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Macroeconomic Impacts of Fiscal Policy Shocks in the UK: A DSGE Analysis[1]

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Abstract

This paper develops and estimates a new-Keynesian dynamic stochastic general equilibrium (DSGE) model for the analysis of fiscal policy in the UK. We find that government consumption and investment yield the highest GDP multipliers in the short-run, whereas capital income tax and public investment have dominating effect on GDP in the long-run. When nominal interest rate is at the zero lower bound, consumption taxes and public consumption and investment are found to be the most effective fiscal instruments throughout the analysed horizon, and capital and labour income taxes are established to be the least effective. The paper also shows that the effectiveness of fiscal policy decreases in a small open-economy scenario and that nominal rigidities improve effectiveness of public spending and consumption taxes, whereas decrease that of income taxes.

Key words: fiscal policy, DSGE model, UK economy

JEL Classification: E32, E63

1 Introduction

Fiscal policy has been used extensively for a long time to stabilise the economy and to foster more efficient, fairer and equitable societies. This is among the reasons why there exists a long tradition in the analysis of fiscal policy in the UK. It was at the heart of the revenue neutral tax exercise of Ramsey (1927) and macroeconomic analysis of Keynes (1936). Following these works was a path-breaking analysis on the optimal tax rule by Mirrlees (1971). In practical terms, the Institute of Fiscal Studies published Meade (1978) on the burden of direct taxes and Mirrlees *et al.* (2010) on both direct and indirect taxes. Whereas the macro impacts of fiscal policy have been studied using various analytical frameworks (Holly and Weale, 2000; NIESR), the burden of direct and indirect taxes on households in terms of the Hicksian equivalent and compensating variations in the welfare taxes to households have been measured using a general equilibrium analysis (Bhattarai and Whalley, 1999). Tax-benefit models have been used to measure the impacts of taxes and benefits on the labour supply (Brewer *et al.*, 2009). The Green Budgets of the IFS have regularly reported on the impacts of taxes on economic growth, inequality, and welfare. The conclusions of the most of above studies are mainly derived from comparative static analysis. This paper applies a dynamic stochastic general equilibrium model (DSGE) for an extensive analysis of the dynamics implied by fiscal policy instruments and multiplier effects, both on the revenue and spending side of the UK's government.

The UK economy has been growing secularly in the past several centuries but is frequently disturbed by transitional shocks arising either from the demand or supply side, or from both sides of the economy. The dynamic stochastic general equilibrium models aim to assess the impacts of such shocks on the transitional dynamics of the economy. Despite a fairly large body of the literature on DSGE models, few studies analyse the impacts of such shocks in the UK. Doing so are among others Batini *et al.* (2003), the Bank of England Quarterly Model (BEQM) by Harrison *et al.* (2005), DiCecio and Nelson (2007), Faccini *et al.* (2011), Gorts and Tsoukalas (2011), Harrison and Oomen (2010), and Millard (2011).[1] The analysis of fiscal policy is however ignored by the above papers.[2] We fill this gap through an extensive analysis of business cycle effects of fiscal policy in the UK.

The fiscal stimulus, a growing debt-to-GDP ratio and the budget deficit have brought much attention in the recent years. Some of the developments in the analysis of fiscal policy by means of the DSGE models include: Coenen and Straub (2005), Lopez-Salido

[1] In the context of theoretical model specifications, DiCecio and Nelson (2007) estimate the closed-economy model of Christiano *et al.* (2005) on the UK data. Harrison and Oomen (2010) estimate the open-economy model similar to Christiano *et al.* (2005), Smets and Wouters (2003), and Adolfson *et al.* (2008). Faccini *et al.* (2011) implement a search and matching framework into a labour market of a medium-size DSGE model. Millard (2011) extends the Harrison and Oomen (2010) model and incorporates three consumption goods: non-energy output, petrol and utilities. Gorts and Tsoukalas (2011) fit two separate sectors that produce consumption and investment good into a medium-size DSGE model.

[2] The only exception to this are Harrison *et al.* (2005) and Harrison and Oomen (2010) who analyse only the effects of government consumption shocks.

and Rabanal (2006), Gali *et al.* (2007), Forni *et al.* (2009), Ratto *et al.* (2009), Cogan *et al.* (2010), Leeper *et al.* (2010b), Christiano *et al.* (2011), Eggertson (2011), Drautzburg and Uhlig (2011), Coenen *et al.* (2013). In the context of fiscal policy, models by Coenen and Straub (2005) and Gali *et al.* (2007) focus primarily on the implications of government spending, and deficit is adjusted using lump-sum taxes. Our paper can be easily distinguished from Forni *et al.* (2009), Ratto *et al.* (2009), Lopez-Salido and Rabanal (2006), in the context of fiscal policy specification, its granularity, or the analysis conducted. Coenen *et al.* (2013) focus on the implications of European Economic Recovery Plan (EERP), whereas Cogan *et al.* (2010) and Drautzburg and Uhlig (2011) on the the American Recovery and Reinvestment Act (ARRA). Christiano *et al.* (2011) and Eggertson (2011) study the effects of fiscal stimulus at the zero lower bound. The fiscal policy setup in this paper follows that in Leeper *et al.* (2010b). The models used for the analysis differ however substantially. In contrast to Leeper *et al.* (2010b) we incorporate the interaction between the fiscal and monetary policies. We also make the distinction between productive and non-productive government spending, introduce into the model non-Ricardian households and nominal frictions in prices and wages. Finally, the model also clearly differs from the long-run growth analysis contained in multi-household and multi-sector dynamic general equilibrium models with perfect foresight as presented in Bhattarai (2007) and staggered-price dynamic general equilibrium model with overlapping generations in Ascari and Rankin (2013).

This study aims to address several questions in the context of UK economy: (1) what are the qualitative and quantitative effects of distortionary taxation (on consumption and on labour and capital income) and government expenditure (consumption, investment and transfers) on the key macroeconomic variables? (2) how in the historical context has fiscal policy been used in controlling for debt and the output gap? (3) which nominal and real frictions present in the economy are crucial for determining the fiscal policy effectiveness? (4) what is the role of the open-economy setup and the imposition of the zero lower bound on the nominal interest rate for the fiscal policy effectiveness?

To answer the above questions, we use a new-Keynesian DSGE model estimated with Bayesian methods on a linearly detrended quarterly macro time series ranging from 1987:Q2 to 2011:Q1.

The results indicate that government consumption and investment shocks are the most stimulating in the short-run (the impact multiplier totals 0.97 and 1.08 respectively, thus on impact a 1% increase in public consumption leads to a 0.97% increase in GDP and a 1% increase in public investment leads to a 1.08% increase in GDP). In the longer horizon the capital income tax and the public investment shock result in the highest multipliers (the present value cumulative 5 year multiplier totals -0.52 and 0.72 respectively). The government consumption impact multiplier obtained in this study is higher than the average impact multiplier of 0.89 obtained in the empirical study of fiscal policy in the UK conducted by Canova and Pappa (2011). The government transfers shock results in a relatively lower multiplier when compared to the remaining fiscal policy instruments. The consumption and labour income tax shocks result in moderate multipliers in the short and longer horizon ranging from (-0.17) to (-0.56). Additionally, we find public and private consumption to be Edgeworth substitutes. Also under the open-economy scenario public consumption and investment remain the most stimulating instruments in the short-term, public investment and capital income taxes in the longer term and transfers yield the smallest multipliers when compared with other fiscal policy instruments. When the nominal interest rate is at the zero lower bound the effectiveness of consumption taxes and public expenditure instruments increases, but decreases that of capital and labour income taxes.

We also show that non-Ricardian households make the fiscal policy more effective, and that nominal rigidities improve effectiveness of public spending and consumption taxes, whereas decrease effectiveness of income taxes.

Finally, the parameter estimates indicate that public investment, consumption and capital taxes play a decisive role in controlling for the government debt over the sample period. Additionally, capital income tax rates and government investment characterise significant procyclical responses to GDP. In contrast, the response of labour income taxes to aggregate output and debt is relatively modest.

This paper is organised as follows. The next section presents a theoretical model of the UK economy. Section three outlines the necessary information on the solution and estimation methods along with the discussion of calibrated parameters, priors, posterior estimates, and the role of frictions. In section four, we discuss the impulse-responses and present value multipliers implied by the fiscal policy shocks. In section five we extend model to other scenarios including the public consumption in the utility function, opening the economy for international trade and setting the zero lower bound on the nominal interest rate as appropriate to the recent experience of the monetary policies. Section six concludes.

2 Specification of a DSGE model for fiscal policy analysis

The model economy is populated by a continuum of households indexed by ι, where, following Campbell and Mankiw (1989) and Mankiw (2000), a share ϑ of them comprise non-Ricardian or rule-of-thumb consumers (indexed by m) who do not have access to the financial and capital markets and simply consume their total disposable income stemming from labour and transfers. The remaining proportion $(1-\vartheta)$ comprise Ricardian consumers (indexed by n), who anticipate and internalise the government's tax and borrowing behaviour and maximise their life-time utility subject to their intertemporal budget constraint. They own the entire capital stock of the economy and possess access to the financial and capital asset markets. Firms produce differentiated goods, choose labour and capital inputs and set prices similarly to the method proposed by Calvo (1983).

The monetary authority sets the nominal interest rate according to a Taylor rule, whereas the fiscal authority determines a set of policy instruments' rules in which they respond to cyclical changes in output and debt. This model features a number of real and nominal frictions as found in Smets and Wouters (2003) and Christiano *et al.* (2005).

2.1 Preferences of Ricardian households

The utility function of each Ricardian household is represented by:

$$E_0 \sum_{t=0}^{\infty} \varepsilon_t^B \beta^t \left(\frac{\left(C_{r,t}^n - H_{r,t}\right)^{1-\sigma_c}}{1-\sigma_c} - \frac{\varepsilon_t^L}{1+\sigma_l} \left(L_{r,t}^n\right)^{1+\sigma_l} \right) \tag{1}$$

where the subjective discount factor β satisfies $0 < \beta < 1$; $\sigma_l \geqslant 0$ denotes the inverse Frisch elasticity of labour $\left(L_{r,t}^n\right)$; $\sigma_c > 0$ denotes the inverse of the intertemporal elasticity of substitution in consumption $\left(C_{r,t}^n\right)$; and $H_{r,t}$ denotes the external habit variable such that $H_{r,t} = hC_{r,t-1}$, where $0 < h < 1$. ε_t^B represents the preference shock and ε_t^L represents the shock to the labour supply. The shocks follow:

$$\ln \varepsilon_t^B = \rho_B \ln \varepsilon_{t-1}^B + \eta^B, \ and \ \ln \varepsilon_t^L = \rho_L \ln \varepsilon_{t-1}^L + \eta^L,$$

where η^B and η^L are i.i.d. processes with standard deviations σ_B, and σ_L. Each Ricardian household maximises its lifetime utility subject to the flow budget constraint, which simply states that the household's total expenditure on consumption $\left(C_{r,t}^n\right)$, investment in physical capital $\left(I_{r,t}^n\right)$ and accumulation of one-period government bonds $\left(b_{r,t}^n\right)$ must equal the household's total disposable income $\left(inc_{r,t}^n\right)$.

$$b_{r,t}^n - \frac{b_{r,t-1}^n}{\pi_t} + I_{r,t}^n + (1+\tau_t^c)\, C_{r,t}^n = inc_{r,t}^n \tag{2}$$

where π_t denotes the gross inflation rate. The presence of consumption tax τ_t^c implies that the wedge arises between the consumer and producer prices. We follow the developments of Woodford (1996), and subsequently Erceg *et al.* (2000) and Christiano *et al.* (2005) and assume complete markets for the state contingent claims in consumption and in assets but not in labour. Consequently, consumption and asset's holdings are equal across all Ricardian households.

The total real disposable income of each Ricardian household consists of: (1) the after tax labour income $\left(1-\tau_t^l\right) w_{r,t}^n L_{r,t}^n$, where $w_{r,t}^n$ represents the real wage rate, and τ_t^l is the effective labour income tax rate; (2) the after tax capital income $\left(1-\tau_t^k\right) r_{k,t} u_t^n K_{r,t-1}^n$, where $r_{k,t}$ denotes the real rate of return on capital, $K_{r,t-1}^n$ denotes the physical stock of capital, and u_t^n is the capital utilisation rate, and τ_t^k is the effective capital income tax rate; [3] (3) the income from profits $Prof_{r,t}^n$; (4) lump-sum government transfers (TR_r^n), (5) the interest income from the bond holdings $\left(\frac{(R_{t-1}-1)b_{r,t-1}^n}{\pi_t}\right)$, where R_{t-1} denotes the nominal interest rate on a one-period bond.

Physical capital accumulates in accordance with the following[4]:

[3] Each household while setting the level of capital utilisation rate incurs a cost equal to $\left(1-\tau_t^k\right) a(u_t^n) K_{r,t-1}^n$. We assume that $\frac{a''(u_t^n)}{a'(u_t^n)} = \kappa$. Consequently, only the dynamics of the model depend on the parameter κ. In the steady state $u = 1$.

