$	$Q_{o,t-1}$	$Y_{w,t-1}$	$P_{o,t-1}$
Labor (jobs)	1.009	0.010	0.023	-0.106	0.108	-0.029
	(0.000)	(0.732)	(0.000)	(0.105)	(0.116)	(0.000)
Real Price of Labor	-0.032	0.467	-0.004	0.068	-0.009	0.018
	(0.031)	(0.000)	(0.560)	(0.420)	(0.918)	(0.015)
Real Price of capital	0.267	0.147	0.687	-0.887	0.419	-0.094
	(0.000)	(0.404)	(0.000)	(0.031)	(0.340)	(0.012)
Oil Production	-	-	-	0.976	-0.078	-0.027
				(0.000)	(0.010)	(0.000)
Real Economic Activity	-	-	-	0.167	0.669	-0.039
				(0.000)	(0.000)	(0.000)
Real Price of Oil	-	-	-	3.065	-0.669	0.847
				(0.000)	(0.003)	(0.000)

Table 2.9: Conditional Variance Decomposition (in percent) using total jobs as alternative measure of labor input

Variable	Labor shocks	Labor price shocks	Capital price shocks	Oil supply shocks	Aggregate demand shocks	Oil-specific demand shocks
Labor (jobs)	29.6	29.3	27.2	2.2	8.0	3.6
Price of labor	31.4	31.8	33.5	2.0	1.1	0.2

Figure 2.4: Impulse responses for all industries using total jobs as alternative measure of labor input

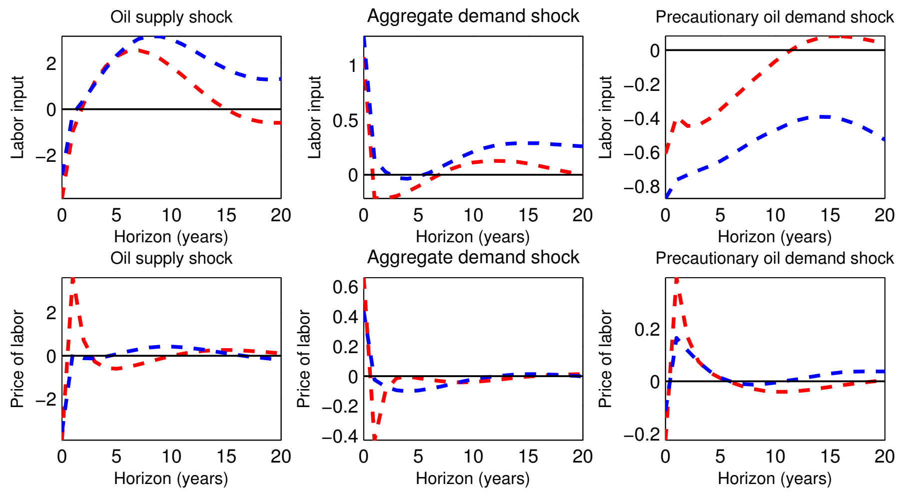


Note: The blue lines represent the median impulse to different oil shocks responses and the green shading represents the area between the 16th and 84th percentiles.

2.7 Conclusion

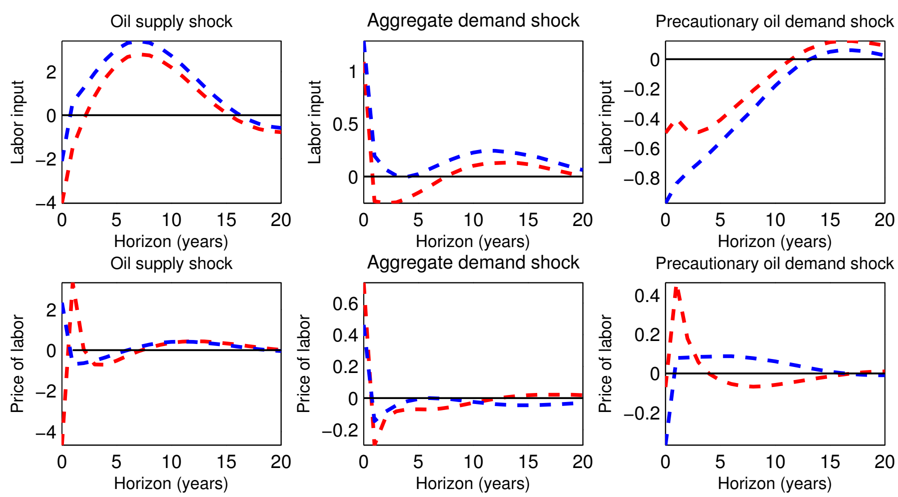
In this paper, I analyze the response of labor and the price of labor in Canadian manufacturing industries to oil demand and oil supply shocks, using a panel structural VAR model. I estimate the model using a fixed effects quasi-maximum likelihood estimator developed in Binder et al. (2005), and I identify the model by imposing zero and sign restrictions together.

Figure 2.5: Impulse responses for high and low trade-exposed industries using total jobs as alternative measure of labor input



Note: The blue line represents the impulse response to different oil shocks for low trade exposed industries; the red line is for high trade exposed industries.

Figure 2.6: Impulse response for high and low energy-intensive industries using total jobs as alternative measure of labor input



Note: The blue line represents the impulse response to different oil shocks for low-energy industries; the red line is for energy-intensive industries.

The estimates are qualitatively satisfactory and most of the coefficients are statistically significant. The impulse responses of labor and the price of labor to various types of oil shocks are different in terms of their sign and magnitude over time.

In particular, an increase in the oil price driven by innovations in global real economic activity tends to have a positive impact on labor demand and the price of labor, whereas oil supply shocks and precautionary oil demand shocks have a negative impact. Finally, the magnitudes of the effects of the different oil shocks on labor demand depend on whether industries are high or low net-trade exposed/energy intensive. However, there is no clear relationship between the response of the price of labor and the degree of trade exposure or energy intensity.

Chapter 3

Welfare Effects of Oil Storage

3.1 Introduction

The role of storage demand on the global oil market has been the interest of recent studies. For instance, Hamilton (2009), Kilian (2009), and Kilian and Murphy (2013) among the most relevant studies, show that oil storage demand has been historically an important factor in understanding the dynamic behavior of crude oil prices on the global oil market. According to Kilian (2009), the sharp increases in the real price of oil in 1990-1991 and in 1999-2000 are almost entirely due to increases in precautionary or speculative oil demand.

There are several reasons for carrying oil inventories: Oil storage, or oil inventories, helps to satisfy the demand in the oil market when there is oil supply disruptions. It facilitates delivery scheduling and provides greater assurance of continuing production. But It can also be used for speculation on future prices of oil.

Oil storage affects expectations about future oil prices and has a direct effect on current oil prices. The introduction of oil storage can play a significant role in increasing uncertainty on the means and variances of oil price, labor, and consumption, and therefore inducing welfare costs, especially for oil importers. Unfortunately, most of studies that analyzed the impact of oil price fluctuations on economic activity as well as on welfare in a DSGE model are focused on oil supply and technology shocks but do not account for oil storage demand on the global oil market.

This paper examines the welfare effects of introducing storage as a (speculative) competitive economic activity on the global oil market. It also examines how welfare effects vary with respect to the size of oil storage under two alternative monetary policy rules. The economic model employed in the analysis is an extension of the three-country DSGE model of Backus and Crucini (2000), in which I introduce oil storage as a (speculative) competitive economic activity into the global oil market and nominal rigidities. The model is characterized by two oil-importing countries (the United States and the euro area), and one oil exporting country. Oil storage is introduce in the model as a competitive economic activity into the global oil market, as in Pindyck (2004). The welfare gains/costs brought about by oil storage are measured by the compensating variations in consumption using a second order approximation of the model's equilibrium conditions around the steady state, as in Schmitt-Grohe and Uribe (2007a) and Kim et al. (2008). This procedure allows to capture the uncertainty effects of shocks both on the means and variances of the endogenous variables.

The main contribution of this study is to evaluate the welfare implications of oil storage using a general equilibrium model that closely mimic the features of the global oil market, where the price of oil is endogenous to the world economy. In the existing literature, only Wright and Williams (1984) have explicitly examined the welfare implications of introducing storage into the oil market, but they used a partial equilibrium model. In addition, while the literature focused on oil supply and technology shocks, this study includes also precautionary or storage oil shocks.

The model's parameters are either calibrated or estimated. The estimation is conduced with Euro area and United States data using Bayesian methods. Given the estimated and calibrated values of the model's structural parameters, the model is simulated using a second order approximation for the welfare analysis.

The results can be summarized as follows. Introducing competitive storage into the global oil market leads to welfare gains, i.e. positive welfare gains, for the oil exporting country, while it leads to welfare costs, i.e. negative welfare gains, for the two oil importing countries. The magnitude of the welfare effects is increasing with respect to the steady state level of oil storage and these welfare effects are mainly driven by oil storage shocks. I also find that the welfare costs in the two oil importing countries are smaller when the monetary police rules respond to the exchange rate fluctuations.

The rest of the paper is organized as follows. Section 3.2 describes the model. Section 3.3 describes the estimation strategy and Data. In Section 3.4, I evaluate the welfare implications of oil storage. Finally, section 3.5 concludes.

3.2 Model Economy

I consider a model of world economy with two oil-importing countries (the United States and the euro area), and one oil exporting country. The model is closely related to the three country model of Backus and Crucini (2000) [1], which I extend by incorporate competitive oil storage on the global oil market and nominal rigidities. Each country in the world economy is specialized in the production of a single good. The two oil-importing countries, produce each a manufactured good. The third country produces oil, which is both a consumption good and an intermediate good used in the production

1. The structure of three country model aims to mimic in a simple way the interaction between large industrialized countries and largely non-industrial oil producers.

of manufactured goods. Consumers in the three countries are identical in preferences. Moreover, the two oil-importing countries are symmetric in production technologies. However, the model allows for differences in policies and disturbances affecting each economy. Following Christiano et al. (2005), I allow nominal and real rigidities, so that monetary policy is non-neutral. The nominal rigidities include stickiness in price of manufactured goods and wage through the Calvo (1983) setup. The real rigidities include capital adjustment costs and an endogenous interest rate risk premium that prevents multiple steady states. I denote the two oil-importing countries by a and b, and the oil-exporting country by o. ζ_a, ζ_b and ζ_o denote their relative sizes. Because the structure of the oil-importing country blocs is symmetric, I will focus on the the country a in describing the model, taking the country b as the foreign economy.

3.2.1 The Oil-Importing Countries

3.2.1.1 Households

In the oil-importing country a, there is a continuum of infinitely lived identical households, indexed by $h \in (0,1)$. The typical household h derives utility from consumption and leisure with separable preferences. At time t, the intertemporal utility function of a typical household h is given by

$$\mathcal{W}_t^a(h) = \mathbb{E}_t \sum_{\tau=0}^{\infty} \beta^{\tau} \left[\frac{\left(C_{t+\tau}^a(h) - \hbar C_{t+\tau-1}^a(h)\right)^{1-\sigma_c}}{1-\sigma_c} - A_{L^a} \frac{L_{t+\tau}^a(h)^{1+\sigma_L}}{1+\sigma_L} \right] \tag{3.1}$$

where $\mathbb{E}_t$ denotes the mathematical expectation operator conditional on information available at time t, $\beta \in (0,1)$ is a constant discount factor, $C_t^a(h)$ is consumption in period t, $L_t^a(h)$ is the fraction of total available time devoted to productive activity in period t. The parameter σ_c represents the inverse of the elasticity of intertemporal substitution of consumption. The parameter σ_L is the inverse of the the Frisch elasticity of labor supply and A_{L^a} a parameter governing the level of labor supply in the steady state.

Parameter $\hbar \in (0,1)$ is the degree of internal habit formation, such that the households' marginal utility of consumption today is affected by the level of aggregate consumption in the last period, C^a_{t-1}. Separability of preferences is assumed, by simplicity, in order to ensure that households have identical consumption and investment plans.