[4] The omission of the subscript n reflects our assumption of complete markets for the state contingent claims in assets which implies that asset's holdings are the same among households.

$$K_{r,t} = (1-\delta_k)K_{r,t-1} + F_t\left(I_{r,t}, I_{r,t-1}\right) \tag{3}$$

where as in Schmitt-Grohe and Uribe (2006): $F_t\left(I_{r,t}, I_{r,t-1}\right) = \left[1 - S\left(\frac{\varepsilon_t^I I_{r,t}}{I_{r,t-1}}\right)\right] I_{r,t}$.[5] Ricardian households maximise their utility subject to the flow budget constraint, the capital accumulation function, and the demand for labour they face from the labour unions.

First-order conditions of Ricardian households

The combination of first-order conditions with respect to consumption and bonds results in a standard Euler equation:

$$U_{r,c,t} = E_t\left[\frac{R_t}{\pi_{t+1}} \frac{(1+\tau_t^c)}{\left(1+\tau_{t+1}^c\right)} \beta U_{r,c,t+1}\right] \tag{4}$$

where $U_{r,c}$ denotes the marginal utility of consumption: $U_{r,c,t} = \varepsilon_t^B \left(C_{r,t} - H_{r,t}\right)^{-\sigma_c}$. The left-hand side of equation (4) represents the marginal utility cost of investing in bonds (to invest household sacrifices current consumption). The right-hand side implies that investing in bonds provides an *ex ante* real rate of return represented by $\frac{R_t}{\pi_{t+1}}$.

The first-order condition with respect to the capital utilisation rate, presented in equation (5), indicates that the real rental rate net of capital taxes is equal to the marginal cost of capital utilisation:

$$\left(1-\tau_t^k\right) r_{k,t} = a'(u_t) \tag{5}$$

A higher rate of return on capital or a lower capital tax rate implies a higher utilisation rate up to the point where extra benefits are equal to extra costs. Equation (5) implies also that the utilisation rate is equal across all the Ricardian households ($u^n = u$).

The first-order condition with respect to capital links the shadow price of capital (Q) between two periods:

$$Q_t = \frac{E_t \pi_{t+1}}{R_t} E_t\left[Q_{t+1}(1-\delta_k) + \left(1-\tau_{t+1}^k\right)\left(r_{k,t+1}u_{t+1}\right) - a(u_{t+1})\right] \tag{6}$$

Equation (6) implies that price of capital is simply a present value of future net income from capital holdings. The price of capital depends positively on the expected price of capital, real rental rate and the utilisation rate. It depends negatively on the real *ex ante* interest rate, expected capital taxes and the capital utilisation cost.

The first-order condition with respect to investment is presented in equation (7). The left-hand side of the equation represents the marginal utility cost of investment in physical capital, which is equal to the marginal utility cost of investment in bonds.[6] An

[5] $S\left(\frac{\varepsilon_t^I I_{r,t}}{I_{r,t-1}}\right) = \frac{\phi_k}{2}\left(\frac{\varepsilon_t^I I_{r,t}}{I_{r,t-1}} - 1\right)^2$ denotes a function specifying the investment adjustment cost. The function possesses the following properties: $S\left(1\right) = S'\left(1\right) = 0$, and $S''\left(1\right) = \phi_k > 0$, where ε_t^I is an investment efficiency shock which follow: $\ln \varepsilon_t^I = \rho_I \ln \varepsilon_{t-1}^I + \eta^I$ where η^I is an i.i.d. process with standard deviation σ_I.

[6] λ_t is a Lagrange multiplier on the budget constraint and is equal to: $\lambda_t = \frac{U_{r,c,t}}{\left(1+\tau_t^c\right)}$.

increase in investment by one unit at time t leads to an increase in the value of capital by $Q_t F_t' (I_{r,t}, I_{r,t-1})$ in period t, and by $Q_{t+1}\beta F_{t+1}' (I_{r,t+1}, I_{r,t})$ in period $t+1$.[7]

$$\lambda_t = Q_t \lambda_t F_t' (I_{r,t}, I_{r,t-1}) + \beta E_t \left[Q_{t+1} \lambda_{t+1} \beta F_{t+1}' (I_{r,t+1}, I_{r,t}) \right] \tag{7}$$

2.1.1 Non-Ricardian households

Non-Ricardian households do not save; they simply consume current, after tax income, which comprises transfers from the government, and after tax labour income.

$$(1 + \tau_t^c) C_{nr,t}^m = \left(1 - \tau_t^l\right) w_{nr,t}^m L_{nr,t}^m + TR_{nr,t}^m \tag{8}$$

2.2 Wage setup

In creating the wage setup, we follow Erceg *et al.* (2000) and Benigno and Woodford (2006). We assume the existence of a competitive labour aggregator, whose only task is to transform households' differentiated labour into a composite labour good. The composite labour is subsequently supplied to monopolistic producers. The aggregator takes every household's wage, W_t^ι, as given and maximises profit represented by:

$$Prof_{L,t} = W_t N_t - \int_0^1 W_t^\iota L_t^\iota d\iota \tag{9}$$

where L_t^ι denotes the amount of labour supplied by a household ι to the union, W_t is the aggregate wage index, and N_t denotes the labour index: $N_t = \left[\int\limits_0^1 (L_t^\iota)^{\frac{\nu-1}{\nu}} d\iota \right]^{\frac{\nu}{\nu-1}}$, where $\nu > 0$ denotes the elasticity of substitution among the differentiated labour inputs. Profit maximisation results in the demand for the labour of a household ι:

$$L_t^\iota = \left(\frac{W_t^\iota}{W_t} \right)^{-\nu} N_t \tag{10}$$

The aggregate wage index is given by: $W_t = \left[\int_0^1 (W_t^\iota)^{1-\nu} d\iota \right]^{\frac{1}{1-\nu}}$.

Ricardian households set nominal wages similarly to a staggered-price mechanism in Calvo (1983). In particular, within each period a fraction of forward-looking households (ϖ_w) are unable to adjust their wage rate. These households simply follow the partial indexation rule and set the wage in accordance to: $W_{r,t}^\iota = \pi_{t-1}^{\gamma_w} W_{r,t-1}^\iota$. The remaining fraction of households $(1 - \varpi_w)$ that are able to set their nominal wages, maximise their utility subject to the budget constraint and the demand for labour from the labour unions.[8] The maximisation results in equation (11).

[7] Note that $F_t'(1) = 1$ and $F_{t+1}'(1) = 0$, thus the steady-state does not depend on the parameter ϕ_k and $Q = 1$.

[8] All households that are able to set their nominal wage, choose the same wage (for evidence see Christiano *et al.* 2005).

$$E_t \sum_{l=0}^{\infty} (\beta \varpi_w)^l L^n_{r,t+l} \lambda_{t+l} \left\{ \frac{\tilde{W}_{r,t} X_{tl}}{P_{t+l}} \frac{U_{r,c,t+l}}{\left(1+\tau^c_{t+l}\right)} - \frac{\nu}{(1-\nu)} \frac{U^n_{r,l,t+l}}{\left(1-\tau^l_{t+l}\right)} \right\} = 0 \quad (11)$$

where $X_{tl} = \pi_t * \pi_{t+1} * ... * \pi_{t+l-1}$ for $l \geqslant 1$ and $X_{tl} = 1$ for $l = 0$ as in Altig *et al.* (2005). $\tilde{W}_{r,t}$ denotes the wage rate set by households that can re-optimise their wages at time t. As shown in Christiano *et al.* (2005) and Erceg *et al.* (2000) all households that can re-optimise their wage choose the same wage rate $\tilde{W}_{r,t}$, therefore lack of indexation n[9]. The first-order condition implies that Ricardian households set their wages so that the present value of the marginal utility of income from an additional unit of labour is equal to the markup over the present value of the marginal disutility of working. When all households are able to negotiate their wage contracts each period, wage becomes: $\frac{\tilde{W}_{r,t}}{P_t} = \frac{\nu}{(1-\nu)} \frac{U_{r,l,t}(1+\tau^c_t)}{U_{r,c,t}\left(1-\tau^l_t\right)}$. Finally, the Ricardian households wage index can be transformed into the following:

$$W_{r,t} = \left[(1-\varpi_w) \tilde{W}^{1-\nu}_{r,t} + \varpi_w \left(\pi^{\gamma_w}_{t-1} W_{r,t-1} \right)^{1-\nu} \right]^{\frac{1}{1-\nu}} \quad (12)$$

For simplicity, we follow Erceg *et al.* (2006) and assume that each non-Ricardian household sets its wage equal to the average wage of optimising households, therefore ($W_t = W_{r,t} = W_{nr,t}$). Because all households face the same labour demand, the labour supply of a non-optimizing household is equal to that of forward-looking household ($L_t = L_{r,t} = L_{nr,t}$).

2.3 Firms

2.3.1 Composite consumption good producer

The competitive producer of the composite good (Y_t) purchases differentiated goods ($Y_{j,t}$) from monopolistic producers indexed by j and combines them into one single good using the following technology: $Y_t = \left[\int_0^1 Y_{j,t}^{\frac{s-1}{s}} dj \right]^{\frac{s}{s-1}}$, where $s > 0$ denotes the elasticity of substitution among the differentiated outputs of intermediate firms. Producer maximises profit as follows:

$$Prof_{F,t} = P_t Y_t - \int_0^1 P_{j,t} Y_{j,t} dj \quad (13)$$

where P_t denotes price of a unit of output and $P_{j,t}$ denotes a price of intermediate output J. the first-order condition results in a demand function for intermediate goods:

$$Y_{j,t} = \left(\frac{P_t}{P_{j,t}} \right)^s Y_t \quad (14)$$

[9]The omission of the subscript n in the utility of consumption U_c reflects our assumption of complete markets for the state contingent claims in consumption which implies that consumption, and therefore utility of consumption are the same among all Ricardian households

The zero profit condition implies that the price index is represented by the following equation: $P_t = \left[\int_0^1 P_{j,t}^{1-s} dj\right]^{\frac{1}{1-s}}$.

2.3.2 Intermediate good production sector

Each monopolistic intermediate producer uses the following production function:

$$Y_{j,t} = \varepsilon_t^A (\bar{K}_{j,t-1})^{\alpha} N_{j,t}^{1-\alpha} (K_{g,t-1})^{\alpha_g} - fc \tag{15}$$

where fc denotes a fixed cost of production, K_g denotes public capital, $\bar{K}_{j,t-1}$ denotes capital services $\left(\bar{K}_t = u_t K_t\right)$, and ε_t^A is a total factor productivity shock which follows:

$$\ln \varepsilon_t^A = \rho_A \ln \varepsilon_{t-1}^A + \eta^A,$$

where η^A is an i.i.d. process with standard deviation σ_A[10]. Firms rent capital services $\left(\bar{K}_{j,t-1}\right)$ and labour $(N_{j,t})$, for which they pay respectively a nominal rental rate $(R_{k,t})$ and a wage rate (W_t). Monopolistic companies minimize costs subject to the technology available. From the combination of first-order conditions, we obtain the wage rental ratio (equation 16), which implies that the capital to labour ratio across all of the monopolistic producers remains the same.

$$\frac{\bar{K}_t}{N_t} = \frac{\bar{K}_{j,t}}{N_{j,t}} = \frac{\alpha}{(1-\alpha)} \frac{W_t}{R_{k,t}} \tag{16}$$

The nominal marginal cost is represented by the following:

$$P_t mc_t = (\frac{1}{1-\alpha})^{1-\alpha} (\frac{1}{\alpha})^{\alpha} \left(\varepsilon_t^A\right)^{-1} K_{g,t-1}^{-\alpha_g} (W_t)^{1-\alpha} (R_{k,t})^{\alpha} \tag{17}$$

The marginal cost, the same across all the intermediate producers, increases as the wage rate and the rate of return on capital increase. A positive total factor productivity shock along with an increase in public capital leads to a decrease in the marginal costs.

Price setting

The profit of an intermediate firm j is given by the following equation:[11]

$$Prof_{j,t} = P_{j,t} Y_{j,t} - mc_t P_t \left(Y_{j,t} + fc\right) \tag{18}$$

Intermediate good producers set prices similarly to the mechanism presented in Calvo (1983). In particular, during every period, a share of these firms (ϖ_p) is not able to reoptimise their price. These firms simply follow the partial indexation rule: $P_{j,t} = \pi_{t-1}^{\gamma_p} P_{j,t-1}$. The remaining fraction of companies $(1 - \varpi_p)$ choose P_t to maximise the profits subject to the demand (equation 14). Maximisation results in equation (19) for newly optimised prices:

[10] Similarly to Christiano *et al.* (2005), Smets and Wouters (2007), Coenen *et al.* (2013) we incorporate fixed cost in production. This allows for a realistic level of economic profits in the steady-state.