In each period, the typical household h is subject to the following flow budget:

$$P^a_t C^a_t(h) + P^a_{I,t} I^a_t(h) + \frac{D^a_t(h)}{R^a_t} + \frac{e_t F^a_t(h)}{\mathcal{F}(F^a_t) R^b_t} = D^a_{t-1}(h) + e_t F^a_{t-1}(h) + W^a_t(h) L^a_t(h) + R^a_{K,t} K^a_t(h) - T^a_t(h) + Div^a_t(h) \quad (3.2)$$

where $I^a_t(h)$ is the investment used to form new physical capital; $D^a_t(h)$ and $F^a_t(h)$ denote holdings of one-period domestic and foreign currency denominated bonds, with gross interest rates R^a_t and R^b_t; e_t is the nominal exchange rate in currency of country a per unit of currency of country a. Here in particular, e_t is the nominal exchange rate in euros per U.S. dollar. An increase of e_t means the nominal depreciation of the Euro area currency. $W^a_t(h)$ is the hourly wage rate received in period t, and $R^a_{K,t}$ is the capital return. The household h also receives nominal dividends $Div^a_t(h)$ from domestic firms in each period t. The variable $T^a_t(h)$ denotes lump-sum taxes that the household h pays to the government. The term $\mathcal{F}(F^a_t)$ is a premium that households of country a have to pay when they borrow from abroad. It ensures that the model has a unique steady state. The function $\mathcal{F}(.)$ is increasing in the ratio of the aggregate real holdings of the foreign assets:

$$\mathcal{F}(F^a_t) = \exp\left(-\phi_F e_t \left(\zeta_a F^a_t - \zeta_a F^a\right) + \tilde{\phi}_t\right) \quad (3.3)$$

where $\zeta_a F^a_t = \int_0^1 F^a_t(h)dh$ is the total level of indebtedness of the country a and $\phi_F > 0$ is a parameter that determines the debt-elasticity of interest-rate premium. The variable $\tilde{\phi}_t$ represents a shock to risk premium on foreign bonds. This shock plays the role of an uncovered interest parity shock. The stock of capital evolves according to the following law of motion:

$$K^a_{t+1}(h) = (1-\delta)K^a_t(h) + V^a_t\left(1 - S(I^a_t(h)/I^a_{t-1}(h))\right) I^a_t(h) \tag{3.4}$$

where $S(x) = \frac{\kappa}{2}(x-1)^2$ with $\kappa > 0$. This functional form implies that it is costly to change the level of investment, the cost is increasing in the change in investment, and there are no adjustment costs in steady state. Parameter δ is the capital depreciation rate. The variable V^a_t is an investment-specific technology shock or the marginal efficiency of investment. It captures the rate of transformation of investment good into installed capital to be used in production.

In each period t, the household h chooses consumption $C^a_t(h)$, nominal domestic and foreign bonds, $D^a_t(h)$ and $F^a_t(h)$, capital stock $K^a_{t+1}(h)$, and investment $I^a_t(h)$ to maximize its welfare 3.1 subject to 3.2 and 3.4. The resulting first-order conditions are as follows:

$$\lambda^a_t(h) = \left(C^a_t(h) - \hbar C^a_{t-1}(h)\right)^{-\sigma_c} - \beta\hbar\mathbb{E}_t\left[\left(C^a_{t+1}(h) - \hbar C^a_t(h)\right)^{-\sigma_c}\right] \tag{3.5}$$

$$\lambda^a_t(h) = \beta R^a_t \mathbb{E}_t\left[\frac{1}{\Pi^a_{t+1}}\lambda^a_{t+1}(h)\right] \tag{3.6}$$

$$\lambda^a_t(h) = \beta\mathcal{F}(F^a_t)R^b_t\mathbb{E}_t\left[\frac{1}{\Pi^a_{t+1}}\frac{e_{t+1}}{e_t}\lambda^a_{h,t+1}\right] \tag{3.7}$$

$$q^a_t = \beta\mathbb{E}_t\left[\left(\frac{\lambda^a_{t+1}(h)}{\lambda^a_t(h)}\right)\left(r^a_{K,t+1} + (1-\delta)q^a_{t+1}\right)\right] \tag{3.8}$$

$$\begin{aligned} p^a_{I,t} =& q^a_t V^a_t\left[1 - S\left(\frac{I^a_t(h)}{I_{t-1}(h)}\right) - S'\left(\frac{I^a_t(h)}{I^a_{t-1}(h)}\right)\left(\frac{I^a_t(h)}{I^a_{t-1}(h)}\right)\right] \\ &+ \beta\mathbb{E}_t\left[\left(\frac{\lambda^a_{t+1}(h)}{\lambda^a_t(h)}\right) q^a_{t+1}V^a_{t+1}S'\left(\frac{I^a_{t+1}(h)}{I^a_t(h)}\right)\left(\frac{I^a_{t+1}(h)}{I^a_t(h)}\right)^2\right] \end{aligned} \tag{3.9}$$

where $\Pi_t^a = P_t^a / P_{t-1}^a$ is the Consumer Price Index gross inflation rate in country a, $\lambda_t^a(h)$ is the Lagrange multiplier associated with the real budget constraint and $\gamma_t^a(h)$ is the Lagrange multiplier associated with 3.4. $p_{I,t}^a = P_{I,t}^a / P_t^a$ is the real price of investment, and $r_{K,t}^a = R_{K,t}^a / P_t^a$ is the real rental price of capital. The variable $q_t^a = \gamma_t^a(h)/\lambda_t^a(h)$ is the shadow price (the Tobin's q) in consumption units, of a unit of K_{t+1}^a at time t. Equations 3.6 and 3.7 together imply the uncovered interest rate parity (UIP) condition:

$$\mathbb{E}_t \left\{ \lambda_{t+1}^a(h) \frac{P_t^a}{P_{t+1}^a} \left(R_t^a - \frac{e_{t+1}}{e_t} \mathcal{F}(F_t^a) R_t^b \right) \right\} = 0 \tag{3.10}$$

Wage setting

Following Christiano et al. (2005), I assume that each household h is a monopolistic supplier of a differentiated labor service. A competitive labor service assembler transforms these different labor services into aggregate labor with and associated aggregate wage index given by the Constant Elasticity of Substitution (C.E.S) aggregators

$$L_t^a = \left(\int_0^1 (L_t^a(h))^{\frac{\theta_w - 1}{\theta_w}} dh \right)^{\frac{\theta_w}{\theta_w - 1}} \quad \text{and} \quad W_t^a = \left(\int_0^1 (W_t^a(h))^{1-\theta_w} dh \right)^{\frac{1}{1-\theta_w}}$$

where $\theta_{w,t} > 1$ is the elasticity of substitution among different types of labor and L_t^a is the aggregate labor demand. In the literature $\frac{\theta_w}{\theta_w - 1}$ represents the markup of wages over the household.s marginal rate of substitution. The demand for each differentiated labor service is given by:

$$L_t^a(h) = \left(\frac{W_t^a(h)}{W_t^a} \right)^{-\theta_w} L_t^a \tag{3.11}$$

In any given period, a fraction $1 - \xi_w^a$ of households are able to reset their wages. The remaining fraction ξ_w^a of households can only partially index their wages to lagged inflation rate, i.e, $w_t^a(h) = \left({\Pi_{t-1}^a}^{\chi_w} / \Pi_{t-1}^a \right) w_{t-1}^a(h)$, where $w_t^a = W_t^a / P_t^a$ the real wage and $\chi_w \in [0, 1]$ measures the degree of indexation to the lagged inflation rate. The indexation rule implies that the real wage of an household who cannot change his wage for periods τ-periods is $w^a_{t+\tau}(h) = \left(\prod_{s=1}^{\tau} \frac{\Pi^a_{t-1}{}^{\chi_w}}{\Pi^a_{t-1}}\right) w^a_t(h)$. The relevant part of the problem of households resetting their wages is:

$$\max_{w^a_t(h)} \mathbb{E}_t \sum_{\tau=0}^{\infty} (\xi^a_w \beta)^\tau \left\{ U(C^a_{t+\tau}(h), L^a_{t+\tau}(h)) + \lambda^a_{t+\tau}(h) \left(\prod_{s=1}^{\tau} \frac{\Pi^a_{t+s-1}{}^{\chi_w}}{\Pi^a_{t+s}} \right) w^a_t(h) L^a_{t+\tau}(h) \right\} \tag{3.12}$$

subject to $L^a_{t+\tau}(h) = \left(\left(\prod_{s=1}^{\tau} \frac{\Pi^a_{t+s-1}{}^{\chi_w}}{\Pi^a_{t+s}} \right) \frac{w^a_t(h)}{w^a_{t+\tau}} \right)^{-\theta_w} L^a_{t+\tau}$.

Because of complete markets, all households who reset their wages at time t choose the same optimal wage, $\tilde{W}^a_t$, that satisfies the following equation:

$$\sum_{\tau=0}^{\infty} (\xi^a_w \beta)^\tau \mathbb{E}_t \left\{ \begin{array}{c} \frac{1}{\tilde{w}_t} \theta_w \left(\left(\prod_{s=1}^{\tau} \frac{\Pi^a_{t+s-1}{}^{\chi_w}}{\Pi^a_{t+s}} \right) \frac{\tilde{w}^a_t(h)}{w^a_{t+\tau}} \right)^{-\theta_w(\sigma_L+1)} A_{L^a} (L^a_{t+\tau})^{\sigma_L+1} \\ +(1-\theta_w)\lambda^a_{t+\tau} \left(\prod_{s=1}^{\tau} \frac{\Pi^a_{t+s-1}{}^{\chi_w}}{\Pi^a_{t+s}} \right)^{1-\theta_w} \left(\frac{\tilde{w}^a_t(h)}{w^a_{t+\tau}} \right)^{-\theta_w} L^a_{t+\tau} \end{array} \right\} = 0 \tag{3.13}$$

Denoting by $w^a_t = W^a_t / P^a_t$ the real wage, the solution of the optimal real wage $\tilde{w}^a_t$ can obtained recursively using the two following equations:

$$\begin{aligned} X^a_{w,t} &= A_{L^a} \left(\frac{\tilde{w}^a_t}{w^a_t} \right)^{-\theta_w(1+\sigma_L)} L^a_t{}^{1+\sigma_L} \\ &\quad +(\xi^a_w \beta) \mathbb{E}_t \left(\frac{\Pi^a_t{}^{\chi_w}}{\Pi^a_{t+1}} \right)^{-\theta_w(1+\sigma_L)} \left(\frac{\tilde{w}^a_t}{\tilde{w}^a_{t+1}} \right)^{-\theta_w(1+\sigma_L)} X_{w,t+1} \qquad (3.14) \\ X^a_{w,t} &= \left(\frac{\theta_w - 1}{\theta_w} \right) \left(\frac{\tilde{w}^a_t}{w^a_t} \right)^{1-\theta_w} \lambda^a_t w^a_t L^a_t \\ &\quad +(\xi^a_w \beta) \mathbb{E}_t \left(\frac{\Pi^a_t{}^{\chi_w}}{\Pi^a_{t+1}} \right)^{1-\theta_w} \left(\frac{\tilde{w}^a_t}{\tilde{w}^a_{t+1}} \right)^{1-\theta_w} X_{w,t+1} \qquad (3.15) \end{aligned}$$

Finally, the aggregate wage index dynamic is given by:

$$(w_t^a)^{1-\theta_w} = \xi_w^a \left(\frac{\Pi_{t-1}^a {}^{\chi_w}}{\Pi_t^a} w_{t-1}^a \right)^{1-\theta_w} + (1-\xi_w^a)(\tilde{w}_t^a)^{1-\theta_w} \tag{3.16}$$

3.2.1.2 Consumption and investment good producers

The final consumption basket C_t^a can be regarded as produced by perfectly competitive consumption distributors using the following Constant Elasticity of Substitution (C.E.S.) aggregator:

$$C_t^a = \left((1-\omega_{oc})^{\frac{1}{\gamma_o}} (C_{Z,t}^a)^{\frac{\gamma_o-1}{\gamma_o}} + \omega_{oc}^{\frac{1}{\gamma_o}} (O_{C,t}^a)^{\frac{\gamma_o-1}{\gamma_o}} \right)^{\frac{\gamma_o}{\gamma_o-1}} \tag{3.17}$$

where $O_{C,t}^a$ represents Oil consumption, and $C_{Z,t}^a$ is a basket of non-oil consumption (core consumption). Parameter γ_o is is the elasticity of substitution between oil and core consumption and $\omega_{o,c}$ defines the weight of oil in consumption. The demand functions, from the profit maximization, are given by:

$$C_{Z,t}^a = (1-\omega_{oc}) \left(\frac{P_{Z,t}^a}{P_t^a} \right)^{-\gamma_o} C_t^a \quad \text{and} \quad O_{C,t}^a = \omega_{oc} \left(\frac{e_t P_{o,t}}{P_t^a} \right)^{-\gamma_o} C_t^a$$

The zero-profit condition implies that the Consumer Price Index (CPI), P_t^a, is given by:

$$P_t^a = \left((1-\omega_{oc})(P_{no,t}^a)^{1-\gamma_o} + \omega_{oc}(e_t P_{o,t})^{1-\gamma_o} \right)^{\frac{1}{1-\gamma_o}} \tag{3.18}$$

Similarly, the core consumption basket $C_{Z,t}^a$ is produced by perfectly competitive distributors using, as inputs, the manufactured goods a and b.

$$C_{Z,t}^a = \left(\omega_{ac}^a {}^{\frac{1}{\gamma_c}} (C_{a,t}^a)^{\frac{\gamma_c-1}{\gamma_c}} + (1-\omega_{ac}^a)^{\frac{1}{\gamma_c}} (C_{b,t}^a)^{\frac{\gamma_c-1}{\gamma_c}} \right)^{\frac{\gamma_c}{\gamma_c-1}} \tag{3.19}$$

where γ_c is the elasticity of substitution between the good a and the good b in the core consumption basket, and ω_{ac}^a defines the weight of good a in the core consumption basket. Denoting by $P_{Z,t}^a$, $P_{a,t}^a$, and $P_{b,t}^a$ the core consumption price index, the local price of the manufactured good a, and the price of the manufactured good b in the country a, respectively, the demand functions, from the profit maximization, are given by:

$$C_{a,t}^a = \omega_{ac}^a \left(\frac{P_{a,t}^a}{P_{Z,t}^a} \right)^{-\gamma_c} C_{Z,t}^a \quad \text{and} \quad C_{b,t}^a = (1 - \omega_{ac}^a) \left(\frac{P_{b,t}^a}{P_{Z,t}^a} \right)^{-\gamma_c} C_{Z,t}^a$$

The zero-profit condition implies that the Consumption Price Index (CPI) P_t^a is given by:

$$P_{Z,t}^a = \left(\omega_{ac}^a (P_{a,t}^a)^{1-\gamma_c} + (1 - \omega_{ac}^a)(P_{b,t}^a)^{1-\gamma_c} \right)^{\frac{1}{1-\gamma_c}} \tag{3.20}$$

Finally, investment good I_t^a is a basket of domestic and foreign manufactured goods a and b, similar in structure to the core consumption basket. Specifically, I assume a common home bias for both core consumption and investment goods so that the price index associated to consumption C_t^a and investment I_t^a are identical.

3.2.1.3 Manufactured good producers

There is a continuum of firms $z \in (0, 1)$ producing differentiated domestic manufactured goods. Firm z produces its good using capital, $K_t^a(z)$, labour, $L_t^a(z)$, and oil, $O_{Y,t}^a(z)$, as inputs according to a Cobb-Douglas technology:

$$Y_{a,t}(z) = Z_{a,t}(L_t^a(z))^{\alpha} \left((1 - \omega_{oy})^{\frac{1}{\nu}} (K_t^a(z))^{1-\frac{1}{\nu}} + \omega_{oy}^{\frac{1}{\nu}} (O_{Y,t}^a(z))^{1-\frac{1}{\nu}} \right)^{\frac{\nu(1-\alpha)}{\nu-1}} \tag{3.21}$$

where $Z_{a,t}$ is a technology shock, common to all domestic manufactured good producers and α is the share of labor in manufactured output. The form of the production technology has been used by as in Kim and Loungani (1992) and Backus and Crucini (2000). It implies that oil and capital are used to produce capital services, which are combined with labor to produce goods. Parameter ω_{oy} is the bias towards oil of producing capital services, while ν represents the elasticity of substitution between capital and oil.

At each period t, given the rental price of capital, $R^a_{K,t}$, the wage rate, W^a_t, and the price of oil (expressed in the currency of country b), $P_{o,t}$, the producer of the variety of manufactured good zth optimally chooses the levels of capital $K^a_t(z)$, labor $L^a_t(z)$, and oil $O^a_{Y,t}(z)$ that minimize its real costs. From the first order conditions, the demand curves for labor, capital, and oil are given, respectively, by:

$$w^a_t = \alpha \times mc_{a,t} \times \frac{Y_{a,t}(z)}{L^a_t(z)} \tag{3.22}$$

$$r^a_{K,t} = mc_{a,t} \times \frac{Y_{a,t}(z)}{K^a_t(z)} \frac{(1-\alpha)(1-\omega_{oy})^{\frac{1}{\nu}}(K^a_t(z))^{1-\frac{1}{\nu}}}{\left((1-\omega_{oy})^{\frac{1}{\nu}}(K^a_t(z))^{1-\frac{1}{\nu}}+\omega_{oy}^{\frac{1}{\nu}}(O^a_{Y,t}(z))^{1-\frac{1}{\nu}}\right)} \tag{3.23}$$

$$e_t p^a_{o,t} = mc_{a,t} \times \frac{Y_{a,t}(z)}{O^a_{Y,t}(z)} \frac{(1-\alpha)\omega_{oy}^{\frac{1}{\nu}}(O^a_{Y,t}(z))^{1-\frac{1}{\nu}}}{\left((1-\omega_{oy})^{\frac{1}{\nu}}(K^a_t(z))^{1-\frac{1}{\nu}}+\omega_{oy}^{\frac{1}{\nu}}(O^a_{Y,t}(z))^{1-\frac{1}{\nu}}\right)} \tag{3.24}$$

where $p_{o,t} = P_{o,t}/P^b_t$ is the real price of oil, $S_t = e_t P^b_t / P^a_t$ is the real exchange rate, and $mc_{a,t} = MC_{a,t}/P^a_t$ is the Lagrange multiplier associated to (3.21). This later also defines the real marginal cost of domestic manufactured good. Given that the production technology is the same for all firms, the marginal cost is also the same for any firm. Using (3.22), (3.23) and (3.24), the marginal cost can be expressed as a function of the real price of oil, the rental price of capital, the real wage, and the level of of technology:

$$mc_{a,t} = Z^{-1}_{a,t}\,(w^a_t)^{\alpha}\left((1-\omega_{oy})(r^a_{K,t})^{1-\nu} + \omega_{oy}(S_t p_{o,t})^{1-\nu}\right)^{\frac{(1-\alpha)}{1-\nu}} \alpha^{-\alpha}(1-\alpha)^{\alpha-1} \tag{3.25}$$

Price setting

I assume Local Currency Pricing (LCP) manufactured good producers, as in Rabanal and Tuesta (2010). Firms set their prices in the buyer's currency. Hence, the law of one price for manufactured goods does not hold because of market segmentation. Following Calvo (1983)'s rule, I further assume that in each period a fraction $1-\xi_{p,a}$ of domestic manufactured good producers reset their prices, while a fraction $\xi_{p,a}$ index their prices by past inflation of manufactured good price index. Then, they maximize the present value of future real profits:

$$\max_{P^a_{a,t}(z),P^b_{a,t}(z),P^o_{a,t}(z)} \mathbb{E}_t \sum_{\tau=0}^{\infty}(\xi_{p,a}\beta)^{\tau}\left(\frac{\lambda^a_{t+\tau}}{\lambda^a_t}\right)\frac{1}{P^a_{t+\tau}} \times \left\{\begin{array}{l} \left(\left(\frac{P^a_{a,t+\tau-1}}{P^a_{a,t-1}}\right)^{\chi_p} P^a_{a,t}(z) - MC_{a,t+\tau}\right) Y^a_{a,t+\tau}(z)+ \\ \left(\left(\frac{P^b_{a,t+\tau-1}}{P^b_{a,t-1}}\right)^{\chi_p} e_t P^b_{a,t}(z) - MC_{a,t+\tau}\right) Y^b_{a,t+\tau}(z)+ \\ \left(\left(\frac{P^o_{a,t+\tau-1}}{P^o_{a,t-1}}\right)^{\chi_p} e_t P^o_{a,t}(z) - MC_{a,t+\tau}\right) Y^o_{a,t+\tau}(z) \end{array}\right\} \quad (3.26)$$

subject to the demand functions:

$$Y^a_{a,t+\tau}(z) = \left(\left(\frac{P^a_{a,t+\tau-1}}{P^a_{a,t-1}}\right)^{\chi_p}\frac{P^a_{a,t}(z)}{P^a_{a,t+\tau}}\right)^{-\theta_p}\zeta_a\left(C^a_{a,t+\tau}+I^a_{a,t+\tau}+G^a_{t+\tau}\right) \quad (3.27)$$

$$Y^b_{a,t+\tau}(z) = \left(\left(\frac{P^b_{a,t+\tau-1}}{P^b_{a,t-1}}\right)^{\chi_p}\frac{P^b_{a,t}(z)}{P^b_{a,t+\tau}}\right)^{-\theta_p}\zeta_b\left(C^b_{a,t+\tau}+I^b_{a,t+\tau}\right) \quad (3.28)$$

$$Y^o_{a,t+\tau}(z) = \left(\left(\frac{P^o_{a,t+\tau-1}}{P^o_{a,t-1}}\right)^{\chi_p}\frac{P^o_{a,t}(z)}{P^o_{a,t+\tau}}\right)^{-\theta_p}\zeta_o C^o_{a,t+\tau} \quad (3.29)$$

where $P^a_{a,t}(z)$, $P^b_{a,t}(z)$, and $P^o_{a,t}(z)$ are prices of the manufactured good a in the countries a, b, and o, respectively. The variables $Y^a_{a,t+\tau}(z)$, $Y^b_{a,t+\tau}(z)$, and $Y^o_{a,t+\tau}(z)$, such that $Y_{a,t+\tau}(z)=Y^a_{a,t+\tau}(z)+Y^b_{a,t+\tau}(z)+Y^o_{a,t+\tau}(z)$, are the associated demands for manufactured good a in each country. The terms $\beta\frac{\lambda^a_{t+\tau}}{\lambda^a_t}$ represents the producer's discount factor coming from the fact that producers act in the interest of households. The parameter $\theta_p>1$ is the elasticity of substitution between the differentiated domestic manufactured goods. It measures the degree of monopoly power of producers of these goods, since $\frac{\theta_p}{\theta_p-1}$ is the markup of price over marginal cost for producers. Parameter $\chi_p\in[0,1]$ captures the degree of indexation. When $\chi_p=0$, there is no indexation and when $\chi_p = 1$ there is full indexation. Given the same marginal cost of production, all firms that reset their prices at time t choose the same optimal price, $\tilde{P}_{a,t}$, satisfying the following equations:

$$\mathbb{E}_t \sum_{\tau=0}^{\infty} (\xi_{p,a}\beta)^{\tau} \left(\frac{\lambda^a_{t+\tau}}{\lambda^a_t}\right) \frac{1}{P^a_{t+\tau}} \left\{ \begin{array}{l} \left(\left(\frac{P^a_{a,t+\tau-1}}{P^a_{a,t-1}}\right)^{\chi_p} \tilde{P}^a_{a,t}(z) - \frac{\theta_p}{\theta_p - 1} MC_{a,t+\tau}\right) Y^a_{a,t+\tau}(z) \\ \left(\left(\frac{P^b_{a,t+\tau-1}}{P^b_{a,t-1}}\right)^{\chi_p} e_t \tilde{P}^b_{a,t}(z) - \frac{\theta_p}{\theta_p - 1} MC_{a,t+\tau}\right) Y^b_{a,t+\tau}(z) \\ \left(\left(\frac{P^o_{a,t+\tau-1}}{P^o_{a,t-1}}\right)^{\chi_p} e_t \tilde{P}^o_{a,t}(z) - \frac{\theta_p}{\theta_p - 1} MC_{a,t+\tau}\right) Y^o_{a,t+\tau}(z) \end{array} \right\} = 0 \quad (3.30)$$

Denoting by $p^x_{a,t} = P^x_{a,t}/P^x_t$ and $\Pi^x_{a,t} = P^x_{a,t}/P^x_{a,t-1}$ the real price and the gross inflation rate of the manufactured good a in country $x \in \{a, b, o\}$, and by $\tilde{\Pi}^x_{a,t} = \tilde{P}^x_{a,t}/P^x_{a,t}$, the solution of the optimal price can be obtained recursively using the following equations:

$$\begin{aligned} X^a_{p,a,t} &= \tilde{\Pi}^a_{a,t} p^a_{a,t} Y^a_{a,t} \\ &\quad + (\xi_{p,a}\beta)\mathbb{E}_t \left(\frac{\lambda^a_{t+1}}{\lambda^a_t}\right) \left(\frac{\Pi^a_{a,t}{}^{\chi_p}}{\Pi^a_{a,t+1}}\right)^{1-\theta_p} \times \left(\frac{\tilde{\Pi}^a_{a,t}}{\tilde{\Pi}^a_{a,t+1}}\right) X^a_{p,a,t+1} \qquad (3.31) \\ X^a_{p,a,t} &= mc_{a,t} Y^a_{a,t} + (\xi_{p,a}\beta)\mathbb{E}_t \left(\frac{\lambda^a_{t+1}}{\lambda^a_t}\right) \left(\frac{\Pi^a_{a,t}{}^{\chi_p}}{\Pi^a_{a,t+1}}\right)^{-\theta_p} X^a_{p,a,t+1} \qquad (3.32) \end{aligned}$$

$$\begin{aligned} X^b_{p,a,t} &= \tilde{\Pi}^b_{a,t} S_t p^b_{a,t} Y^b_{a,t} \\ &\quad + (\xi_{p,a}\beta)\mathbb{E}_t \left(\frac{\lambda^a_{t+1}}{\lambda^a_t}\right) \left(\frac{\Pi^b_{a,t}{}^{\chi_p}}{\Pi^b_{a,t+1}}\right)^{1-\theta_p} \left(\frac{\tilde{\Pi}^b_{a,t}}{\tilde{\Pi}^b_{a,t+1}}\right) \left(\frac{S_t}{S_{t+1}}\right) X^b_{p,a,t+1} \qquad (3.33) \\ X^b_{p,a,t} &= mc_{a,t} Y^b_{a,t} + (\xi_{p,a}\beta)\mathbb{E}_t \left(\frac{\lambda^a_{t+1}}{\lambda^a_t}\right) \left(\frac{\Pi^b_{a,t}{}^{\chi_p}}{\Pi^b_{a,t+1}}\right)^{-\theta_p} X^b_{p,a,t+1} \qquad (3.34) \end{aligned}$$

$$\begin{aligned} X^o_{p,a,t} &= \tilde{\Pi}^o_{a,t} \frac{S_t}{Xo_t} p^o_{a,t} Y^o_{a,t} \\ &\quad + (\xi_{p,a}\beta)\mathbb{E}_t \left(\frac{\lambda^a_{t+1}}{\lambda^a_t}\right) \left(\frac{\Pi^o_{a,t}{}^{\chi_p}}{\Pi^o_{a,t+1}}\right)^{1-\theta_p} \left(\frac{\tilde{\Pi}^o_{a,t}}{\tilde{\Pi}^o_{a,t+1}}\right) \left(\frac{Xo_{t+1} S_t}{Xo_t S_{t+1}}\right) X^o_{p,a,t+1} \qquad (3.35) \\ X^o_{p,a,t} &= mc_{a,t} Y^o_{a,t} + (\xi_{p,a}\beta)\mathbb{E}_t \left(\frac{\lambda^a_{t+1}}{\lambda^a_t}\right) \left(\frac{\Pi^o_{a,t}{}^{\chi_p}}{\Pi^o_{a,t+1}}\right)^{-\theta_p} X^o_{p,a,t+1} \qquad (3.36) \end{aligned}$$