[11] Equation (18) implies that for profits to be equal zero in the steady-state: $fc = \frac{(1-mc)}{mc} Y$.

$$E_t \sum_{l=0}^{\infty} (\beta\varpi)^l \lambda_{t+l} \left[\frac{\widetilde{P}_t X_{tl}}{P_{t+l}} - \frac{s}{1-s} mc_{t+l} \right] P_{t+l} Y_{j,t+l} = 0 \tag{19}$$

where $\tilde{P}_t$ denotes the price set by firms that can re-optimise their price at time t. In the case that all firms are allowed to reoptimise their prices, the above condition reduces to: $\widetilde{P}_t = \frac{s}{s-1} P_t mc_t$, which indicates that the optimised price is equal to a markup over the marginal costs. In addition, $(\beta\varpi)^l \lambda_{t+l}$ denotes a discount factor of future profits for firms. Here, λ_t denotes the Lagrange multiplier on the Ricardian household's budget constraint and is treated by firms as exogenous. The price index $P_t = \left[\int_0^1 P_{j,t}^{1-s} dj \right]^{\frac{1}{1-s}}$ can be rewritten as:

$$P_t = \left[(1-\varpi) \widetilde{P}_t^{1-s} + \varpi \left(\pi_{t-1}^{\gamma_p} P_{t-1} \right)^{1-s} \right]^{\frac{1}{1-s}} \tag{20}$$

2.4 Fiscal and monetary policies

Equation (21) provides the government budget constraint, which requires the total expenditure of government on consumption (G), investment (IG), transfers, and the repayment of last-period debt with interests, to be equal to the revenue from taxes and new bond issuance.

$$\tau_t^c C_t + \tau_t^l w_t L_t + \tau_t^k r_{k,t} u_t K_{t-1} + b_t = \left(\frac{R_{t-1}}{\pi_t} \right) b_{t-1} + G_t + IG_t + TR_t \tag{21}$$

The public capital accumulation equation is represented by:

$$K_{g,t} = (1 - \delta_{k,g}) K_{g,t-1} + IG_t \tag{22}$$

where $\delta_{k,g}$ denotes depreciation rate of public capital. Fiscal policy instruments rules are set similarly to those used by Leeper *et al.* (2010b). First, expenditure instruments respond countercyclically to GDP deviations from the steady-state, whereas taxes respond to them procyclically. As a consequence fiscal instruments play a role of automatic stabilizers. Second, fiscal instruments keep real debt dynamics under control in order not to allow for high debt to GDP ratios.[12] Six fiscal instruments are linked to the debt level and GDP as follows:[13]

$$\hat{x}_t = -\phi_{b,x} \hat{b}_{t-1} - \phi_{y,x} \hat{Y}_t + \varepsilon_t^X \tag{23}$$

$$\hat{z}_t = \phi_{b,z} \hat{b}_{t-1} + \phi_{y,z} \hat{Y}_t + \varepsilon_t^Z \tag{24}$$

where ε^X and ε^Z denote respectively fiscal shocks which follow:

$$\ln \varepsilon_t^X = \rho_X \ln \varepsilon_{t-1}^X + \eta^X, \; and \; \ln \varepsilon_t^Z = \rho_Z \ln \varepsilon_{t-1}^Z + \eta^Z,$$

[12] Romer and Romer (2010) find for example that most of the tax changes in the USA are motivated by: (1) a change in government spending, (2) other factors likely to affect output in in the close future, (3) budget deficit, (4) higher growth.

[13] Hats over variables denote deviations from the steady-state.

where η^X and η^Z are i.i.d. processes with standard deviations σ_X and σ_Z, $X \in \{G, IG, TR\}$, and $Z \in \{\tau^c, \tau^k, \tau^l\}$.[14] Finally, we follow the approach set in the monetary policy literature, and assume that the shocks in the above fiscal policy rules constitute an unexpected changes in policy which is an analogous approach to errors in the case of Taylor rule, (see for example Forni *et al.*, 2009 and Leeper *et al.*, 2010b).

Nominal interest rate follows a Taylor type rule that links it to its own lag term, inflation and output gap as measured by coefficients ρ, ρ_π, and ρ_y:

$$\hat{R}_t = \rho \hat{R}_{t-1} + (1-\rho)\,\rho_\pi \hat{\pi}_t + (1-\rho)\,\rho_y \hat{Y}_t + \eta_t^M \tag{25}$$

where η_t^M denotes an i.i.d. normal error term on the interest rate rule.

2.5 Aggregation and market clearing

The aggregate quantity, expressed in per-capita terms, of any household quantity variable Z_t^ι, is represented by $Z_t = \int_0^1 Z_t^\iota d\iota = (1-\vartheta)Z_{r,t} + \vartheta Z_{nr,t}$, as all members of each household type choose identical allocations in equilibrium. Subsequently:

$$C_t = \vartheta C_{nr,t} + (1-\vartheta)\, C_{r,t} \tag{26}$$

$$L_t = \vartheta L_{nr,t} + (1-\vartheta)\, L_{r,t} \tag{27}$$

$$TR_t = \vartheta TR_{nr,t} + (1-\vartheta)\, TR_{r,t} \tag{28}$$

where $L_t = L_{r,t} = L_{nr,t}$ as explained in Subsection 2.2, and $TR_t = TR_{nr,t} = TR_{r,t}$ by definition. Because only Ricardian households accumulate financial and physical assets, and are the only recipients of profits in the model economy, we obtain the following conditions for the per-capita investment, physical capital, public bonds and profits:

$$I_t = (1-\vartheta)\, I_{r,t} \tag{29}$$

$$K_t = (1-\vartheta)\, K_{r,t} \tag{30}$$

$$b_t = (1-\vartheta)\, b_{r,t} \tag{31}$$

$$Prof_t = (1-\vartheta)\, Prof_{r,t} \tag{32}$$

The labour market is in equilibrium when the total labour demanded by the intermediate firms equals total labour supplied by households at a wage rate (W_t). The capital rental market is in equilibrium when capital supplied by Ricardian households is equal to the capital demanded by intermediate producers at a market rental rate ($R_{k,t}$). The final goods market is in equilibrium when the aggregate supply equals the aggregate public and private demand for consumption and investment goods.

$$Y_t - \left(1 - \tau_t^k\right) a(u_t) K_{t-1} = C_t + G_t + I_t + IG_t \tag{33}$$

Log-linearized equations describing the equilibrium of the model are presented in the on-line Appendix.

[14] We have estimated model with fiscal policy responding to one-period lagged output, but it yields a lower marginal likelihood than the benchmark scenario.

3 Bayesian Estimation

We use perturbation techniques to solve the models and Bayesian methods to estimate them[15]. Sims's *csminwel* function is used as the optimiser for the mode's computation. In order to determine whether multiple modes exist, we have conducted at least 20 searches for the mode using various starting values. With the exception of few cases where the numerical optimization procedure failed to converge, the searches for the posterior mode converged to the same parameter and likelihood values. In the second stage, using the random walk Metropolis-Hastings algorithm we construct the posterior distribution. We generate four Markov chains of length 500,000. The acceptance ratios yields approximately 0.25, which is in line with the range of ratios proposed in the literature (see for example Gelman *et al.*, 1997).

In the benchmark estimation, we use twelve data series for the period from 1987:Q2 to 2011:Q1. The length of the sample period is determined by the availability of the tax data. The time series used in the estimation comprise per capita: private consumption, GDP, private investment, hours, wages, inflation, government consumption, government investment, transfers, and effective tax revenue from consumption, labour and capital (see the Appendix for more details on dataset).

3.1 Calibration

Most of the parameters related to the steady-state are calibrated and their values are presented in Table **??**. The discount factor (β) is set to 0.99 as in Harrison and Oomen (2010), which implies a steady-state annual real interest rate of 4 per cent. We fix the depreciation rate of public capital (δ_g) at 0.015, which results in an annual depreciation rate of public capital of 6 per cent. This value together with the ratio of public investment to GDP (0.02) pins down the ratio of public capital stock to annual GDP at 0.32 to match the ONS data on the public capital stock and public investment. For the depreciation rate of private capital we follow Harrison and Oomen (2010) and choose $\delta = 0.025$, which implies an annual depreciation rate of 10 per cent. The steady-state wage markup parameter $\left(\frac{\nu}{\nu-1}\right)$ is set to 1.05 as in Christiano *et al.* (2005). The share of capital in the production function (α) is calibrated to 0.30, which results in a steady-state share of labour income in total output of 70 per cent as in Harrison and Oomen (2010). The calibration of α, together with the value of the capital tax rate $\left(\tau^k\right)$, and the private capital depreciation rate, fixes the share of private investment expenditure in GDP at 15 per cent as in the UK data for the period from 1987:Q2 to 2011:Q1. Also the ratio of private consumption to GDP (0.63) fits well the data for the sample period. The elasticity of output to public capital (σ_g) is set to 0.01 which is within the range of estimates in the literature (for more details see Sthler and Thomas (2012) and references therein).

We select the steady-state values of effective tax rates so that they match the corresponding rates implied by the data for the sample period. This implies 20 per cent for the VAT (consumption tax rate: τ^c), and 29 per cent for the labour and capital tax

[15]For solution, estimation and necessary calculations, we use Dynare 4.2.4 by Adjemian *et al.* (2011) and MATLAB.

Table 1: Calibrated parameters and steady-state ratios

Share/Paramenter	Definition	Value
A. Expenditure shares		
C/GDP	Private consumption to GDP ratio	0.63
I/GDP	Private investment to GDP ratio	0.15
G/GDP	Gov. consumption to GDP ratio	0.20
IG/GDP	Gov. investment to GDP ratio	0.02
B. Production sector		
α	Share of capital in production function	0.30
δ	Private capital depreciation rate	0.025
δ_g	Public capital depreciation rate	0.015
σ_g	Elasticity of output to government investment	0.01
C. Taxes and fiscal policy		
τ^c	Consumption tax rate	0.20
τ^l	Labour tax rate	0.29
τ^k	Capital tax rate	0.29
TR/GDP	Transfers to GDP ratio	0.17
b/GDP	Annualised gov. debt to GDP ratio	0.60
D. Other calibrated parameters		
β	Discount factor	0.99
$\frac{\nu}{\nu-1}$	Steady-state wage markup	1.05

rates $\left(\tau^l, \tau^k\right)$. [16]

A share of public consumption and public investment in GDP is calibrated respectively at 20 per cent and 2 per cent to match their empirical counterparts over the sample period. The endogenous public transfers to GDP ratio is pinned down at approximately 17 per cent.

3.2 Prior Distributions

Assumptions about priors are presented in Table **??** and **??**. Priors are set in line with the existing studies. We use inverse gamma priors for standard deviations of shocks, with prior means set to 0.01, except for investment shocks where we set the prior means to 0.1.[17]

[16] The model share of taxes in the total tax revenue are 0.49, 0.21, 0.30 for labour, capital and consumption tax respectively. For the period from 1987:Q2 to 2011:Q1 data show these averages to be 0.46 (42, 52), 0.25 (20, 27), 0.30 (25, 32) - brackets show minimum and maximum values respectively.

[17] We follow Harrison and Oomen (2010) and set the means of investment shocks at a higher level.

We select a beta distribution for shock persistence parameters with prior means set to 0.8 and standard deviations to 0.1. In line with Coenen *et al.* (2013) we select normal distribution priors for all fiscal policy response parameters. The parameters controlling the response of fiscal policy instruments to GDP have prior' means set to 0.5 and standard deviations to 0.5, whereas debt aversion parameters have prior means set to 0.2 and standard deviations to 0.1. We use a beta distribution for the share of non-Ricardian households with a prior mean of 0.3, close to the estimates of Ratto *et al.* (2009) and Coenen *et al.* (2013). We choose the prior mean of the habit formation parameter to 0.7, similarly to the estimate of Harrison and Oomen (2010) for the UK. The prior mean of constant relative risk aversion is set to 0.66, as in Harrison and Oomen (2010). For the prior mean of the inverse Frisch elasticity of labour, we choose a value of 1, as in Christiano *et al.* (2005). Turning to the monetary policy rule, for the degree of interest rate smoothing parameter we select a beta distribution with a prior mean equal to 0.7, whereas for the Taylor rule coefficients on inflation and output we select a normal distribution and set prior means respectively to 1.5 and 0.125 as is standard in the literature. The prior means for the price and wage indexation parameters are set to 0.3, whereas the prior mean of the Calvo price and wage stickiness parameters is fixed at 0.5 with a standard deviation of 0.1. Finally, we select the normal distribution prior for the capital adjustment cost with the mean set to 4, as in Smets and Wouters (2003), and choose a normal distribution prior for the utilisation parameter with a mean of 0.8 and a standard deviation of 0.2.