Finally, from the the aggregate price dynamics we obtain the following equations:

$$1 \quad = \quad \xi_{p,a}\left(\frac{\Pi^{x}_{a,t-1}{}^{\chi_p}}{\Pi^{x}_{a,t}}\right)^{1-\theta_p} + (1-\xi_{p,a})(\tilde{\Pi}^{x}_{a,t})^{1-\theta_p} \quad \text{for } x \in \{a,b,o\} \tag{3.37}$$

3.2.1.4 Government and Monetary and policies

I assume that the Central Bank follows a Taylor-type rule. In particular, the short-term nominal interest rate is set in response to deviations of CPI inflation from its steady state level and output growth. Moreover, I allow for the possibility of including nominal exchange rate depreciation in the policy rule:

$$\frac{R^a_t}{R^a} = \left(\frac{R^a_t}{R^a}\right)^{\rho^a_R}\left[\left(\frac{\Pi^a_t}{\Pi^a}\right)^{r^a_{\Pi}}\left(\frac{Y^a_t}{Y^a_{t-1}}\right)^{r^a_{\Delta y}}\left(\frac{e_t}{e_{t-1}}\right)^{r^a_{\Delta e}}\right]^{1-\rho^a_R}\exp(\epsilon^a_{R,t}) \tag{3.38}$$

where $\epsilon^a_{R,t}$ is an uncorrelated monetary policy shock that corresponds to a deviation from the policy rule. Lubik and Schorfheide (2007) have implemented similar Taylor rules. One interest of this paper is to instigate how the the welfare effects of oil storage vary depending on whether the monetary policy rule responds to exchange rate depreciation.

The government is assumed to consume a fixed share g_y of the domestic manufactured good amount at each period t. This consumption of amount $G^a_t = g_y Y_{a,t}$ has no direct effect on household utility. Fiscal policy is specified as a zero debt policy. The government levies lump-sum taxes $T^a_t = \int_0^1 T^a_t(h)dh$ so that the government budget is balanced: $T^a_t = P^a_{a,t}G^a_t$.

3.2.2 The Oil-Exporting Country

I consider a simplified structure of the oil-exporting country. There a representative household in the oil-exporting country that consumes oil and manufactured goods exclusively imported from the the two oil-importing countries. Moreover, the oil-exporting country adopts a one-to-one peg with the U.S. dollar (the currency of the country b). The problem of the representative household is given by

$$\mathcal{W}_t^o = \mathbb{E}_t \sum_{\tau=0}^{\infty} \beta^\tau U(C_{t+\tau}^o, L_{t+\tau}^o) \tag{3.39}$$

Subject to the following budget constraint:

$$P_t^o C_t^o + \frac{F_t^o}{\mathcal{F}(F_t^o) R_t^b} = F_{t-1}^o + W_t^o L_t^o + Div_t^o \tag{3.40}$$

where $L_{o,t}$, is the labor supply and W_t^o the corresponding wage rate, C_t^o is a consumption basket, and P_t^o the corresponding CPI. The composition of the consumption basket in the oil exporting country is identical to one of the two oil-importing countries. For simplicity, I assume that the oil producer likes goods a and b equally well so that $\omega_{ac}^o = 0.5$. The variables F_t^o and Div_t^o are the one-period foreign bonds and the profits from oil firms.

On the the production side, I assume that the oil-exporting country is endowed with an oil field of unbounded capacity and there is a continuum of firms $z \in (0, 1)$ that produce oil in a monopolistically competitive framework. Each oil producer uses the following technology:

$$Y_{o,t}(z) = Z_{o,t}\; L_t^o(z)^{\alpha} \tag{3.41}$$

where $Y_{o,t}(z)$ is the level of firm's z oil production, $Z_{o,t}$ is an exogenous technology common to all oil producers, and $L_t^o(z)$ is the level of labor used in oil production. As in the case of manufactured good producers, oil producers have market power and hence fix a price with a markup over real marginal cost but oil prices are not subject to nominal rigidities and can be adjusted instantaneously. Given the wage rate, the optimal price for all oil producers is given by $P_{o,t} = \frac{\theta_o}{\theta_o - 1} \times \frac{W_t}{\alpha Z_{o,t} {L_t^o}^{\alpha}}$, where $\theta_o > 1$ denotes the elasticity of substitution among varieties of oil. It also corresponds to the the degree of monopoly power of oil producers. L_t^o corresponds to the aggregate labor input of all oil producers.

3.2.3 Oil Storers

Following Pindyck (2004), I assume that there are storers or speculators on the global oil market who are allow to hold oil as inventories. These storers are distributed across the world according to the relative country size. Oil inventories serve to reduce costs of adjusting production over time, and also to reduce marketing costs by facilitating production and delivery scheduling and avoiding stockouts. The profit maximization problem for the storers is:

$$\max_{OS_t} \left\{ a \; {R_t^b}^{-1} \; E_t(P_{o,t+1}) OS_t - P_{o,t} OS_t - \Phi(OS_t, Z_{os,t}) - \Xi_t OS_t \right\} \tag{3.42}$$

where $\Phi(OS_t, Z_{os,t})$ is the cost of delivery scheduling and avoidance of stock-outs, $Z_{os,t}$ is an exogenous storage demand shock, $\Xi_t > 0$ is the per-unit storage cost. The parameter $(1-a)$, with $a \in (0,1)$, is defined as the *waste*. It ensures that the stock of oil inventories is stationary. From the first order condition, the optimal demand of oil storage for speculators is given by the following inter temporal equation:

$$Cy_t - \Xi_t = P_{o,t} - a \; {R_t^b}^{-1} \; E_t(P_{o,t+1}) \tag{3.43}$$

In the commodity literature, $Cy_t = -\partial\Phi(OS_t, Z_{os,t})/\partial OS_t$ defines the marginal convenience yield. I assume that $Cy_t/P_t^b = \psi OS_t^{-\varsigma} Z_{os,t}$ and $\Xi_t/P_t^b = \Xi$, as in Pindyck (2004). Equation 3.43 says that the expected marginal revenue from storing a barrel of crude oil must equal to the total marginal storage cost. The presence of oil storage has a direct effect on current oil price. An exogenous shock on $Z_{os,t}$ will be interpreted as a precautionary oil demand shock or simply an oil storage shock. The main interest of this paper is to evaluate the welfare gains/costs for each of the three countries of introducing storage as a competitive economic activity into the global oil market.

3.2.4 Exogenous variables

There are nine structural exogenous processes in the model. Excepted the monetary policy shocks, each of them, in log deviations from steady state, evolves exogenously according to the following first-order autoregressive process:

$$\log(X_t) = (1-\rho_X)\log(X) + \rho_X \log(X_t) + \epsilon_{X,t} \tag{3.44}$$

where $X = \left\{V^a, V^b, Z_a, Z_b, Z_o, Z_{os}, \tilde{\phi}\right\}$. The persistence parameters, ρ_X, are bounded between 0 and 1, and the innovations, $\epsilon_{X,t}$, are mutually independent, serially uncorrelated and normally distributed with means zero and variances σ_X^2. The monetary policy shocks, $\epsilon_{R^x,t}$, with $x \in \{a, b\}$ are i.i.d. and normally distributed with mean zero and variance $\sigma_{R^x,t}^2$.

3.2.5 Market clearing conditions

The equilibrium condition on the global market of crude oil is:

$$\zeta_o Y_{o,t} = (OS_t - aOS_{t-1}) + \zeta_o O_{C,t}^o + \zeta_a(O_{C,t}^a + O_{Y,t}^a) + \zeta_b(O_{C,t}^b + O_{Y,t}^b) \tag{3.45}$$

When there is oil storage, the oil market clearing condition implies that the current oil production must equal the sum of oil consumption, plus the change in oil storage, while in the absence of oil storage, the oil market clearing condition requires only that the current oil production equals the sum of oil consumption. The oil price $P_{o,t}$ must adjust endogenously to clear the world oil market. Through the equation 3.43 and the oil market equilibrium condition 3.45, expectations about future oil price can have a direct effect on the current oil price. Therefore, the introduction of competitive storage into the global oil market will induce an interrelated set of responses in the path of prices, output, labor, consumption, and hence consumers' welfare.

Market clearing for the two manufactured goods a and b are given by :

$$\zeta_a Y_{a,t} = \zeta_b v^b_{p,a,t}(C^b_{a,t} + I^b_{a,t}) + \zeta_a v^a_{p,a,t}(C^a_{a,t} + I^a_{a,t} + G^a_t) + \zeta_o v^o_{p,a,t} C^o_{a,t} \quad (3.46)$$

$$\zeta_b Y_{b,t} = \zeta_b v^b_{p,b,t}(C^b_{b,t} + I^b_{b,t} + G^b_t) + \zeta_a v^a_{p,b,t}(C^a_{b,t} + I^a_{b,t}) + \zeta_o v^o_{p,b,t} C^o_{b,t} \quad (3.47)$$

where $v^x_{p,y,t} = \int_0^1 \left(\frac{p^x_{y,t}(z)}{p^x_{y,t}}\right)^{-\theta_p} dz$ for $y \in \{a, b\}$ and $x \in \{a, b, o\}$ measures the price dispersion due to the Calvo price setting. As in the case of the aggregate price index, we can show that this price dispersion index has the following dynamics:

$$v^x_{p,y,t} = \xi_{p,y} \left(\frac{{\Pi^x_{y,t-1}}^{\chi_p}}{\Pi^x_{y,t}}\right)^{-\theta_p} v^x_{p,y,t-1} + (1 - \xi_{p,y})\, {\tilde{\Pi}^x_{y,t}}^{-\theta_p} \quad (3.48)$$

The aggregate supply of the manufactured good $y \in \{a, b\}$ is given by

$$Y_{y,t} = Z_{y,t}\, {L^y_t}^{\alpha} \left((1 - \omega_{oy})^{\frac{1}{\nu}}\, {K^y_t}^{1-\frac{1}{\nu}} + \omega_{oy}^{\frac{1}{\nu}}\, {O^y_{Y,t}}^{1-\frac{1}{\nu}}\right)^{\frac{\nu(1-\alpha)}{\nu-1}} \quad (3.49)$$

where $K_t^y = \int_0^1 K_t^y(z)dz$ is the aggregate demand of capital, $L_t^y = \int_0^1 L_t^y(z)dz$ aggregate labor demand, and $OY_t^y = \int_0^1 OY_t^y(z)dz$ is the aggregate demand for oil in country y. The aggregate labor supply of households is given by

$$\mathcal{L}_t^y = L_t^y \int_0^1 \left(\frac{w_t^y(h)}{w_t^y}\right)^{-\theta_w} dh = L_t^y v_{w,t}^y \quad \text{for } y \in \{a,b\} \tag{3.50}$$

The variable Δw_t^y defines the wage dispersion which evolves according to:

$$v_{w,t}^y = \xi_w^y \left(\frac{w_{t-1}^y}{w_t^y}\frac{{\Pi_{t-1}^y}^{\chi_w}}{\Pi_t^y}\right)^{-\theta_w} v_{w,t-1}^y + (1-\xi_w^y)\,{\tilde{\Pi}_{w,t}^y}^{-\theta_w} \quad \text{for } y \in \{a,b\} \tag{3.51}$$

Domestic debt is in zero net supply, i.e $D_t^b = D_t^a = 0$ for all t. Market clearing for the internationally traded assets requires that the sum of the net foreign asset position of the three countries has to add up to zero:

$$\zeta_a F_t^a + \zeta_b F_t^b + \zeta_o F_t^o = 0 \tag{3.52}$$

3.3 Data and Model Estimation

The model is transformed in real terms by deflating all nominal variables for each country by corresponding consumer price index. The models parameters are either calibrated or estimated.

I choose to fix the parameters with standard values in the literature or those I think are weakly identified by the dataset used for the estimation. Table 3.1 presents the calibrated parameters. The two importing countries a, ie. the Euro area, and b, i.e. the U.S., are assumed to have equal size at $\zeta_a = \zeta_b = 0.25$.[2] The discount factor, β, is set at 0.99, which implies an annual steady-state real interest rate of 4 percent. I set $\delta = 0.025$, which implies an annual rate of depreciation on capital equal to 10 percent. The

2. Referring to Rabanal and Tuesta (2010) and Lubik and Schorfheide (2006), I consider that the U.S. and the Euro Area are roughly of the same size.

exogenous government spending to domestic output ratio, g_y is set at 0.20. The parameter σ_c is set at 2, implying an elasticity of intertemporal substitution in consumption of 0.5. The inverse of the Frisch wage elasticity of labor supply, σ_L, is set at unit. Parameters A_{L^a} and A_{L^b} are set so that the steady state level of labor to total time is 1/3. The labor share, α is set at 0.64. The bias toward domestic manufactured good, ω_{ac}^a, is set at 0.95, as in Rabanal and Tuesta (2010). The parameters ω_{oc} and ω_{oy} are set so that the cost of US total oil consumption expenditure as share of GDP is 0.4, with one-third of total oil usage accounted for by households, and two-thirds by firms. The substitution elasticities for prices and wages, θ_p and θ_w, are set to 11 and 6, consistent with markups equal to 1.1 and 1.2, respectively. These two later values are also standard in the DSGE literature. Following Elekdag et al. (2008), I assume a markup of 476 percent, i.e. $\theta_o = 1.21$, for oil producers. Following Pindyck (2004), the storage elasticity of convenience yield, ς, is set equal to 2. The steady state levels of real price of oil and real exchange rate are assumed to be equal to unity.

All other parameters of the model are estimated using Bayesian approach, which is became standard in estimating DSGE models.[3] The elasticity of substitution between oil and consumption, γ_o, is set at 0.4 while I set a small value for the elasticity of substitution between capital and oil, $\nu = 0.2$. The Calvo parameters for price stickiness are constrained to be equal, $\xi_{p,a} = \xi_p^b$, with a prior mean at 0.75, implying average durations between price optimizations of 4 quarters. The Calvo parameters for wages stickiness are also constrained to be equal, $\xi_w^a = \xi_w^b$, with a prior mean at 0.75. The parameters describing the monetary policy rule are set as follows. The parameters ϕ_Π^a, $\phi_{\Delta y}^a$, and $\phi_{\Delta e}^a$, are set equal to 1.5, 0.5 and 0.10. The interest rate smoothing parameter ρ_R^a is set at 0.5. I choose identical priors for parameters of monetary policy rule for the country b. I use beta distributions for parameters

3. The Bayesian estimation approach has been applied, for example, in Lubik and Schorfheide (2006), Lubik and Schorfheide (2007), Adolfson et al. (2007) and Rabanal and Tuesta (2010).

Table 3.1: Calibrated parameters

Description	Parameter	Value
Size of country a	ζ_a	0.25
Size of country b	ζ_b	0.25
Size of country o	ζ_o	0.50
Discount factor	β	0.99
Depreciation rate of capital	δ	0.025
Steady state of inflation rate	Π	2%
Inverse of intertemporal elasticity of substitution	σ_c	2
Inverse of Frisch wage elasticity of labor supply	σ_L	1
Labor share in production	α	0.64
Storage elasticity of convenience yield	ς	2
Per unit physical storage cost	Ξ	0.005
Oil waste	$1 - a$	0.001
Elasticity of substitution among labor services	θ_w	6
Elasticity of substitution among manufacturing goods	θ_p	10
Elasticity of substitution among oil	θ_o	1.21
Bias toward domestic manufactured good in consump.	ω_{ac}^{a}	0.95
Bias towards manufactured good a in consumption	ω_{ac}^{o}	0.50
Share of Government spending to domestic production	g_y	0.20
Fraction of time spent working (country a and b)	L_a, L_b	1/3
Stead state or real price of oil	p_o	1
Stead state or real exchange rate	s	1
Total oil consumption expenditure as share of GDP	$p_o * (OY_b + OC_b)/GDP_b$	0.4
Share of household oil consumption to total oil cons.	$OY_b/(OY_b + OC_b)$	1/3

bounded between 0 and 1. For parameters assumed to be positive I use a Inverse-gamma distribution, and for parameters bounded to be non-negative I use gamma distribution. Table 3.2 gives an overview of the prior distribution of the estimated parameters. I report prior means, standard deviation and prior domains for convenience.

I use nine time series in the estimation of the model. The sample period goes from 1973:1 to 2005:4. The series includes real GDP, inflation, and nominal interest rate for the U.S. and the Euro Area, as well as data on real exchange rate between the Euro Area and the United States. I also include series on real price of oil and world oil production. The real price of oil is measured by the spot price of oil deflated by the U.S. Consumer Price Index.

The spot price of oil is the West Texas Intermediate price in U.S. dollars per barrel. The world's oil production is measured in barrel/day. Oil production is divided by world population of 15 years and over. The U.S. real GDP is divided by the U.S. total population of 16 years and over, while the euro area real GDP is divided by the euro area total population of 15 years and over. The series on inflations are based on the Consumer Price Indexes. The real exchange rate is obtained by multiplying the nominal exchange rate in euros per U.S. dollar by the ratio of the U.S. CPI to the Euro Area CPI.[4] I extract from the database of Energy Information Administration, International Petroleum. Series on population for the Euro area and the World are taken from World Development Indicators of the World Bank database. The original series on world population are in annual frequency and are converted to quarterly frequency using a quadratic interpolation. I extract from the FRED database, maintained by the Federal Reserve Bank of St. Louis, the nominal oil prices (OILPRICE), the real GDP, Consumer Price Index (CPIAUCSL), and the effective Federal Funds Rate (FEDFUNDS) for United States. The real GDP (YER), Consumer Price Index (HIPC) and short term nominal rate (STN) for the Euro area are extracted from the Area Wide Model (AWM) database from of the European Central Bank. All series are seasonally adjusted.

The model parameters are estimated using the log-linearized version of the model. Therefore, all the observable variables are transformed into log deviations from their Hodrick-Prescott trend with a smoothing parameter of 1600. I estimate separately the model under the two restrictions $r_{\Delta e} > 0$ and $r_{\Delta e} = 0$ in the monetary policy rule for the country a as well as for

4. Starting in 1999 I use the official U.S.-Euro dollar exchange rate obtained from the Fred database. Prior to 1999, I construct a synthetic bilateral exchange rate series based on the weight U.S. dollar per National Currency Unit exchange rates for the Euro Area countries. These weights are 0.201 for France, 0.283 for Germany, 0.111 for Spain, 0.024 for Portugal, 0.015 for Ireland, 0.195 for Italy, 0.030 for Austria, 0.069 for Netherlands, 0.036 for Belgium, 0.003 for Luxembourg, 0.017 for Finland, and 0.025 for Greece.

Table 3.2: Prior distributions

Description	Param.	Shape	Domain	Mean	S.D.
Steady state of oil storage to oil production	$\bar{OS}/\bar{Y}_o$	G	$\mathbb{R}^+$	0.50	0.25
Investment adjustment costs	κ	G	$\mathbb{R}^+$	1.00	0.75
Degree of internal habit formation	$\hbar$	B	$[0,1)$	0.65	0.10
Debt-interest rate elasticity	ϕ_F	G	$\mathbb{R}^+$	0.02	0.01
Elasticity of subst. between goods a and b	γ_c	I	$\mathbb{R}^{++}$	1.50	1.00
Elasticity of substitution between C and O	γ_o	I	$\mathbb{R}^{++}$	0.40	0.20
Elasticity of substitution between K and O	ν	I	$\mathbb{R}^{++}$	0.20	0.10
Calvo probability in nominal wages	ξ_w^a	B	$[0,1)$	0.75	0.15
Calvo probability in nominal prices	ξ_p^a	B	$[0,1)$	0.75	0.15
Degree of wage indexation	χ_w	B	$[0,1)$	0.50	0.20
Degree of price indexation	χ_p	B	$[0,1)$	0.50	0.20
Monetary policy smoothing coefficient	ρ_{R^a}	B	$[0,1)$	0.50	0.20
Monetary policy smoothing coefficient	ρ_{R^b}	B	$[0,1)$	0.50	0.20
Monetary policy inflation coefficient	r_{Π^a}	G	$\mathbb{R}^+$	1.50	1.00
Monetary policy inflation coefficient	r_{Π^b}	G	$\mathbb{R}^+$	1.50	1.00
Monetary policy output growth coefficient	$r_{\Delta y^a}$	G	$\mathbb{R}^+$	0.50	0.20
Monetary policy output coefficient	$r_{\Delta y^b}$	G	$\mathbb{R}^+$	0.50	0.20
Monetary policy exchange rate coefficient	$r_{\Delta e}^a$	G	$\mathbb{R}^+$	0.10	0.07
Monetary policy exchange rate coefficient	$r_{\Delta e}^b$	G	$\mathbb{R}^+$	0.10	0.07
Persistence of oil storage shock	$\rho_{Z_{os}}$	B	$[0,1)$	0.75	0.15
Persistence of investment shock	ρ_{V^a}	B	$[0,1)$	0.75	0.15
Persistence of investment shock	ρ_{V^b}	B	$[0,1)$	0.75	0.15
Persistence of TFP shock	ρ_{Z_a}	B	$[0,1)$	0.75	0.15
Persistence of TFP shock	ρ_{Z_b}	B	$[0,1)$	0.75	0.15
Persistence of oil supply shock	ρ_{Z_o}	B	$[0,1)$	0.75	0.15
Persistence of risk premium shock	$\rho_{\tilde{\phi}}$	B	$[0,1)$	0.75	0.15
Standard deviation of oil storage shock	$\sigma_{Z_{os}}$	I	$\mathbb{R}^{++}$	2.00	2.00
Standard deviation of investment shock	$100 * \sigma_{V^a}$	I	$\mathbb{R}^{++}$	1.00	2.00
Standard deviation of investment shock	$100 * \sigma_{V^b}$	I	$\mathbb{R}^{++}$	1.00	2.00
Standard deviation of TFP shock	$100 * \sigma_{Z_a}$	I	$\mathbb{R}^{++}$	5.00	5.00
Standard deviation of TFP shock	$100 * \sigma_{Z_b}$	I	$\mathbb{R}^{++}$	5.00	5.00
Standard deviation of oil supply shock	$100 * \sigma_{Z_o}$	I	$\mathbb{R}^{++}$	1.00	2.00
Standard deviation of interest rate shock	$100 * \sigma_{R^a}$	I	$\mathbb{R}^{++}$	0.20	1.00
Standard deviation of interest rate shock	$100 * \sigma_{R^b}$	I	$\mathbb{R}^{++}$	0.20	1.00
Standard deviation of risk premium shock	$100 * \sigma_{\tilde{\phi}}$	I	$\mathbb{R}^{++}$	1.00	2.00

Note: N stands for Normal, B Beta, G Gamma, U Uniform, and I Inverted-Gamma1. S.D. stands for Standard Deviation. $\mathbb{R}^+ = \{$x | x is a nonnegative real number$\}$, $\mathbb{R}^{++} = \{$x | x is a strictly positive real number$\}$.

the country b. Table 3.3 presents the estimation results, which include the posterior means, standard deviation together with the 90 percent highest posterior density interval. Let's examine in detail the estimates of the fully model under the restriction $r_{\Delta e} > 0$.

The steady state level of the ratio of oil storage to oil production, $\bar{OS}/\bar{Y}_o$ has a posterior mean of about 0.30, which is above its prior mean. The posterior mean estimates for the external habit formation parameters is $\hbar = 0.42$, which is between the estimates reported in Rabanal and Tuesta (2010) and Lubik and Schorfheide (2006). Adjustment cost parameter of new investment is estimated above its prior mean. The posterior mean of the elasticity of substitution between manufactured goods a and b, γ_c, is about 1.30, which is above the estimates report in Rabanal and Tuesta (2010). The elasticity of substitution between oil and consumption is 0.35, which is consistent with the estimates reported in Kilian and Murphy (2013). The posterior mean for the elasticity of substitution between oil and capital, $\gamma_o = 0.13$, is close to the calibrated value in Backus and Crucini (2000). The posterior means of γ_c and γ_o confirm that oil is less substitutable in production that in consumption.