3.3 Posterior Estimates

The details of posterior estimates of the model presented in Section 2 are in columns $5-8$ of Table **??** and **??**. In this subsection we discuss posterior means. According to the results, agents exhibit a moderate degree of habit formation in consumption $(b = 0.71)$, which is similar to the value of 0.59 found in Millard (2011) and 0.69 in Harrison and Oomen (2010). The inverse of the intertemporal elasticity of substitution coefficient is estimated at 0.95. The above estimates imply that the elasticity of Ricardian households' consumption with respect to the short-term *ex ante* real interest rate is equal to 0.31 and is close to the value of 0.47 obtained by Harrison and Oomen (2010) and somewhat lower than 0.66 found in Millard (2011).[18]

The investment adjustment cost parameter is estimated at 6.39, similar to 6.71, a value obtained for the euro area by Adolfson *et al.* (2008). The parameter governs the transmission mechanism from the price of installed capital to investment.[19] The parameter can be interpreted as the inverse elasticity of investment with respect to an increase in the installed capital.[20] Its estimate implies that a 1 per cent increase in the

[18]This result stems from the transformation of the consumption equation to $\hat{C}_{r,t} = b\hat{C}_{r,t-1} - \frac{(1-b)}{\sigma_c}\sum_{i=0}^{+\infty}(R_{t+i} - \pi_{c,t+i+1})$, where we have neglected the preference shock.

[19]The presence of investment adjustment costs in this form improves the performance of the model by inducing hump-shape responses of the investment (for more discussion, please see Burnside *et al.*, 2004 and Christiano *et al.*, 2005).

[20]Disregarding shocks to the investment technology, the investment equation can be transformed to $\hat{I}_t = \hat{I}_{t-1} - \frac{1}{\phi}\sum_{i=0}^{+\infty}\beta^i\hat{Q}_{t+i}$.

Table 2: Priors and Posteriors

Parameter's name		Prior			Posterior											
		type	mean	s.d.	mode	mean	conf. int.		mode	mean	conf. int.		mode	mean	conf. int.	
					benchmark				gov. cons. in util.				open economy			
gov. con. resp. to debt	ϕ_b^g	N	0.20	0.10	0.16	0.17	0.08	0.27	0.16	0.18	0.08	0.27	0.14	0.14	0.07	0.21
gov. inv. resp. to debt	ϕ_b^{ig}	N	0.20	0.10	0.20	0.20	0.04	0.36	0.20	0.20	0.04	0.36	0.19	0.19	0.03	0.36
trans. resp. to debt	ϕ_b^{tr}	N	0.20	0.10	0.07	0.08	-0.06	0.22	0.07	0.08	-0.06	0.22	0.08	0.09	-0.05	0.22
cap. tax resp. to debt	ϕ_b^{tk}	N	0.20	0.10	0.13	0.13	-0.02	0.27	0.13	0.13	-0.02	0.27	0.13	0.13	-0.01	0.27
con. tax resp. to debt	ϕ_b^{tc}	N	0.20	0.10	0.09	0.11	-0.01	0.23	0.09	0.11	-0.01	0.23	0.14	0.15	0.04	0.27
lab. tax resp. to debt	ϕ_b^{tl}	N	0.20	0.10	0.00	0.02	-0.10	0.14	0.00	0.02	-0.09	0.15	-0.03	-0.01	-0.11	0.09
gov. cons. resp. to GDP	ϕ_y^g	N	0.50	0.50	0.23	0.24	0.07	0.42	0.26	0.26	0.07	0.45	0.26	0.27	0.13	0.40
gov. inv. resp. to GDP	ϕ_y^{ig}	N	0.50	0.50	0.89	0.88	0.08	1.66	0.88	0.88	0.10	1.67	0.89	0.87	0.08	1.68
trans. resp. to GDP	ϕ_y^{tr}	N	0.50	0.50	0.29	0.31	-0.04	0.66	0.29	0.31	-0.03	0.66	0.38	0.37	0.01	0.73
cap. tax resp. to GDP	ϕ_y^{tk}	N	0.50	0.50	0.56	0.58	0.09	1.07	0.56	0.57	0.08	1.04	0.87	0.86	0.35	1.38
cons. tax resp. to GDP	ϕ_y^{tc}	N	0.50	0.50	0.15	0.14	-0.26	0.56	0.15	0.14	-0.28	0.54	0.15	0.16	-0.23	0.54
lab. tax resp. to GDP	ϕ_y^{tl}	N	0.50	0.50	0.05	0.08	-0.19	0.34	0.04	0.08	-0.18	0.35	-0.09	-0.08	-0.34	0.18
AR(1) public cons.	ρ_g	B	0.80	0.10	0.93	0.92	0.88	0.97	0.93	0.92	0.88	0.97	0.91	0.91	0.86	0.96
AR(1) public investment	ρ_{ig}	B	0.80	0.10	0.38	0.39	0.26	0.53	0.38	0.40	0.26	0.53	0.35	0.37	0.23	0.50
AR(1) transfers	ρ_{tr}	B	0.80	0.10	0.88	0.87	0.80	0.95	0.88	0.87	0.80	0.95	0.88	0.88	0.81	0.95
AR(1) capital tax	ρ_{tk}	B	0.80	0.10	0.80	0.80	0.71	0.89	0.80	0.80	0.71	0.89	0.79	0.79	0.69	0.89
AR(1) cons. tax	ρ_{tc}	B	0.80	0.10	0.74	0.75	0.64	0.87	0.74	0.75	0.64	0.87	0.80	0.80	0.70	0.90
AR(1) labour tax	ρ_{tl}	B	0.80	0.10	0.73	0.75	0.63	0.88	0.73	0.76	0.63	0.88	0.72	0.74	0.62	0.86
AR nominal interest rate	ρ	B	0.70	0.10	0.73	0.74	0.69	0.80	0.74	0.75	0.69	0.80	0.70	0.71	0.66	0.75
inflation response	ρ_π	N	1.50	0.10	1.62	1.60	1.46	1.76	1.62	1.61	1.46	1.76	1.62	1.61	1.46	1.76
output response	ρ_y	N	0.13	0.05	0.11	0.12	0.06	0.19	0.11	0.12	0.06	0.19	0.08	0.09	0.04	0.14
inverse elast. of labour	σ_L	N	1.00	0.35	1.28	1.31	0.82	1.81	1.30	1.33	0.83	1.83	1.35	1.38	0.88	1.88
CRRA coefficient	σ_c	N	0.66	0.20	0.97	0.95	0.69	1.23	0.95	0.93	0.65	1.21	0.82	0.87	0.60	1.14
investment adjust. cost	ϕ	N	4.00	1.50	6.32	6.39	4.47	8.33	6.34	6.42	4.48	8.34	7.17	7.23	5.36	9.09
capital utilization cost	κ	N	0.80	0.20	0.79	0.77	0.46	1.08	0.79	0.77	0.45	1.08	0.83	0.82	0.51	1.12
domestic price index	γ_p	B	0.30	0.15	0.03	0.08	0.00	0.15	0.03	0.08	0.00	0.15	0.04	0.09	0.00	0.17
wage index	γ_w	B	0.30	0.15	0.18	0.21	0.05	0.35	0.18	0.21	0.05	0.35	0.19	0.22	0.06	0.37
calvo domestic prices	ϖ_p	B	0.50	0.10	0.74	0.74	0.67	0.81	0.74	0.74	0.66	0.81	0.77	0.78	0.70	0.85
calvo wages	ϖ_w	B	0.50	0.10	0.52	0.56	0.46	0.66	0.53	0.56	0.46	0.66	0.48	0.51	0.42	0.61
habit formation	h	B	0.70	0.10	0.67	0.71	0.57	0.87	0.65	0.71	0.57	0.85	0.89	0.89	0.84	0.94
fixed cost	φ	N	1.15	0.10	1.61	1.63	1.51	1.75	1.61	1.63	1.51	1.75	1.59	1.60	1.47	1.73
sh. of non-Ricardians	ϑ	B	0.30	0.10	0.35	0.37	0.25	0.49	0.35	0.37	0.25	0.50	0.12	0.13	0.06	0.20
AR(1) tfp.	ρ_A	B	0.80	0.10	0.98	0.95	0.91	1.00	0.98	0.95	0.90	1.00	0.97	0.95	0.90	0.99
AR(1) preferences	ρ_B	B	0.80	0.10	0.73	0.68	0.53	0.83	0.74	0.68	0.54	0.82	0.67	0.66	0.56	0.78
AR(1) private inv.	ρ_I	B	0.80	0.10	0.37	0.40	0.26	0.54	0.38	0.40	0.26	0.55	0.40	0.42	0.28	0.57
AR(1) wage markup	ρ_W	B	0.50	0.10	0.33	0.34	0.24	0.44	0.33	0.34	0.23	0.44	0.34	0.34	0.24	0.45
AR(1) price markup	ρ_P	B	0.50	0.10	0.47	0.47	0.32	0.61	0.47	0.47	0.32	0.61	0.55	0.51	0.35	0.67
sh. of gov. cons. - util.	a	B	0.75	0.10					0.78	0.76	0.61	0.92				
subst. elas. cons. - util.	μ	G	1.00	0.50					0.83	1.08	0.51	1.69				
habit gov. cons.	h_g	B	0.70	0.10					0.71	0.68	0.53	0.85				
calvo imp. priv. cons.	$\gamma_{c,m}$	B	0.50	0.10									0.56	0.55	0.43	0.66

Table 3: Priors and Posteriors

		Prior			Posterior											
Parameter's name		type	mean	s.d.	mode	mean	conf. int.		mode	mean	conf. int.		mode	mean	conf. int.	
					benchmark				gov. cons. in util.				open economy			
index imp. priv. cons.	$\gamma_{c,m}$	B	0.30	0.15									0.06	0.10	0.01	0.19
calvo imp. priv. inv.	$\varpi_{i,m}$	B	0.50	0.10									0.45	0.50	0.34	0.66
index imp. priv. inv.	$\gamma_{i,m}$	B	0.30	0.15									0.07	0.11	0.01	0.21
calvo export	ϖ_x	B	0.50	0.10									0.53	0.53	0.40	0.66
index export	γ_x	B	0.30	0.15									0.08	0.13	0.02	0.23
calvo imp. gov. cons.	$\varpi_{g,m}$	B	0.50	0.10									0.70	0.69	0.58	0.80
index imp. gov. cons.	$\gamma_{g,m}$	B	0.30	0.15									0.05	0.08	0.01	0.16
calvo imp. gov. inv.	$\varpi_{ig,m}$	B	0.50	0.10									0.31	0.35	0.18	0.51
index imp. gov. inv.	$\gamma_{ig,m}$	B	0.30	0.15									0.06	0.10	0.01	0.19
Elas. of subst. gov. cons.	s_g	IG	1.50	2.00									0.68	0.80	0.43	1.16
Elas. of subst. priv. cons.	s_c	IG	1.50	2.00									0.84	0.87	0.52	1.21
Elas. of subst. priv. inv.	s_i	IG	1.50	2.00									2.70	2.57	1.63	3.51
Elas. of subst. foreign.	s_f	IG	1.50	2.00									1.00	1.07	0.72	1.40
markup imp. priv. cons.	$\frac{\upsilon_{c,m}}{\upsilon_{c,m}-1}$	N	1.15	0.10									1.26	1.26	1.11	1.41
markup imp. priv. inv.	$\frac{\upsilon_{i,m}}{\upsilon_{i,m}-1}$	N	1.15	0.10									1.34	1.33	1.19	1.47
markup imp. gov. inv.	$\frac{\upsilon_{ig,m}}{\upsilon_{ig,m}-1}$	N	1.15	0.10									1.07	1.07	0.90	1.24
markup imp. gov. cons.	$\frac{\upsilon_{g,m}}{\upsilon_{g,m}-1}$	N	1.15	0.10									1.17	1.17	1.01	1.34
risk premium		IG	0.01	2.00									0.00	0.01	0.00	0.01
AR(1) export price	ρ_X	B	0.50	0.10									0.47	0.46	0.31	0.61
AR(1) risk premium shock	ρ_R	B	0.50	0.10									0.79	0.79	0.73	0.85
AR(1) imp. priv. cons.	$\rho_{C,m}$	B	0.50	0.10									0.36	0.37	0.22	0.51
AR(1) imp. priv. inv.	$\rho_{I,m}$	B	0.50	0.10									0.66	0.60	0.42	0.76
AR(1) imp. gov. cons.	$\rho_{G,m}$	B	0.50	0.10									0.42	0.42	0.26	0.59
AR(1) imp. gov. inv.	$\rho_{IG,m}$	B	0.50	0.10									0.54	0.49	0.32	0.66
s.d. tfp. shock	σ_A	IG	0.01	Inf	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
s.d. pref. shock	σ_B	IG	0.01	Inf	0.06	0.08	0.05	0.11	0.06	0.08	0.05	0.11	0.07	0.08	0.05	0.11
s.d. inv. shock	σ_I	IG	0.10	Inf	0.08	0.08	0.07	0.09	0.08	0.08	0.06	0.09	0.07	0.07	0.06	0.09
s.d. wage markup shock	σ_W	IG	0.01	Inf	0.38	0.50	0.24	0.75	0.40	0.52	0.25	0.81	0.32	0.40	0.21	0.58
s.d. price markup shock	σ_P	IG	0.01	Inf	0.05	0.05	0.02	0.08	0.05	0.05	0.02	0.08	0.06	0.08	0.02	0.13
s.d. gov. cons. shock	σ_G	IG	0.01	Inf	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
s.d. gov. inv. shock	σ_{IG}	IG	0.10	Inf	0.55	0.56	0.48	0.63	0.55	0.56	0.49	0.63	0.57	0.58	0.50	0.65
s.d. transfers shock	σ_{TR}	IG	0.01	Inf	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
s.d. capital tax shock	σ_{TK}	IG	0.01	Inf	0.05	0.05	0.05	0.06	0.05	0.05	0.05	0.06	0.05	0.05	0.05	0.06
s.d. cons. tax shock	σ_{TC}	IG	0.01	Inf	0.04	0.04	0.03	0.04	0.04	0.04	0.03	0.04	0.03	0.03	0.03	0.03
s.d. labour tax shock	σ_{TL}	IG	0.01	Inf	0.02	0.02	0.02	0.03	0.02	0.02	0.02	0.03	0.02	0.02	0.02	0.02
s.d. monetary policy shock	σ_M	IG	0.01	Inf	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
s.d. export markup shock	σ_X	IG	0.01	Inf									0.11	0.12	0.06	0.17
s.d. risk premium shock	σ_R	IG	0.01	Inf									0.01	0.01	0.00	0.01
s.d. imp. priv. cons. shock	$\sigma_{C,m}$	IG	0.01	Inf									0.12	0.12	0.07	0.18
s.d. imp. priv. inv. shock	$\sigma_{I,m}$	IG	0.01	Inf									0.11	0.14	0.06	0.23
s.d. imp. gov. cons. shock	$\sigma_{G,m}$	IG	0.01	Inf									0.59	0.65	0.23	1.06
s.d. imp. gov. inv. shock	$\sigma_{IG,m}$	IG	0.01	Inf									0.59	0.74	0.38	1.10