The posterior mean for the degree of price stickiness is estimated at $\xi_p = 0.79$, implying expected price durations of about 4.8 quarters. The degree of wage stickiness is estimated to be $\xi_w = 0.57$, implying that nominal wages remain unchanged, on average, for about 2.3 quarters. The estimates of ξ_p and ξ_w are in line with Rabanal and Tuesta (2010). The posterior mean for the degree of price indexation, $\chi_p = 0.06$, is much smaller than the mean value of the prior distribution. This small value implies that manufactured goods' producers in both countries are almost full forward-looking in their price setting.

Turning to the parameters for monetary policy rules, the estimated value of the interest rate smoothing coefficients for Euro area and U.S. are $\rho_{R^a} = 0.81$ and $\rho_{R^a} = 0.71$, respectively. The estimates of r_{Π^a} and r_{Π^b}, which measure the response of monetary policy to inflation for Euro area and U.S., are 2.20 and 2.37, respectively. The estimates of the posterior mean $r_{\Delta Y_a}$ and $r_{\Delta Y_b}$, which measure the response of output growth in the Euro area and U.S., are 0.63 and 0.60 respectively. Relatively to the estimates of Rabanal and Tuesta (2010), The monetary policy rule estimates in this work imply strong responses to inflation and output growth movements by both the Euro area and the U.S. monetary authorities.

Overall the estimates of the structural parameters fall within plausible ranges in the literature. The posterior means of the estimates under the two alternative the monetary policy rule, $r_{\Delta e} >$ and $r_{\Delta e} = 0$ are very close (absolute relative difference less than 10%) with an exception for the parameters σ_{Z_a}, and σ_{Z_b}.

3.4 Welfare implications of oil storage

I first present the approach to evaluate the welfare implications of introducing oil storage and then, I present and discuss the results. I examine how the conditional and unconditional welfare effects vary with respect to the steady state level of oil storage under two alternative monetary policy rules. In the baseline monetary policy rule, the central bank adjusts its interest rate in response to deviations in CPI inflation and output growth to their steady state levels, and also to nominal exchange rate depreciation, i.e $r_{\Delta e} > 0$. In the alternative monetary policy rule, the central bank adjusts its interest rate in response only to deviations in CPI inflation and output growth to their steady state levels, i.e. $r_{\Delta e} > 0$.

The aggregate conditional and unconditional welfares are defined, by $\mathcal{W}_t = \int_0^1 \mathcal{W}_t(h)dh$ and $\mathcal{W} = \mathbb{E}[\mathcal{W}_t]$, respectively. Here, $\mathbb{E}$ denotes the unconditional expectations operator, Using the labor demand curve faced by each household and the fact that all households have the same consumption plans, I obtain:

$$\mathcal{W}_t = \mathbb{E}_t \sum_{\tau=0}^{\infty} \beta^{\tau} \left[\frac{\left(C_{t+\tau} - \hbar C_{t+\tau-1}\right)^{1-\sigma_c}}{1-\sigma_c} - A_L \frac{\mathcal{L}_{t+\tau}{}^{1+\sigma_L}}{1+\sigma_L} \right] \tag{3.53}$$

$$\mathbb{E}\left(\mathcal{W}_t\right) = \mathbb{E} \sum_{\tau=0}^{\infty} \beta^{\tau} \left[\frac{\left(C_{t+\tau} - \hbar C_{t+\tau-1}\right)^{1-\sigma_c}}{1-\sigma_c} - A_L \frac{\mathcal{L}_{t+\tau}{}^{1+\sigma_L}}{1+\sigma_L} \right] \tag{3.54}$$

where the conditional welfare is computed given that at time t all state variables take their steady-state values. The welfare gain of introducing oil storage is measured by the percentage of consumption compensating variation, i.e. the fraction of lifetime consumption from the model without oil storage, that I call m_1, that should be added in order to equate the welfare level in the model with oil storage, that I call m_2. Let $\left\{\bar{C}_t\right\}_{\tau=t}^{\infty}$ denotes the lifetime consumption and $\left\{\bar{\mathcal{L}}_t\right\}_{\tau=t}^{\infty}$ the lifetime labor under the model m_1. The conditional welfare gain, $\lambda_{c,t}$, of introducing oil storage is obtained by solving for $\lambda_{c,t}$ the following equation:

$$\mathcal{W}_t = \mathbb{E}_t \sum_{\tau=0}^{\infty} \beta^{\tau} \left[\frac{\left(\bar{C}_{t+\tau} - \hbar \bar{C}_{t+\tau-1}\right)^{1-\sigma_c}}{1-\sigma_c} \left(1+\lambda_{c,t}\right)^{1-\sigma_c} - A_L \frac{\bar{\mathcal{L}}_{t+\tau}{}^{1+\sigma_L}}{1+\sigma_L} \right] \tag{3.55}$$

Similarly, the unconditional welfare gain of introducing oil storage, λ_t^u, is obtained by solving for $\lambda_{c,t}$ the following equation:

$$\mathbb{E}\left(\mathcal{W}_t\right) = \mathbb{E} \sum_{\tau=0}^{\infty} \beta^{\tau} \left[\frac{\left(\bar{C}_{t+\tau} - \hbar \bar{C}_{t+\tau-1}\right)^{1-\sigma_c}}{1-\sigma_c} \left(1+\lambda_u\right)^{1-\sigma_c} - A_L \frac{\bar{\mathcal{L}}_{t+\tau}{}^{1+\sigma_L}}{1+\sigma_L} \right] \tag{3.56}$$

Solving for $\lambda_{c,t}$ and λ_u yields:

$$\lambda_{c,t} = \left[\frac{\mathcal{W}_t + \bar{\mathcal{W}}_{t,L}}{\bar{\mathcal{W}}_t + \bar{\mathcal{W}}_{t,L}} \right]^{\frac{1}{1-\sigma_c}} - 1 \tag{3.57}$$

$$\lambda_u = \left[\frac{\mathbb{E}\left(\mathcal{W}_t\right) + \mathbb{E}\left(\bar{\mathcal{W}}_{t,L}\right)}{\mathbb{E}\left(\bar{\mathcal{W}}_t\right) + \mathbb{E}\left(\bar{\mathcal{W}}_{t,L}\right)} \right]^{\frac{1}{1-\sigma_c}} - 1 \tag{3.58}$$

where $\bar{\mathcal{W}}_t$ and $\mathcal{W}_t$ are the conditional welfares obtained under the models m_1 and m_2, respectively. $\bar{\mathcal{W}}_{t,L} = \mathbb{E}_t \sum_{\tau=0}^{\infty} \beta^{\tau} \left[A_L \frac{\bar{\mathcal{L}}_{t+\tau}{}^{1+\sigma_L}}{1+\sigma_L} \right]$ is obtained under the model m_1.

To correctly evaluate the the welfare gains, a second-order accurate approximation is necessary. However, Likelihood estimation of second-order approximated models is difficult computationally. To deal with this computational problem, the estimation of the model is conducted based on the log linearized model. Then, for welfare analysis, the model is simulated with the calibrated and estimated values of the model's parameters using a second-order accurate approximation, as in Schmitt-Grohe and Uribe (2007a) and Kim et al. (2008). I use *Dynare* toolbox for *Matlab*, developed by Adjemian et al. (2012). [5], to calculate the second-order approximation of the model and to get theoretical moments of the model's endogenous variables, including the conditional welfare $\mathcal{W}_t$.

Panel A of table 3.4 presents the results of the welfare gains when simulating the model with all shocks and depending on whether or not the monetary policy rule responds to exchange rate depreciation. For each scenario of the monetary policy rule, I report the results at different value of the steady state level of oil inventories by keeping all the other parameters equal to their estimates. The welfare gains in the table 3.4 are expressed in percentage of consumption compensating variation. The numbers in parentheses are the unconditional welfare gains.

When the monetary policy rule includes the exchange rate depreciation, the welfare gains of introducing oil storage are negative (costs) and are quite similar in magnitudes for the two oil importing countries a and b, even if they are slightly larger for country a. The conditional welfare gains for the country a vary between -5.95% to -0.87%, while the unconditional welfare gains/costs range from -0.77% to -0.12%. For the country b, the conditional

5. The option for the pruning algorithm in *Dynare*, described in Kim et al. (2008), is also used to obtaining a stable solution of the second-order when iteratively computing simulations of the solution.

welfare gains of oil storage shocks vary between -5.22% to -0.75%, while the unconditional welfare gains/costs range from -0.75% to -0.13%. For the oil exporting country, the welfare gains are positive and very large in magnitude. The conditional welfare gains vary between 11.48% and 77.73%, while the unconditional welfare gains vary between 2.23% and 15.09%. The magnitude of welfare gains are so large in the oil exporting country because the households consumption in this country is exclusively financed by oil revenues.

The results in table 3.4, also show that the magnitude of the welfare effects are slightly larger when the monetary policy rule does not responding to exchange rate fluctuations, i.e. when $r_{\Delta e} = 0$ than when monitory policy rule responds to exchange rate fluctuations, i.e. when $r_{\Delta e} => 0$. Exchange rate stability improves only slightly the welfare costs of oil storage in both oil importing countries.

When comparing the conditional welfare gains to the unconditional welfare gains, the results clearly indicate a quite large difference in magnitude. The magnitude of welfare gains/costs obtained using the unconditional welfare measure is smaller due to the fact that the unconditional welfare comparison ignores the welfare changes on the transition dynamics from one state to another. Ignoring welfare changes during the transitional period may lead to misleading welfare results, especially if welfare costs during the transitional period are large enough to offset any long-term gains.

Panel B of table 3.4 shows the welfare gains/costs implied by oil storage shocks obtained by setting all the other exogenous shocks equal to zero, i.e. by simulating the different variants of the model with only oil storage shocks, $\sigma_{Z_{os}} \neq 0$. The results indicate that both the conditional and unconditional welfare effects slightly decrease for all countries. In Panel C, the different variants of the model are simulated without oil storage shocks, i.e. with only $\sigma_{Z_{os}} = 0$. The welfare effects drastically decrease for all countries. The results of welfare gains from Panels A, B and C suggest that the welfare gains of introducing oil storage, for each of the three countries, are mainly driven by the effects of oil storage shocks.

Overall, the results of welfare effects for the different countries are interesting and qualitatively consistent with the literature. Intuitively, the introduction of competitive oil storage contribute to increase the price of oil, which deteriorates the trade balance of oil importing countries while improving the trade balance of the oil exporting country. Therefore, it results to wealth transfers from oil importing countries to the oil exporting country. This evidence is consistent with Bodenstein et al. (2007) who found that oil market-specific shock that boosts the oil price results in a wealth transfer toward oil exporters and depresses the oil importers consumption.

3.5 Conclusion

In this paper, I examine the welfare effect of introducing competitive storage into the global oil market using a three-country DSGE model characterized by two oil importing countries and one oil exporting country. The main results indicates that the introduction of competitive oil storage leads to a wealth transfer toward the oil exporting country. The magnitude of the welfare effects are increasing with respect to the steady state level of oil inventories. When using unconditional welfare comparison rather that conditional welfare, the welfare effects are smaller due to the fact that the unconditional welfare measure ignores the dynamic transitional effects of introducing oil storage. Moreover, including the exchange rate depreciation in the monetary policy reactions allows only to marginally reduce the welfare costs associated with the introduction of oil storage for both oil-importing countries.

This work can be extended in two main directions. First, in the present model, I conduct the welfare analysis under estimated values of the monetary policy rule coefficients. I do not use optimized monetary policy rule coefficients in which the monetary authority optimally chooses policy rule coefficients that maximizes the aggregate utility of households, as in Bergin et al. (2007). Second, in this work, I examined the welfare implications only for households of introducing oil storage. It would be interesting to also examine the welfare implications for producers of the introduction oil storage.

Table 3.3: Posterior estimates

		Monetary policy rule $r_{\Delta e} > 0$			Monetary policy rule $r_{\Delta e} = 0$		
Parameter	Density	Mean	S.D.	90% HPD.	Mean	S.D.	90% HPD.
$\bar{OS}/\bar{Y}_o$	Gamma	0.28	0.10	[0.12, 0.43]	0.31	0.11	[0.10, 0.48]
κ	Gamma	0.50	0.10	[0.27, 0.72]	0.44	0.11	[0.27, 0.61]
$\hbar$	Beta	0.42	0.12	[0.26, 0.57]	0.42	0.12	[0.27, 0.59]
ϕ_F	Gamma	0.04	0.02	[0.00, 0.06]	0.03	0.02	[0.00, 0.06]
γ_c	Inv. gamma	1.28	0.06	[1.19, 1.38]	1.28	0.07	[1.18, 1.37]
γ_o	Inv. gamma	0.38	0.17	[0.30, 0.46]	0.38	0.38	[0.29, 0.46]
ν	Inv. gamma	0.13	0.09	[0.08, 0.17]	0.13	0.20	[0.08, 0.17]
ξ_w^a	Beta	0.57	0.12	[0.39, 0.75]	0.56	0.13	[0.37, 0.74]
ξ_p^a	Beta	0.79	0.02	[0.76, 0.82]	0.77	0.03	[0.74, 0.81]
χ_w	Beta	0.52	0.27	[0.20, 0.86]	0.51	0.27	[0.19, 0.84]
χ_p	Beta	0.11	0.06	[0.02, 0.20]	0.11	0.06	[0.02, 0.20]
ρ_{R^a}	Beta	0.81	0.04	[0.76, 0.86]	0.80	0.04	[0.74, 0.85]
ρ_{R^b}	Beta	0.71	0.05	[0.63, 0.79]	0.69	0.05	[0.62, 0.77]
r_{Π^a}	Gamma	2.20	0.32	[1.60, 2.78]	2.05	0.33	[1.54, 2.56]
r_{Π^b}	Gamma	2.37	0.36	[1.75, 2.98]	2.29	0.37	[1.69, 2.87]
$r_{\Delta y^a}$	Gamma	0.63	0.12	[0.42, 0.84]	0.60	0.11	[0.40, 0.81]
$r_{\Delta y^b}$	Gamma	0.60	0.12	[0.37, 0.82]	0.56	0.13	[0.35, 0.76]
$r_{\Delta e}^a$	Gamma	0.02	0.01	[0.00, 0.03]	0.00	0.00	[0.00, 0.00]
$r_{\Delta e}^b$	Gamma	0.01	0.01	[0.00, 0.03]	0.00	0.00	[0.00, 0.00]
$\rho_{Z_{os}}$	Beta	0.76	0.05	[0.67, 0.84]	0.75	0.06	[0.66, 0.84]
ρ_{V^a}	Beta	0.49	0.07	[0.38, 0.61]	0.50	0.09	[0.38, 0.60]
ρ_{V^b}	Beta	0.41	0.09	[0.28, 0.54]	0.42	0.10	[0.28, 0.55]
ρ_{Z_a}	Beta	0.26	0.09	[0.14, 0.37]	0.26	0.10	[0.14, 0.38]
ρ_{Z_b}	Beta	0.46	0.10	[0.29, 0.63]	0.48	0.10	[0.31, 0.64]
ρ_{Z_o}	Beta	0.82	0.09	[0.72, 0.93]	0.83	0.11	[0.72, 0.94]
$\rho_{\tilde{\phi}}$	Beta	0.87	0.04	[0.81, 0.92]	0.86	0.04	[0.80, 0.91]
$\sigma_{Z_{os}}$	Inv. gamma	1.83	0.24	[1.42, 2.24]	1.84	0.25	[1.41, 2.27]
$100 * \sigma_{V^a}$	Inv. gamma	1.29	0.22	[0.77, 1.80]	1.16	0.26	[0.76, 1.55]
$100 * \sigma_{V^b}$	Inv. gamma	1.58	0.24	[0.98, 2.12]	1.42	0.24	[0.96, 1.87]
$100 * \sigma_{Z_a}$	Inv. gamma	7.20	1.55	[4.57, 9.73]	6.43	1.63	[4.16, 8.75]
$100 * \sigma_{Z_b}$	Inv. gamma	5.39	1.10	[3.32, 7.30]	4.75	1.07	[3.06, 6.34]
$100 * \sigma_{Z_o}$	Inv. gamma	1.04	0.33	[0.64, 1.42]	0.98	0.42	[0.57, 1.36]
$100 * \sigma_{R^a}$	Inv. gamma	0.17	0.01	[0.15, 0.19]	0.17	0.01	[0.14, 0.19]
$100 * \sigma_{R^b}$	Inv. gamma	0.25	0.02	[0.22, 0.29]	0.25	0.02	[0.22, 0.28]
$100 * \sigma_{\tilde{\phi}}$	Inv. gamma	0.75	0.16	[0.50, 0.99]	0.80	0.17	[0.54, 1.06]

Note: For the description of the parameters, see Table 3.2. Posteriors are obtained from 2 chains of 200,000 draws generated using a random walk Metropolis-Hasting algorithm, where I discard the initial 100,000. The HPD stands for the highest posterior density. S.D. stands for Standard Deviation.

Table 3.4: Conditional (unconditional) welfare gains of oil storage

	Monetary policy rule $r_{\Delta e} > 0$				Monetary policy rule $r_{\Delta e} = 0$			
$\bar{OS}/\bar{Y}_o$	0.10	Est.	0.50	0.75	0.10	Est.	0.50	0.75
Panel A: Simulations with all shocks								
Welfare gain in country a	-0.87	-2.03	-4.03	-5.72	-0.91	-2.10	-4.20	-5.95
	(-0.13)	(-0.30)	(-0.56)	(-0.77)	(-0.12)	(-0.27)	(-0.51)	(-0.70)
Welfare gain in country b	-0.75	-1.75	-3.48	-4.95	-0.79	-1.83	-3.67	-5.22
	(-0.13)	(-0.29)	(-0.55)	(-0.75)	(-0.13)	(-0.29)	(-0.54)	(-0.74)
Welfare gain in country o	11.48	26.55	52.37	74.15	12.09	27.63	55.00	77.73
	(2.23)	(5.09)	(10.02)	(14.36)	(2.35)	(5.29)	(10.53)	(15.09)
Panel B: Simulations with only storage shock, i.e. $\sigma_{Z_{os}} \neq 0$								
Welfare gain in country a	-0.56	-1.36	-2.80	-4.07	-0.58	-1.40	-2.91	-4.23
	(-0.14)	(-0.32)	(-0.60)	(-0.81)	(-0.14)	(-0.32)	(-0.60)	(-0.82)
Welfare gain in country b	-0.52	-1.26	-2.60	-3.77	-0.54	-1.31	-2.73	-3.96
	(-0.14)	(-0.33)	(-0.61)	(-0.83)	(-0.14)	(-0.32)	(-0.61)	(-0.83)
Welfare gain in country o	6.47	15.80	32.64	47.41	6.75	16.33	34.13	49.54
	(1.33)	(3.09)	(5.96)	(8.39)	(1.33)	(3.05)	(5.92)	(8.32)
Panel C: Simulations without oil storage shock, i.e. only $\sigma_{Z_{os}} = 0$								
Welfare gain in country a	-0.31	-0.66	-1.21	-1.63	-0.33	-0.69	-1.27	-1.70
	(0.01)	(0.03)	(0.04)	(0.05)	(0.03)	(0.05)	(0.10)	(0.13)
Welfare gain in country b	-0.23	-0.48	-0.87	-1.16	-0.24	-0.51	-0.93	-1.24
	(0.02)	(0.04)	(0.06)	(0.08)	(0.02)	(0.04)	(0.08)	(0.10)
Welfare gain in country o	4.93	10.62	19.56	26.55	5.25	11.18	20.70	27.99
	(1.49)	(3.32)	(6.46)	(9.15)	(1.61)	(3.56)	(6.98)	(9.88)

Note: Welfare gains are expressed in per cent of consumption compensation. The numbers in parentheses are unconditional welfare gains. Est. corresponds to the estimates of the steady state level in oil inventories $\bar{OS}/\bar{Y}_o$. In the other cases, I fix $\bar{OS}/\bar{Y}_o = 0.10$, 0.50 and 0.75. In Panel A, models are simulated with all shocks. In Panel B, models are simulated with only oil storage shocks, i.e., only $\sigma_{Z_{os}} \neq 0$, while in Panel C, models are simulated without oil storage shocks, i.e. only $\sigma_{Z_{os}} = 0$. All simulations are run using the estimated parameters.

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Appendices

A Appendices of chapter 1

A.1 Data Sources

This appendix lists the time series used to construct the observable variables for the estimation. All series consist of 112 quarterly observations from 1983Q1 to 2010Q4.

Statistics Canada, Cansim Databank, table 383- 0022, millions of chained 2002 dollars seasonally adjusted at annual rate:

1. Real Gross Domestic Product, Statistics.

   Personal expenditure on consumer goods and services, Statistics Canada.

2. Business gross fixed capital formation, Statistics Canada.

3. Business investment in inventories, Statistics.

Statistics Canada, Cansim Cansim Databank, table 176-0064:

5. Exchange rate, Canadian dollars per unit of United States dollar, noon spot rate, average.

Energy Information Administration, International Petroleum, table 11.1b, thousand barrels per day.

6. Oil Production in Canada.

7. Oil Production in World.

Federal Reserve Bank of St Louis, Fred Databank:

8. Civilian Non-institutional Population over 16, FRED, identification number: CANLFTOTQDSMEI.

9. Personal Consumption Expenditures Deflator (2002=1000) for Canada, Statistics Canada, Cansim Databank, table 380-0003.

10. Personal Consumption Expenditures Deflator (2009=1000) for USA, FRED, identification number: DPCERD3Q086SBEA.

11. Crude Oil Prices in Dollars per Barrel, West Texas Intermediate, identification number: OILPRICE.

Personal Transformations:

12. Real Per Capita Consumption = (2)/(9)/(8).

13. Real Per Capita Investment = [(3)+(4)]/(9)/(8).

14. Per Capita Oil Production in Canada= (6)/(8).

15. Per Capita Oil Production in the Rest Of World= (7-6)/(8).

16. Real Exchange Rate = (5*10)/(9).

17. Real Price of Oil = (11)/(10).

A.2 The Log-linearized model

Variables with hats correspond to their log-deviation from their steady state level.

1. Euler equation for consumption:

$$\hat{\Lambda}_t = \frac{1}{(1-\hbar)(1-\hbar\beta)}\left(-(\hat{C}_t - \hbar\hat{C}_{t-1}) + \hbar\beta(\hat{C}_{t+1} - \hbar\hat{C}_t)\right)$$
$$\hat{\Lambda}_t = E_t\hat{\Lambda}_{t+1} + \hat{r}_t$$

2. Labor supply:

$$-\hat{\Lambda}_t + \left(\frac{N}{1-N}\right)\hat{N}_t = \hat{w}_t$$

3. Log-linearized capital first-order condition

$$\hat{r}_t = (1-\beta(1-\delta))\,E_t\hat{r}^k_{s,t+1} + \beta(1-\delta)E_t\hat{q}_{s,t+1} - \hat{q}_{s,t} \quad \text{for} \quad s \in \{o,d\}$$

4. Log-linearized investment first-order condition

$$\hat{q}_{s,t} + A_{I,t} = \kappa_s\left(\Delta\hat{I}_{s,t} - \beta E_t\Delta\hat{I}_{s,t+1}\right) \quad \text{for} \quad s \in \{o,d\}$$

5. Capital accumulation:

$$\hat{K}_{s,t+1} = (1-\delta)\hat{K}_{s,t} + \delta\hat{I}_{s,t} + \delta A_{I,t} \quad \text{for} \quad s \in \{o,d\}$$

6. Uncovered interest parity condition:

$$\hat{r}_t = \hat{r}^\star_t + \hat{\Phi}_{B^\star_t} + E_t\Delta\hat{s}_{t+1}$$

7. Let $d^\star_t = -\frac{e_t B^\star_t}{P_{Y,t}Y_t}$. The Risk premium of borrowing abroad is:

$$\hat{\Phi}_{B^\star_t} = \phi_{b^\star}\left(\frac{eD^\star}{P_Y Y}\right)\hat{d}^\star_t$$

8. Final good composition:

$$\begin{aligned}\hat{Y}^z_{d,t} &= \hat{Z}_t - \vartheta \hat{p}_{d,t} \\ \hat{Y}_{m,t} &= \hat{Z}_t - \vartheta \hat{p}_{m,t} \\ 0 &= \omega \hat{p}_{d,t} + (1-\omega)\hat{p}_{m,t}\end{aligned}$$

9. Production sector of crude oil:

$$\hat{Y}_{o,t} = \hat{A}_{o,t} + \left(\tfrac{R^k_o K_o}{P_o Y_o}\right)\hat{K}_{o,t} + \left(\tfrac{P_X X}{P_o Y_o}\right)\hat{X}_t$$

$$\hat{w}_{o,t} = \hat{s}_t + \hat{p}^{\star}_{o,t} - \frac{1}{\mu}\hat{N}_{o,t} + \frac{1}{\mu}\hat{Y}_{o,t} + (1 - \frac{1}{\mu})\hat{A}_{o,t}$$

$$\hat{p}_{X,t} = \hat{s}_t + \hat{p}^{\star}_{o,t} - \frac{1}{\mu}\hat{X}_t + \frac{1}{\mu}\hat{Y}_{o,t} + \left(1 - \frac{1}{\mu}\right)\hat{A}_{o,t}$$

$$\hat{p}_{o,t} = \hat{s}_t + \hat{p}^{\star}_{o,t}$$

10. Supply of oil reserves:

$$\hat{X}_t = 0$$

11. Production sector of domestic good:

$$\begin{aligned}
\hat{Y}_{d,t} &= \hat{A}_{d,t} + + \left(\frac{W_d N_d}{P_d Y_d}\right) \hat{N}_{d,t} \left(\frac{R^k_d K_d}{P_d Y_d}\right) \hat{K}_{d,t} + \left(\frac{P_o O}{P_d Y_d}\right) \hat{O}_t \\
\hat{w}_{d,t} &= \hat{p}_{d,t} - \frac{1}{\nu}\hat{N}_{d,t} + \frac{1}{\nu}\hat{Y}_{d,t} + (1 - \frac{1}{\nu})\hat{A}_{d,t} \\
\hat{r}^k_{d,t} &= \hat{p}_{d,t} - \frac{1}{\nu}\hat{K}_{d,t} + \frac{1}{\nu}\hat{Y}_{d,t} + (1 - \frac{1}{\nu})\hat{A}_{d,t} \\
\hat{p}_{o,t} &= \hat{p}_{d,t} - \frac{1}{\nu}\hat{O}_t + \frac{1}{\nu}\hat{Y}_{d,t} + (1 - \frac{1}{\nu})\hat{A}_{d,t}
\end{aligned}$$