price of capital is followed by a $\frac{1}{\phi(1-\beta)} = 15.65$ per cent increase in investment. Smets and Wouters (2003) estimate this elasticity at 16 per cent for the euro area, whereas Christiano *et al.* (2005) estimate it at 38 per cent for the USA.

The capital utilisation adjustment parameter ($\kappa = 0.77$) can be defined as the inverse elasticity of utilisation with respect to the rental rate of capital net of capital taxes. Our result is higher than the value of 0.46 obtained by Millard (2011) and the value of 0.56 by Harrison and Oomen (2010) and is closer to 0.85 in Smets and Wouters (2007) and 0.77 in Edge *et al.* (2003) for the USA. The fixed cost parameter estimate ($\varphi_y = 1.63$) is slightly higher than 1.46 in Christiano *et al.* (2005) and 1.50 in Smets and Wouters (2003).[21]

The estimate of a price stickiness parameter (0.74) implies that prices change roughly every 3.85 quarters. The Frisch elasticity of labour supply is equal to 1.31, which is consistent with macroeconomic estimates, and implies that the labour supply is relatively elastic with respect to the changes in real wages. The estimate of the wage stickiness parameter (0.56) implies that wages adjust on average approximately every nine months, which is similar to the results found by Millard (2011). Estimates of monetary policy parameters take the following values: persistence parameter, (0.74); response to inflation, (1.60); and the response to the output parameter, (0.12) and are in line with previous UK data estimates. The share of non-Ricardian households is estimated to be 0.37 which is consistent with estimates for EU and US (see for example Ratto *et al.*, 2009). Turning to the fiscal policy parameters, the most persistent fiscal policy shocks are the government consumption shock with a half-life of 33 months, and the transfers shock with a half life of 20 months. Tax shocks feature lower persistence with a half-life oscillating at around (10) – (12) months. The least persistent is the public investment shock with a half-life of only 3 months.[22]

The estimates of fiscal policy parameters are presented in Table **??**. The 90 per cent confidence intervals of some of them (response of transfers, consumption and labour taxes to debt and GDP, and the response of capital taxes to debt) include 0 which implies that these were not used systematically in the controlling for debt and GDP.

The parameter estimates imply that the government consumption, investment, and capital income tax played the most important role in controlling the government debt over the sample period, and that capital income tax rates and government investment play an important role in controlling for the GDP fluctuations. In contrast, labour income taxes do not respond strongly to the aggregate output.

[21] It can be shown that for $fc = \frac{1-mc}{mc}Y$, and $mc = \frac{1}{x}$, where x is a markup; $\varphi_y = \left(1 + \frac{fc}{Y}\right) = \left(1 + \frac{(1-mc)Y}{mcY}\right) = x$. It also implies an elasticity of substitution between intermediate goods equal to 2.6 as $\varkappa = \frac{s}{s-1}$ where (s) denotes the elasticity of substitution.

[22] The reason behind the low persistence of public, but also private investment, shock is the transfer of nuclear reactors from British Nuclear Fuels Ltd (government investment) to the Nuclear Decommissioning Authority (business investment) in April 2005. This transfer (approximately equal to two-and-a-half quarters expenditure on public investment) is a large one quarter shock which decreases the persistence of the both investment shocks.

3.4 Comparison of Models

Table 4: Model comparison

	Marginal Likelihood
BVAR(1)	2128.64
BVAR(2)	2224.80
BVAR(3)	2215.66
BVAR(4)	2223.00
BVAR(5)	2268.31
BVAR(6)	2265.95
DSGE model	2369.51

To assess the fit of the model we compare it to the BVAR models of lag order from 1 to 6.[23] In the BVAR setup, we follow Juillard *et al.* (2006) and Ratto *et al.* (2009) and set the prior decay parameter to 0.5, the tightness of the prior parameter to 3, the parameter determining the weight on own-persistence to 2, and the parameter determining the degree of co-persistence to 5. Table **??** presents the marginal likelihoods of the estimates BVARs and indicates that the model similarly to Juillard *et al.* (2006) and Ratto *et al.* (2009), yields better fit than the BVARs.

3.5 The role of frictions and other parameters

After confirming the good fit of the model we move to the analysis of frictions and their role in the transmission mechanism of fiscal policy. Table **??** presents the posterior mode' estimates of nine models in which we either change the fiscal policy setup, turn off the frictions (each one at a time), or change values of other parameters. Table **??** is a continuation of Table **??** and presents additionally the marginal likelihoods of the estimated models and the implied GDP multipliers. The columns of both tables present respectively results for the model: (1) of the benchmark economy, (2) in which fiscal policy rules respond only to debt, (3) without habit formation, (4) without non-Ricardian households, (5) without price stickiness, (6) without wage stickiness, (7) without variable capital utilisation, (8) without capital investment adjustment cost.

Closer look at the fiscal policy related parameters indicates that these do not show significant fluctuations with respect to the various specifications of the model (see Table **??**). Namely, public consumption, investment and capital taxes always respond the strongest to the level of debt and government investment and capital tax to GDP. Also, the labour tax is characterised by the weakest response to debt and GDP fluctuations.

The marginal likelihoods' values point toward three interesting observations. First, the benchmark model is preferable than the models in which we exclude frictions. Second, the model in which fiscal policy do not control for the GDP fluctuations yields only slightly lower marginal likelihood (by 0.01) with respect to the benchmark model, suggesting that the data are not very instructive about the model choice in this case. Third,

[23] For the discussion of BVAR see Doan *et al.* (1984) and Villemot (2011).

the share of non-Ricardian households, the characteristic of the model which plays in the literature an important role in explaining the response of private to public consumption shock, plays along with the variable capital utilisation the least important role out of the analysed frictions in the model. Also, the multipliers show that its implications are far more important for transfers and the consumption and labour taxes, than for government consumption.

The marginal likelihoods of the estimated models clearly indicate the frictions do play a role in the performance of the model; in particular nominal frictions and capital investment adjustment cost. It is important therefore to see what the role of these frictions in the transmission mechanism of fiscal policy is. We start by looking at the habit formation in consumption (h), which has two implications for the model. First, the weight on the past consumption increases, and second, the elasticity of consumption with respect to the real interest rate decreases. As a result, presence of habit implies that the response of Ricardian consumption takes a hump-shaped form. Therefore the level of consumption following the shock is smaller on impact when compared to the situation when habit is not present (for further discussion see Fuhrer, 2000, Woodford, 2003, and Christiano *et al.,* 2005). Subsequently, higher levels of habit formation imply lower short-term multipliers of consumption in absolute terms. Therefore, in the case of a fiscal policy shock resulting in a positive (negative) response of consumption, as the value of the parameter increases, the short-term responses of consumption become smaller (higher), which results in a lower (higher) short-term GDP multiplier. In the presented model expansionary fiscal policy conducted with spending instruments leads to a decrease in consumption (see Figure 1), therefore absence of habit leads to lower GDP multipliers (see Table 6), whereas expansionary fiscal policy conducted with tax cuts leads a to higher consumption (see Figure 2), thus higher GDP multipliers (see Table 6).

The share of non-Ricardian households (ϑ) determines the behaviour of total consumption, which takes the form of Ricadian households' consumption for $\vartheta = 0$, and that of non-Ricardian households for $\vartheta = 1$. As the value of ϑ increases, and when fiscal policy shock results in the consumption response of rule-of-thumb households higher than that of forward-looking households, the total consumption multiplier and subsequently the GDP multiplier increases. In the presented model, the consumption' response of non-Ricardian households is greater in all the experiments, apart from the capital tax cut (see Figure 1 and 2). As a result the model without non-Ricardian households yields lower responses of consumption and therefore lower multiplier in all the cases apart form the capital tax cut (see Table 6).

The price stickiness parameter (ϖ_p) governs the size of the elasticity of inflation with respect to marginal costs. As Dixon and Rankin (1994) indicate, price stickiness makes any policy that influences aggregate demand effective. When the price stickiness parameter is increased, the transmission mechanism from marginal costs to inflation is abated (the elasticity of inflation with respect to the marginal costs decreases). Consequently, for fiscal policy shocks resulting in the marginal cost increase, as the parameter's value increases, an increase in inflation becomes smaller. This implies a lower response of the

Table 5: Sensitivity of the estimated model to real and nominal frictions

Parameter		*bench−mark*	$\phi^{*}_{x,y}=$ 0	$h=$ 0.01	$\vartheta=$ 0.01	$\varpi_p=$ 0.01	$\varpi_w=$ 0.01	$\kappa=$ 10000	$\phi_k=$ 0.1
gov. con. resp. to debt	ϕ_b^g	0.16	0.10	0.15	0.16	0.16	0.16	0.16	0.15
gov. inv. resp. to debt	ϕ_b^{ig}	0.20	0.19	0.19	0.20	0.20	0.19	0.20	0.20
trans. resp. to debt	ϕ_b^{tr}	0.07	0.04	0.08	0.06	0.07	0.06	0.07	0.08
cap. tax resp. to debt	ϕ_b^{tk}	0.13	0.10	0.13	0.13	0.16	0.17	0.14	0.11
con. tax resp. to debt	ϕ_b^{tc}	0.09	0.08	0.11	0.08	0.09	0.10	0.09	0.10
lab. tax resp. to debt	ϕ_b^{tl}	0.00	-0.01	0.02	-0.02	0.00	0.09	0.01	-0.02
gov. cons. resp. to GDP	ϕ_y^g	0.23		0.21	0.22	0.22	0.22	0.24	0.16
gov. inv. resp. to GDP	ϕ_y^{ig}	0.89		0.88	0.86	0.84	0.83	0.87	0.71
trans. resp. to GDP	ϕ_y^{tr}	0.29		0.41	0.09	0.28	0.16	0.33	0.28
cap. tax resp. to GDP	ϕ_y^{tk}	0.56		0.52	0.62	0.84	0.67	0.74	0.79
cons. tax resp. to GDP	ϕ_y^{tc}	0.15		0.33	-0.03	0.14	0.28	0.07	0.05
lab. tax resp. to GDP	ϕ_y^{tl}	0.05		0.16	-0.08	0.06	0.04	0.10	0.03
AR(1) public cons.	ρ_g	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93
AR(1) public inv.	ρ_{ig}	0.38	0.40	0.40	0.38	0.38	0.49	0.39	0.44
AR(1) transfers	ρ_{tr}	0.88	0.89	0.89	0.88	0.88	0.88	0.88	0.88
AR(1) capital tax	ρ_{tk}	0.80	0.82	0.80	0.80	0.78	0.77	0.79	0.80
AR(1) cons. tax	ρ_{tc}	0.74	0.76	0.73	0.77	0.74	0.74	0.75	0.75
AR(1) labour tax	ρ_{tl}	0.73	0.72	0.75	0.72	0.73	0.81	0.74	0.72
AR nominal interest rate	ρ	0.73	0.73	0.72	0.73	0.73	0.57	0.72	0.63
inflation response	ρ_π	1.62	1.62	1.52	1.64	1.62	1.85	1.64	1.54
output response	ρ_y	0.11	0.11	0.14	0.10	0.10	0.02	0.12	0.25
inverse elast. of labour	σ_L	1.28	1.27	1.36	1.22	1.30	1.06	1.27	1.32
CRRA coefficient	σ_c	0.97	0.99	1.29	1.04	0.98	0.73	0.99	1.09
investment adjust. cost	ϕ	6.32	6.32	6.06	6.33	6.25	5.92	6.23	
capital utilization cost	κ	0.79	0.77	0.80	0.79	1.03	0.88		0.89
price index	γ_p	0.03	0.03	0.03	0.03	0.23	0.21	0.03	0.08
wage index	γ_w	0.18	0.17	0.16	0.16	0.24	0.36	0.23	0.16
calvo prices	ϖ_p	0.74	0.75	0.77	0.74		0.39	0.71	0.60
calvo wages	ϖ_w	0.52	0.52	0.63	0.47	0.55		0.52	0.60
habit formation	h	0.67	0.68		0.69	0.61	0.44	0.63	0.57
fixed cost	φ	1.61	1.62	1.61	1.57	1.70	1.66	1.62	1.63
share of non-Ricardians	ϑ	0.35	0.32	0.60		0.37	0.14	0.35	0.46
AR(1) tfp.	ρ_A	0.98	0.98	0.97	0.98	0.98	0.90	0.98	0.92
AR(1) preferences	ρ_B	0.73	0.73	0.87	0.72	0.79	0.81	0.74	0.85
AR(1) private inv.	ρ_I	0.37	0.37	0.38	0.37	0.39	0.24	0.39	0.82
AR(1) wage markup	ρ_W	0.33	0.33	0.31	0.34	0.36	0.89	0.33	0.29
AR(1) price markup	ρ_P	0.47	0.46	0.49	0.46	0.83	0.83	0.50	0.60

$*$ where $x \in \{g, ig, tr, tc, tl, tk\}$

nominal interest rate and, subsequently a less contractionary effect on the economy. Hence, for fiscal policy shocks which induce an increase in marginal costs, higher levels of price stickiness result in a higher GDP multiplier (as the transmission mechanism to inflation is abated). However, in the case of the shocks which result in a decrease in

Table 6: Sensitivity of the estimated model to real and nominal frictions

Parameter		*bench−*	$\phi^*_{x,y}=$	$h=$	$\vartheta=$	$\varpi_p=$	$\varpi_w=$	$\kappa=$	$\phi_k=$
		mark	0	0.01	0.01	0.01	0.01	10000	0.1
tfp.	σ_A	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
pref.	σ_B	0.06	0.06	0.05	0.05	0.05	0.03	0.05	0.07
inv.	σ_I	0.08	0.08	0.08	0.07	0.08	0.07	0.08	1.46
wage	σ_W	0.38	0.37	0.77	0.27	0.42	0.02	0.37	0.63
price	σ_P	0.05	0.05	0.06	0.05	0.01	0.01	0.04	0.02
gov. cons.	σ_G	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
gov. inv.	σ_{IG}	0.55	0.55	0.55	0.55	0.55	0.56	0.55	0.55
trans.	σ_{TR}	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
cap. tax	σ_{TK}	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
cons. tax	σ_{TC}	0.04	0.03	0.04	0.03	0.04	0.04	0.04	0.04
lab. tax	σ_{TL}	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
mon. pol.	σ_M	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Marginal Likelihood		2529.72	2529.71	2518.76	2522.71	2486.38	2457.74	2523.35	2474.49
Gov. cons. mtp.									
Q1		0.96	1.02	0.86	0.88	0.87	0.75	0.88	0.58
Q4		0.75	0.80	0.71	0.69	0.68	0.56	0.67	0.19
Q12		0.45	0.50	0.43	0.42	0.44	0.35	0.40	-0.03
Q20		0.29	0.33	0.26	0.27	0.27	0.18	0.22	-0.15
Gov. inv. mtp.									
Q1		1.08	1.18	1.09	0.99	0.98	0.85	1.01	0.79
Q4		0.97	1.06	1.00	0.89	0.89	0.64	0.91	0.39
Q12		0.81	0.89	0.83	0.76	0.79	0.46	0.77	0.26
Q20		0.76	0.83	0.75	0.72	0.73	0.33	0.71	0.22
Trans. mtp.									
Q1		0.29	0.28	0.47	0.01	0.27	0.08	0.27	0.24
Q4		0.21	0.21	0.38	-0.02	0.20	0.02	0.19	0.06
Q12		0.05	0.05	0.18	-0.12	0.04	-0.13	0.05	-0.10
Q20		-0.08	-0.07	0.04	-0.22	-0.10	-0.30	-0.08	-0.19
Cons. tax mtp.									
Q1		-0.51	-0.52	-0.93	-0.21	-0.50	-0.53	-0.48	-0.36
Q4		-0.60	-0.62	-0.82	-0.35	-0.58	-0.62	-0.55	-0.17
Q12		-0.50	-0.53	-0.58	-0.33	-0.47	-0.42	-0.43	0.03
Q20		-0.35	-0.37	-0.43	-0.20	-0.32	-0.20	-0.27	0.13
Cap. tax mtp.									
Q1		-0.45	-0.51	-0.35	-0.55	-0.81	-0.94	-0.04	-0.73
Q4		-0.57	-0.65	-0.40	-0.67	-0.92	-1.28	-0.05	-0.99
Q12		-0.66	-0.77	-0.38	-0.79	-0.82	-1.49	-0.03	-0.71
Q20		-0.59	-0.71	-0.25	-0.75	-0.71	-1.56	0.01	-0.54
Lab. tax mtp.									
Q1		-0.33	-0.33	-0.57	-0.04	-0.33	-0.52	-0.32	-0.29
Q4		-0.31	-0.31	-0.50	-0.07	-0.34	-0.86	-0.31	-0.17
Q12		-0.26	-0.28	-0.35	-0.11	-0.32	-1.07	-0.30	-0.10
Q20		-0.19	-0.22	-0.24	-0.07	-0.26	-1.13	-0.26	-0.03

marginal costs, higher levels of price stickiness result in lower GDP multipliers. In the presented model marginal cost increases in all the cases apart form the income taxes. Therefore for these instruments the low level of nominal stickiness (0.01) implies stronger responses of nominal interest rates which puts downward pressure on the expenditure of Ricardian households and results in lower GDP multipliers. On the other hand, for income tax cut low level of nominal stickiness results in stronger decrease of nominal interest rate and therefore higher GDP multipliers.

The wage stickiness parameter (ϖ_w) governs the size of the elasticity of the real wage rate with respect to the wage markup (the difference between the real wage and the wage that would prevail under the flexible wage setup). A higher parameter indicates lower elasticity; therefore, wage becomes less dependent on the markup. Changes in the wage are passed on primarily through two channels: the labour income (mainly implies changes in the consumption of the rule-of-thumb customers) and through the inflation channel (mainly implies changes in the interest rate sensitive consumption and the investment of optimising households). The effect on GDP multiplier depends on which channel prevails.

The capital utilisation adjustment parameter (κ) determines the elasticity of utilisation with respect to the rental rate of capital net of capital taxes. As $\kappa \to \infty$ the model is characterised by the full capital utilisation, whereas when $\kappa \to 0$ capital utilisation becomes more responsive to changes in rental rate. Presence of capital utilisation in the model dampens the fluctuations in marginal costs as fluctuations in rental rate of capital are smaller i.e. the lower the parameter the lower the deviation of marginal cost in absolute terms and subsequently inflation and real rate, also in absolute terms. Therefore in the presented model, if we set κ to a high level then rental rate and subsequently real rate become more responsive to fiscal policy shocks, but capital utilisation does not change. Because it takes long time for capital to accumulate, the multipliers decrease. This is visible in particular in the case of capital tax rate cut, where this channel plays an important role.

The investment adjustment cost parameter (ϕ) governs the size of the elasticity of investment with respect to the Tobin's Q. The higher the parameter, the lower the elasticity, therefore investment becomes less dependent on the price of capital. Consequently, lower values of the parameter increase the response of investment, leading subsequently to higher multipliers. In the presented model only capital tax cut results in the positive response of price of capital. Therefore absence of this friction in this case results in a much stronger response of investment, and therefore higher GDP multiplier (see Table 6). On the other hand, in the remaining cases Tobin's Q decreases, therefore absence of the friction results in lower response of investment and therefore lower GDP multipliers.

4 Impulse-response functions and fiscal multipliers

This section discusses impulse-response functions and present value multipliers of the fiscal policy shocks in the closed-economy setup. To enable comparability across the figures, for the impulse of public spending, investment, and transfers, we use shock equal to a 1 per cent of the steady-state value of GDP. In the case of tax rates we calibrate a standard deviation of shock such that the initial change in the particular tax revenue is equal to a 1 per cent of the steady-state value of GDP.

On each graph presenting impulse-responses, the horizontal axis denotes time in quarters, and the vertical axis denotes the percentage deviation from the steady-state. For each shock, we also provide cumulative present value multipliers of GDP, private consumption and private investment for the short-term (first quarter and four quarters) and the longer term (twelve and twenty quarters). Multipliers are calculated as in

Mountford and Uhlig (2009) with the following formula:

$$PV_t = \frac{\sum_{j=0}^{k}\left(\prod_{i=0}^{j} R_{t+i}^{-1}\right)\Delta Y_{t+j}}{\sum_{j=0}^{k}\left(\prod_{i=0}^{j} R_{t+i}^{-1}\right)\Delta X_{t+j}} \tag{34}$$

where $X_t = \left\{G, IG, TR, \tau_{inc}^c, \tau_{inc}^k \tau_{inc}^l\right\}$.

4.1 Government spending

The dynamics implied by public consumption, investment and transfers shock are presented in Figure 1. The model predicts that the government consumption shock results in a persistent increase in the government's demand for goods and services. The increased demand for goods and services leads subsequently to a higher capital utilisation and an increase in a demand for labour, which put upward pressure on the capital rental rate and the wage rate.[24] The subsequent increase in the marginal cost translates into a higher inflation. Both, higher inflation and an increase in output imply that the monetary authority increases the nominal interest rate.

Consumption of non-Ricardian households increases due to an increase in the labour income. Forward-looking households cut on the interest rate sensitive consumption and investment. Total consumption decreases as Ricardian households are in majority. An increase in government spending leads to an increase in the government's deficit, debt, and is subsequently followed by the fiscal policy reversal.

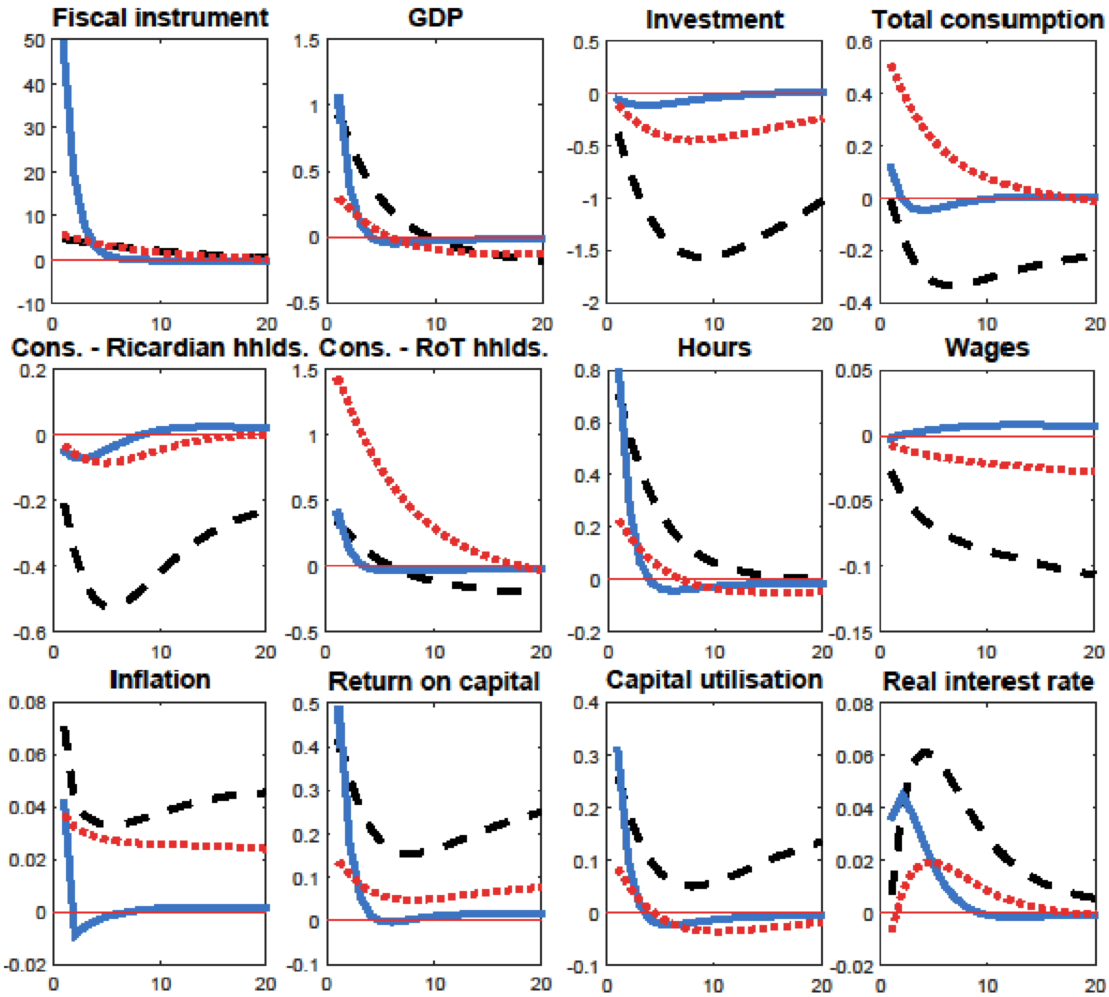
Our results can be compared with the empirical study of fiscal policy in the UK conducted by Perotti (2005), who estimates the impulse-responses of private investment to be significantly negative, which is in line with the results implied by our model.[25] He obtains a positive and significant response of the *ex ante* real interest rate, which is in line with this study and a negative response of inflation, which is not the case here. Perotti (2005) estimates the cumulative response of consumption to be negative in the fourth quarter but positive in the twelfth quarter. In both cases, the responses are not statistically significant.[26]

[24] Consumption of Ricardian households decreases strongly in response to public consumption shock, what makes these households more willing to supply labour. This effect prevails over the higher labour demand, therefore the wage rate decreases.