12. Price of imported good:

$$\hat{p}_{m,t} = \hat{s}_t + \zeta_t$$

13. Foreign oil demand:

$$\hat{O}^\star_t = \hat{Y}^\star_t - \nu \hat{p}^\star_{o,t}$$

14. Exports of domestic good:

$$\hat{Y}^{\mathrm{x}}_{d,t} = \hat{Y}^\star_t - \vartheta_{\mathrm{x}}(\hat{p}_{d,t} - \hat{s}_t)$$

15. Precautionary demand of crude oil

$$\hat{OS}_t = \theta \left[\beta(E_t \hat{p}^\star_{o,t+1} - \hat{r}^\star_t) - \hat{p}^\star_{o,t}\right] + \hat{Z}_{os,t}$$

16. Net exports of oil:

$$\hat{Y}_{o,t} = \frac{O}{Y_o}\hat{O}_t + \frac{O^{\mathrm{x}}}{Y_o}\hat{O}^{\mathrm{x}}_t$$

17. Net foreign asset dynamic:

$$\begin{aligned}\left(\frac{1}{\Phi_{B^\star}R^\star}\right)\left(\frac{eD^\star}{P_Y Y}\right)\hat{d}^\star_t &= \left(\frac{1}{\phi_{B^\star}R^\star}\right)\left(\frac{eD^\star}{P_Y Y}\right)(\hat{\Phi}_{B^\star,t}+\hat{r}^\star_t)\\ &+\left(\frac{eD^\star}{P_Y Y}\right)\left(\Delta\hat{s}_t-\Delta\hat{p}_{Y,t}-\Delta\hat{Y}_t+\hat{b}^\star_{t-1}\right)\\ &-\left(\frac{eP^\star_o O^{\mathrm{x}}}{P_Y Y}\right)\left(\hat{p}_o+\hat{O}^{\mathrm{x}}_t-\hat{p}_{Y,t}-\hat{Y}_t\right)\\ &-\left(\frac{P_d Y^{\mathrm{x}}_d}{P_Y Y}\right)\left(\hat{p}_d+\hat{Y}^{\mathrm{x}}_d-\hat{p}_{Y,t}-\hat{Y}_t\right)\\ &+\left(\frac{P_m Y_m}{P_Y Y}\right)\left(\hat{p}_{m,t}+\hat{Y}_m-\hat{p}_{Y,t}-\hat{Y}_t\right)\end{aligned}$$

18. Real gross domestic product (GDP):

$$\hat{Y}_t = \left(\frac{P.C}{P_Y Y}\right)\hat{C}_t+\left(\frac{P.I}{P_Y Y}\right)\hat{I}_t+\left(\frac{eP^\star_o O^{\mathrm{x}}}{P_Y Y}\right)\hat{O}^{\mathrm{x}}_t+\left(\frac{P_d Y^{\mathrm{x}}_d}{P_Y Y}\right)\hat{Y}^{\mathrm{x}}_{d,t}-\left(\frac{P_m Y_m}{P_Y Y}\right)\hat{Y}_{m,t}$$

19. GDP deflator

$$\hat{p}_{Y,t} = \left(\frac{eP^\star_o O^{\mathrm{x}}}{P_Y Y}\right)\hat{p}_{o,t}+\left(\frac{P_d Y^{\mathrm{x}}_d}{P_Y Y}\right)\hat{P}_{d,t}-\left(\frac{P_m Y_m}{P_Y Y}\right)\hat{p}_{m,t}$$

20. Markets clearing:

$$\begin{aligned}
\hat{N}_t &= \left(\frac{N_o}{N}\right)^{\frac{\varsigma+1}{\varsigma}} \hat{N}_{o,t} + \left(\frac{N_d}{N}\right)^{\frac{\varsigma+1}{\varsigma}} \hat{N}_{d,t} \\
\hat{w}_{o,t} &= \hat{w}_t + \frac{1}{\varsigma}(\hat{N}_{o,t} - \hat{N}_t) \\
\hat{w}_{d,t} &= \hat{w}_t + \frac{1}{\varsigma}(\hat{N}_{d,t} - \hat{N}_t) \\
\hat{I}_t &= \left(\frac{I_o}{I}\right) \hat{I}_{o,t} + \left(\frac{I_d}{I}\right) \hat{I}_{d,t} \\
\hat{Y}_{d,t} &= \left(\frac{Y_d^z}{Y_d}\right) \hat{Y}_{d,t}^z + \left(\frac{Y_d^{\text{x}}}{Y_d}\right) \hat{Y}_{d,t}^{\text{x}} \\
\hat{Z}_t &= \left(\frac{C}{Z}\right) \hat{C}_t + \left(\frac{I}{Z}\right) \hat{I}_t \\
\left(\frac{OS}{Y_o^\star}\right)(\hat{OS}_t - \hat{OS}_{t-1}) &= \hat{Y}_{o,t}^\star + \left(\frac{Y_o}{Y_o^\star}\right) \hat{Y}_{o,t} - \left(\frac{O^\star}{Y_o^\star}\right) \hat{O}_t^\star - \left(\frac{O}{Y_o^\star}\right) \hat{O}_t
\end{aligned}$$

21. Exogenous processes:

$$\hat{\lambda}_t = \rho_\lambda \hat{\lambda}_{t-1}^\star + \epsilon_{\lambda,t}$$

where $\lambda = \{Y_o^\star, Y^\star, Z_{os}, A_o, A_d, A_I, \zeta\}$. The interest rate in the foreign economy, which is exogenous to the domestic economy, is determined by $\hat{r}_t^\star = E_t \hat{Y}_{t+1}^\star - \hat{Y}_t^\star$.

B Appendices of chapter 2

B.1 Fixed effects quasi-maximum likelihood estimator

Consider eliminating the individual fixed effects from the first difference model:

$$\Delta \mathbb{Y}_{i,t} = \Phi \Delta \mathbb{Y}_{i,t-1} + \Delta \epsilon_{i,t} \tag{59}$$

where the first subscript $i \in \{1, .., N\}$ refers to the cross-sectional dimension and the second subscript $t \in \{1, .., N\}$ refers to the time dimension of the panel of observations. The observations $\mathbb{Y}_{i,t}$ and the disturbances $\epsilon_{i,t}$ are $m \times 1$ vectors. Let $\xi_{i,t} = \mathbb{Y}_{i,t} - \mu_i$ for t=2,...,T, with $\Delta\mathbb{Y}_{i,1} = -(I_m - \Phi)\xi_{i,0} + \epsilon_{i,1}$. We need the following assumptions:

1. The disturbances, $\epsilon_{i,t}$, are independently and identically distributed (i.i.d.) for all i and t with $E(\epsilon_{i,t}) = 0$ and $Var(\epsilon_{i,t}) = \Omega_\epsilon$ being a positive definite matrix.
2. The initial deviations, $\xi_{i,0}$, are i.i.d. across i, with zero means and the constant nonsingular variance $E(\xi_{i,0}\xi'_{i,0}) = \Psi_{\xi_{i,0}}$.
3. The following moment restrictions are satisfied: $E(\kappa_{i,0}u'_{i,0}) = 0$, $E(\kappa_{i,0}\Delta\epsilon'_{i,t}) = 0$ for t=2,...,T, where $\kappa_{i,0} = (I_m - \Phi)\xi_{i,0}$.
4. The second moments of the cross-product matrix $E(r_{i,t}r'_{i,t})$, t=2,...,T, with $r_{i,t} = (\Delta\mathbb{Y}'_{i,1}, \Delta\epsilon'_{i,t})'$ exist.

If the error terms and the initial observation are normally distributed, the quasi-maximum likelihood estimator is obtained by maximizing the log-likelihood function derived from the joint density function of the vector $\Delta\mathbb{Y}_i = \text{vec}(\Delta\mathbb{Y}_{i,1}, ..., \Delta\mathbb{Y}_{i,T})$. The log-likelihood function is given by:

$$\mathcal{L}(\rho) = -\frac{mNT}{2}\log(2\pi) - \frac{N}{2}\log|\Sigma_{\Delta_\eta}| - \frac{N}{2}tr\left((R'\Sigma_{\Delta_\eta}^{-1}R)\frac{1}{N}\sum_{i}^{N}\Delta\mathbb{Y}_i\Delta\mathbb{Y}'_i\right)$$

where $\rho = (vec(\Phi)', vec(\Omega_\epsilon)', vec(\Psi)')'$ and $\Psi = (I_m - \Phi)\Psi_{\xi_{i,0}}(I_m - \Phi') + \Omega_\epsilon$ is the variance-covariance matrix of the initial observation $\Delta\mathbb{Y}_{i,1}$, which is not restricted to be covariance stationary. The matrix Σ_{Δ_η} has a block tridiagonal structure, with $-\Omega_\epsilon$ on the first lower and upper off-diagonal blocks, and $2\Omega_\epsilon$ on all but first (1,1) diagonal blocks. The matrix R, of dimension $mT \times mT$, has I_m elements on the diagonal blocks, and Φ on the first lower off-diagonal blocks. Formally

$$\Sigma_{\Delta_\eta} = \begin{pmatrix} \Psi & -\Omega_\epsilon & & & 0 \\ -\Omega_\epsilon & 2\Omega_\epsilon & -\Omega_\epsilon & & \\ & \ddots & \ddots & \ddots & \\ & & -\Omega_\epsilon & 2\Omega_\epsilon & -\Omega_\epsilon \\ 0 & & & -\Omega_\epsilon & 2\Omega_\epsilon \end{pmatrix} \text{ and } R = \begin{pmatrix} I_m & & & 0 \\ -\Phi & I_m & & \\ & \ddots & \ddots & \\ 0 & & -\Phi & I_m \end{pmatrix}$$

B.2 Impulse Response functions and Variance decomposition

Let (B,Φ) be any value of structural parameters such that B satisfies $\Omega_\epsilon = BB'$. Then, the impulse response of the i-th variable to the j-th structural shock at finite horizon h corresponds to the element in row i and column j of the matrix

$$\Theta_h = J\Phi^h J'B$$

where $J = \begin{bmatrix} I_M & 0 & ... & 0 \end{bmatrix}$ so that J is an $M \times Mp$ dimensional matrix. In this particular case, $p = 1$ and J is the identity matrix I_M. The proportion of the h-step forecast error variance of the i-th variable accounted for by innovations in the j-th variable is

$$\omega_{ij,h} = \sum_{k=0}^{h-1} \left(e_i \Theta_k e_j'\right)^2 / \left(\sum_{k=0}^{h-1} \Theta_k \Theta_k'\right)_{ii}$$

where e_j is the j-th column of the identity matrix I_M and the subscript ii refers to that element of the matrix.

B.3 Data sources and variable definitions

1. World oil production (thousands of barrels per day). Source: U.S. Energy Information Administration.

2. Real price of oil: obtained by the spot price of oil deflated by the U.S. Consumer Price Index. The spot price of oil is measured by West Texas Intermediate [OILPRICE] in dollars per barrel. Source: Federal Reserve Bank of St. Louis, with the series names in brackets.

3. Foreign aggregate demand for manufacturing products, $Y^{\star}_{w,t}$, is measured by the G17 Industrial Production Index. Source: Federal Reserve Bank of St. Louis.

4. Labor input by manufacturing industries: obtained by chained-Fisher aggregation of hours worked by all workers, classified by education, work experience, and class of workers (paid workers versus self-employed and unpaid family workers) using hourly compensation as weights. Source: Statistics Canada (Cansim Table 383-0022).

5. Relative price of labor is the ratio of labor compensation to the Fisher volume index of labor input deflated by Consumer Price Index. Labor compensation consists of all payments in cash or in kind made by domestic producers to workers for services rendered. It includes the salaries and supplementary labor income of paid workers, plus an imputed labor income of self-employed workers. Source: Statistics Canada (Cansim Table 383-0022). The Industrial Product Price Index is extracted from Cansim Table 329-0057.

6. Relative price of capital is the ratio of capital cost to the Fisher volume index of capital input, deflated by Consumer Price Index. Capital cost represents the surplus profits, depreciation, rent, and net interest intended as compensation to the owners of capital. Capital input measures the services derived from the stock of fixed reproducible business assets (equipment and structures), inventories, and land. It is obtained by chained-Fisher aggregation of capital stocks using the cost of capital to determine weights. Source: Statistics Canada (Cansim Table 383-0022).