[25] Perotti (2005) uses the Structural Vector Autoregression (SVAR) approach to estimate, among others, the effect of a government spending shock on key macroeconomic variables in the US, the UK and the euro area. He divides his sample into two parts, one from 1963:1 to 1979:4 and the second from 1980:1 to 2001:2, and reports cumulative responses in the fourth and twelfth quarters. We compare our results with the results based on the sample from 1980:1 to 2001:2, as this period is closer to our sample.

[26] The response of consumption to the government spending shock is discussed widely in the literature. Our result is similar to those of Harrison *et al.* (2005), Harrison and Oomen (2010) and models estimated on the euro area data (see for example Coenen and Straub, 2005, and Ratto *et al.,* 2009). It must be noted that it differs from Gali *et al.* (2007) who built a small DSGE model in which they obtain a positive response of consumption to a government spending shock. However, these authors assume flexible wages and calibrate the weight on the non-Ricardian households to 0.5. It is possible to obtain a positive response of consumption in our model by imposing flexible wages and increasing the weight of non-Ricardian households.

Figure 1: Impulse-responses for expenditure shocks



The blue line (-) relates to public investment, the black line (- -) relates to public consumption, and the red line (.) to public transfers.

Columns $2-4$ of Table **??** provide present value multipliers of output, consumption and investment for the closed-economy model. The magnitudes of the government spending multipliers differ significantly in the literature. Ramey (2011) conducts a literature review on the impact of government spending on GDP in the USA and concludes that the estimates of deficit-financed government spending multiplier lie somewhere between 0.8 and 1.5. In the context of the UK, our benchmark economy setup implies the impact government spending multiplier of 0.97. This result is slightly higher than the average impact multiplier obtained in an empirical study on fiscal policy in the UK conducted by Canova and Pappa (2011), (0.89). When longer horizon is considered, the multiplier becomes smaller. Present value multiplier of consumption and investment remains negative over the longer horizon. This finding is consistent with Ramey (2012), who reports that government consumption crowds out total private expenditure on consumption and investment.

The main difference between the effects of the public investment and public consumption shock is that the former, apart from an increase in the aggregate demand leads also to a rise in the public capital, which subsequently results in an increase in the supply of monopolistic producers and puts downward pressure on prices.[27] The impact increase in the capital utilisation rate and the demand for labour is stronger than in the case of the government consumption shock. The rental rate of capital increases on impact, and the wage rate is above the steady-state following the positive public investment shock (the increase in the wage rate is related to an increase in Ricardian households' consumption, which causes that these households are less willing to supply labour, driving therefore, the wage rate up).

The marginal cost initially increases stronger than in the case of a public consumption shock. The increase in the *ex ante* real interest rate is also larger only at the outset. Afterwards, as public capital accumulates, marginal cost, inflation and the nominal interest rate are below the levels implied by the government consumption shock.

The interest rate sensitive private investment is initially crowded out but is above the steady-state level in around four years. Traum and Yang (2015) and Baxter and King (1993) obtain a positive response of investment in the USA. Such a result is possible to obtain in our model with higher values of the elasticity of output to the public capital.

Similarly to Ratto *et al.* (2009) we obtain a positive response of total consumption to a public investment shock.[28] The main reason behind this is that the response of Ricardian households' consumption is positive in less than eight quarters and that the initial crowding out effect is relatively small. Moreover, the consumption of rule-of-thumb households increases strongly on impact. An increase in the elasticity of output to public capital, or the share of non-Ricardian households results in an even stronger response of total consumption.

The values of government investment multipliers are clearly higher than that implied by government consumption. The effects on GDP and private investment are the highest out of all three public spending instruments.

The direct implication of a transfer shock is an increase in consumption of non-Ricardian households (Ricardian households smooth consumption). Subsequent increase in demand leads to a short-lived increase in the capital utilisation and the labour demand. The capital rental rate increases, whereas the wage rate decreases. In the context of Ricardian households' expenditure, the increase in the real interest rate implies that they cut on consumption and investment.

The GDP multiplier is less favourable when compared with multipliers implied by the remaining government spending instruments. The reason is that transfers have positive

[27] The presence of public capital in the production function implies that from a perspective of a firm an increase in public investment is analogous to an increase in total factor productivity.

[28] Ratto *et al.* (2009) estimate their model on the euro area data.

influence just on the consumption of non-Ricardian households who comprise only a fraction of households. The increase of the share of non-Ricardian households leads to higher multipliers implied by the shock to transfers. It needs to be noted though that the multiplier is similar to that in McKay and Reis (2016).[29] Given the results presented in Table 7 the spending side effects are much stronger than that reported in Jha *et al.* (2014) for developing economies.

4.2 Government Revenue

The dynamics implied by consumption tax, labour and capital tax shock are presented in Figure 2.[30] A decrease in the consumption tax rate results in a fall in consumer prices lasting approximately 7 months. Consequently, the consumption of both optimising and non-optimising households increases. Higher demand for goods, implied by the consumption tax cut, results in an increase of the demand for labour and a higher capital utilisation.

A decrease in the consumption tax leads to an increase in output. Government debt increases; therefore, the total government's expenditure on transfers, public consumption and investment decreases. A decrease in the consumption tax leads to a long-lasting fall in private investment. Table **??** includes present value multipliers for consumption tax shocks. In the short-term, a consumption tax cut induces relatively high multipliers for consumption and GDP.[31] Whereas the cumulative consumption multiplier increases over time, the GDP multiplier drops in the longer horizon.

The instant effect of a decrease in the capital income tax rate is the reallocation of production inputs from labour to capital, which results in a higher capital utilisation and a lower labour demand. The lower demand for labour puts downward pressure on the wage, which is more than offset by the increase of consumption of Ricardian households. The marginal cost decreases as a result of the fall in the rental rate of capital. This is followed by a decrease in inflation and the nominal interest rate. Consumption of non-optimising households decreases due to a drop in labour income, whereas the interest-rate-sensitive investment and consumption of Ricardian households increases. A decrease in the capital income tax rate is also characterised by a substantial increase in a capital utilisation cost. Table **??** presents multipliers of the capital income tax, which can be compared to the results of Leeper *et al.* (2010a) and Leeper *et al.* (2010b). GDP multiplies remain high irrespective of the period of consideration.

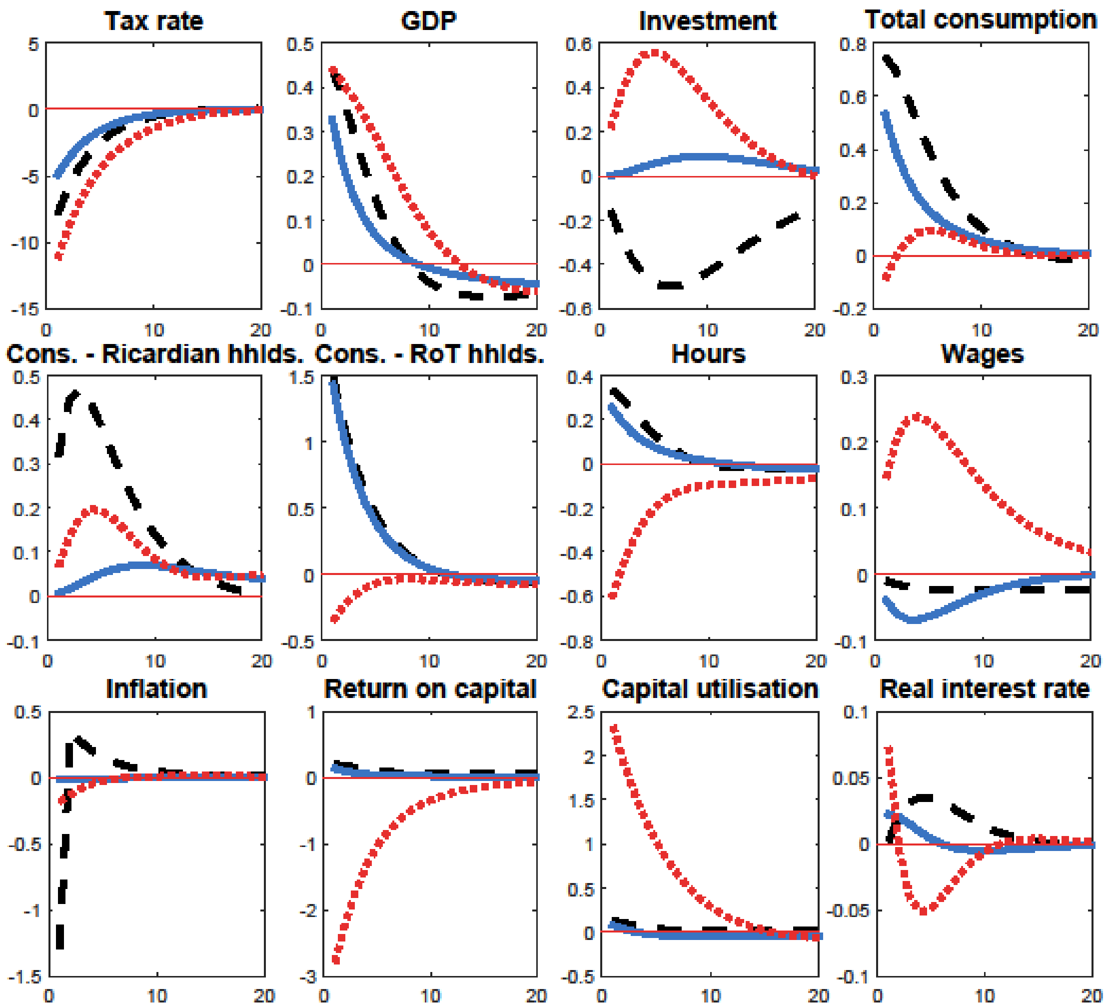
The instant effect of a decrease in the labour tax is the reallocation of production

[29] McKay and Reis (2016) look at the effects of fiscal stabilisers on the dynamics of the business cycle. Their model differs from a standard new-Keynesian DSGE model as it is a merge of a new-Keynesian model with the standard incomplete-markets model of consumption and inequality.

[30] The results can be compared to Cloyne (2013) who estimates the average effects of exogenous tax changes on the UK economy. For the period from 1979Q2 to 2008Q1 (the closest to the period that we use in our estimation) Cloyne (2013) obtains impact multiplier of 0.47, with the peak multiplier of 2.47. Whereas the impact multiplier is in line with our estimates, the peak multipliers estimated (not reported here, as we report cumulative multipliers) in this study are lower in magnitude.

[31] Note that in contrast to public spending multipliers where plus is a desired sign of a multiplier (increase in spending leads to an increase in GDP), in the case of taxes minus is the desired sign (an increase in a tax leads to fall in GDP).

Figure 2: Impulse-responses for tax shocks



The blue line (-) relates to labour income tax cut, the black line (- -) relates to consumption tax cut, and the red line (.) to capital income tax cut.

inputs from capital to labour, leading to an increase in a labour demand. The labour tax cut has a positive impact on GDP and households' disposable income. The consumption of both types of households increases. The increase among the non-optimising households is stronger, as labour income is the main determinant of their consumption. Inflation falls as a result of a lower marginal cost. The model predicts that as a result of a decrease in the labour tax, private investment increases. A decrease in the labour tax results in a lower expenditure of government on consumption, transfers and investment. The GDP multiplier is lower than in the case of the capital tax. The multiplier would yield higher values for higher levels of non-Ricardian households (stronger effect on consumption) and lower nominal rigidities (stronger downward pressure on the nominal interest rate). Also, more volatility due the changes in capital income tax than in the labour income tax is due to more impacts of capital income taxes on investment and the accumulation of physical capital.[32]

5 Extensions

5.1 Public consumption in utility

It is not a surprising result that public consumption yields lower multipliers than public investment due to the supply side effects that public investment generates. The benchmark assumption that households do not receive utility from public goods may be perceived as unrealistic. Therefore we relax it by assuming that government consumption is no longer treated as a wasteful spending by households, but enters in their non-separable utility function, which now becomes:

$$E_0 \sum_{t=0}^{\infty} \varepsilon_t^B \beta^t \left(\frac{1}{1-\sigma_c} X_t^{\iota(1-\sigma_c)} - \frac{\varepsilon_t^L}{1+\sigma_l} \left(L_t^\iota\right)^{(1+\sigma_l)} \right) \tag{35}$$

$$X_t^\iota = \left[a \left(C_t^\iota - H_t\right)^{\frac{\mu-1}{\mu}} + (1-a)\left(G_t - H_{g,t}\right)^{\frac{\mu-1}{\mu}} \right]^{\frac{\mu}{\mu-1}} \tag{36}$$

where X_t denotes effective consumption, $H = hC_{t-1}$ and $H_g = h_g G_{t-1}$. This specification is similar to that of Bouakez and Rebei (2007) and Leeper *et al.* (2010a). The implementation of public consumption into the utility as in equation (35) results in changes in two equations; first is the consumption equation of Ricardian households (37), and the second is the equation determining the wage markup (38)

$$\begin{aligned} \hat{C}_{r,t} = n * &\left\{ \begin{array}{c} \mu \left[\hat{R}_t - E_t \hat{\pi}_{c,t+1} + E_t \hat{\varepsilon}_{t+1}^B - \hat{\varepsilon}_t^B \right] \\ + \frac{(1-f)(1-\mu\sigma_c)}{1-h_g} \left[E_t \hat{G}_{t+1} - (1+h_g)\hat{G}_t + h_g \hat{G}_{t-1} \right] \end{array} \right\} \\ &+ \frac{1}{1+h} E_t \hat{C}_{r,t+1} + \frac{h}{1+h} \hat{C}_{r,t-1} \end{aligned} \tag{37}$$

$$\begin{aligned} X_t^w = \hat{w}_t - \sigma_l \hat{L}_t &- \frac{1-(1-\mu\sigma_c) f}{\mu(1-h_c)} \left[\hat{C}_{r,t} + h\hat{C}_{r,t-1} \right] \\ &+ \frac{(1-f)(1-\mu\sigma_c)}{\mu(1-h_g)} \left[\hat{G}_t - h_g \hat{G}_{t-1} \right] - \frac{\tau^c}{1+\tau^c} \hat{\tau}_t^c - \frac{\tau^l}{1-\tau^l} \hat{\tau}_t^l \end{aligned} \tag{38}$$

[32] We have also conducted experiments in which we apply expansionary fiscal policy in an economy where each steady-state tax rate is increased at a time by 10%. The results are not very sensitive to such changes. This leads to a slightly higher tax multipliers (in absolute terms) in the analysed period. For consumption taxes the Q4 multiplier is -0.56 and the Q20 multiplier is -0.34; for labour taxes the Q4 multiplier is -0.32 and the Q20 multiplier is -0.25; for capital taxes the Q4 multiplier is -0.54 and the Q20 multiplier is -0.56.

where:

$$n = \left[\frac{1}{(1-\mu\sigma_c) f - 1}\right] \frac{(1-h)}{(1+h)} < 0$$

$$f = \frac{a\left(C_r\left(1-h\right)\right)^{\frac{\mu-1}{\mu}}}{a\left(C_r\left(1-h\right)\right)^{\frac{\mu-1}{\mu}} + (1-a)\left(G\left(1-h_g\right)\right)^{\frac{\mu-1}{\mu}}} \in \; <0,1> \text{ and,}$$

$$\hat{\pi}_{c,t+1} = \hat{\pi}_{t+1} - \frac{\tau^c}{1+\tau^c}\hat{\tau}_t^c + \frac{\tau^c}{1+\tau^c}\hat{\tau}_{t+1}^c$$

The elasticity of substitution between public and private consumption (μ) takes values from 0 to ∞. Equation (37) implies that as the elasticity of substitution increases ($\mu \to \infty$) the weight on the *ex ante* real interest rate in the consumption units increases, whereas the weight on the government consumption $\left(\frac{(1-f)(1-\mu\sigma_c)}{(1-h_g)}\right)$ decreases. Therefore, for higher levels of the elasticity the *ex ante* real interest rate remains a dominant force in determination of Ricardian households' consumption. When $\mu > \frac{1}{\sigma_c}$ private and public spending are Edgeworth substitutes and increase in public consumption leads directly to a decrease in private expenditure of Ricardian households. Public and private consumption are Edgeworth complements when $\mu < \frac{1}{\sigma_c}$, and in that case increase in public consumption have positive impact on private consumption through the analysed channel. Similar effects can be noted in the case of the wage markup. When $\mu > \frac{1}{\sigma_c}$ any increase in public spending has a negative effect on the wage. On the other hand, small values of μ imply a positive effect of public consumption on the wage; therefore, an increase in the wage is associated with an increase in the consumption expenditure. Interestingly, strong complementarity of public and private consumption can imply an increase in the wage rate and consumption in response to a public consumption shock.

The second parameter determining the effects of public consumption expenditure on private is the share of public consumption in total consumption $0 < (1-a) < 1$. When $a = 0 \Rightarrow f = 0$ total consumption of Ricardian households is public and when $a = 1 \Rightarrow f = 1$ total consumption is private. Clearly the lower the level of a the higher the effects of public on private consumption, as $\frac{(1-f)(1-\mu\sigma_c)}{(1-h_g)}$ increases.

Finally, positive effect of public on private consumption can be achieved by assuming high value of habit formation in government consumption (h_g) which results in a significant weight on public consumption variables in equation 37 and 38.

The results of estimation are presented in Table **??** and **??**.[33] The habit formation parameter is estimated to 0.68, the elasticity of substitution to 1.08, and the share parameter to 0.76. Table **??** shows present value GDP multipliers for the estimated model with government consumption in utility.

[33]We set the prior mean for the share of public good in consumption (a) to 0.75, a level calibrated by Coenen *et al.* (2013) for the euro area. We set the beta prior mean for habit formation (h_g) to 0.7 and a standard deviation of 0.1. For the elasticity of substitution (μ) we select gamma distribution prior with a mean of 1 and a standard deviation of 0.5.

Table 7: Multipliers

	benchmark			public cons. in utility			open economy			zero lower bound benchmark			zero lower bound open economy		
	Y	C	I	Y	C	I	Y	C	I	Y	C	I	Y	C	I
Gov. cons. mtp.															
Q1	0.97	-0.01	-0.06	0.97	-0.01	-0.06	0.79	-0.00	-0.04	1.23	0.15	0.02	1.05	0.05	0.01
Q4	0.76	-0.12	-0.15	0.76	-0.13	-0.15	0.64	-0.06	-0.09	1.26	0.17	0.04	1.10	0.07	0.02
Q12	0.44	-0.27	-0.31	0.43	-0.28	-0.31	0.42	-0.17	-0.20	1.11	0.09	-0.03	0.98	0.04	-0.03
Q20	0.25	-0.35	-0.42	0.24	-0.36	-0.42	0.28	-0.26	-0.28	0.92	0.00	-0.12	0.84	-0.03	-0.10
Gov. inv. mtp.															
Q1	1.08	0.07	-0.01	1.08	0.07	-0.01	0.82	0.02	-0.01	1.11	0.10	0.00	0.85	0.03	-0.00
Q4	0.96	0.01	-0.04	0.96	0.01	-0.04	0.76	-0.01	-0.02	1.09	0.09	0.00	0.84	0.02	-0.01
Q12	0.78	-0.03	-0.08	0.77	-0.03	-0.08	0.68	-0.06	-0.08	1.05	0.11	0.00	0.83	-0.00	-0.05
Q20	0.72	-0.02	-0.08	0.71	-0.02	-0.08	0.65	-0.09	-0.11	1.04	0.14	0.01	0.83	-0.01	-0.07
Trans. mtp.															
Q1	0.30	0.32	-0.02	0.31	0.33	-0.02	0.07	0.11	-0.01	0.42	0.40	0.02	0.15	0.13	0.01
Q4	0.23	0.30	-0.05	0.23	0.30	-0.05	0.03	0.11	-0.02	0.48	0.45	0.05	0.18	0.15	0.02
Q12	0.05	0.25	-0.11	0.05	0.26	-0.11	-0.07	0.11	-0.05	0.46	0.47	0.06	0.15	0.19	0.02
Q20	-0.09	0.23	-0.14	-0.09	0.23	-0.14	-0.17	0.10	-0.07	0.36	0.45	0.04	0.07	0.19	-0.00
Cons. tax mtp.															
Q1	-0.49	-0.52	0.03	-0.50	-0.53	0.03	-0.13	-0.21	0.01	-0.62	-0.61	-0.01	-0.22	-0.23	-0.00
Q4	-0.56	-0.67	0.08	-0.57	-0.68	0.08	-0.16	-0.33	0.04	-0.91	-0.89	-0.03	-0.36	-0.39	-0.00
Q12	-0.46	-0.79	0.22	-0.47	-0.80	0.22	-0.18	-0.58	0.15	-1.19	-1.20	-0.05	-0.55	-0.72	0.05
Q20	-0.30	-0.78	0.30	-0.31	-0.79	0.30	-0.13	-0.69	0.26	-1.18	-1.24	-0.03	-0.57	-0.86	0.13
Cap. tax mtp.															
Q1	-0.44	0.06	-0.03	-0.44	0.05	-0.03	-0.50	0.02	-0.02	-0.35	0.11	-0.01	-0.37	0.05	-0.00
Q4	-0.53	-0.01	-0.08	-0.53	-0.01	-0.08	-0.58	-0.01	-0.06	-0.36	0.10	-0.03	-0.33	0.06	-0.01
Q12	-0.60	-0.07	-0.16	-0.60	-0.07	-0.16	-0.64	-0.07	-0.13	-0.36	0.06	-0.09	-0.26	0.07	-0.03
Q20	-0.52	-0.07	-0.18	-0.52	-0.07	-0.17	-0.59	-0.10	-0.15	-0.25	0.06	-0.10	-0.16	0.07	-0.04
Lab. tax mtp.															
Q1	-0.35	-0.35	0.00	-0.35	-0.35	0.00	-0.10	-0.11	-0.00	-0.34	-0.35	0.00	-0.04	-0.10	0.01
Q4	-0.31	-0.34	0.00	-0.31	-0.35	0.00	-0.11	-0.12	-0.01	-0.28	-0.33	0.01	0.02	-0.08	0.02
Q12	-0.24	-0.36	-0.03	-0.25	-0.36	-0.03	-0.11	-0.16	-0.03	-0.19	-0.33	0.00	0.12	-0.07	0.03
Q20	-0.17	-0.37	-0.04	-0.17	-0.37	-0.04	-0.06	-0.18	-0.04	-0.11	-0.33	-0.01	0.20	-0.07	0.04

Multipliers do not differ much from the benchmark calibration implying that model with non-separable non-wasteful public consumption in utility does not introduce significant changes in contrast to results of Coenen *et al.* (2013) for the euro area. In fact, the estimates imply that the GDP multiplier for the public consumption shock is lower than in the case when public consumption does not enter utility because $(1 - \mu\sigma_c) < 0$. For the remaining instruments the effect is negligible and naturally improving multipliers.

5.2 Open economy scenario

We also estimate an open-economy model of UK to analyse the implications of fiscal policy with international trade. The small open-economy specification follows closely Adolfson *et al.* (2008). We extend it by allowing for import of public consumption and investment, (see on-line appendix for more details on the model). The estimation results are presented in columns (13) − (16) of Table **??** and **??** respectively[34][35]. The estimates of price stickiness parameters in the importing sector are lower than in the domestic sector as in Millard (2011). These estimates imply that prices of imports and exports react to the changes in marginal costs roughly every $1.5 - 3$ quarters. Low estimates of all the price indexation parameters, ranging from 0.08 to 0.13, indicate that the estimated Phillips curves are mostly forward-looking. The markups in the importing industries in the private sector are higher than those in the public sector, suggesting that the willingness to substitute among the imported goods in the private sector is relatively lower than for the case of the public sector. Now we turn to the discussion of multipliers in the open-economy (Table **??**).

The GDP multipliers tend to be lower in the open-economy than in the closed-economy as a fraction of the stimulus is diverted directly or indirectly to the rest of the world through the import channel. The only exception is for capital taxes. A decrease in capital taxes causes a drop in the inflation of domestically produced goods. It then lowers not only the real interest rate but also causes a depreciation of real exchange rate resulting in an increase in exports and GDP. The presence of this channel implies that for capital taxes the GDP multiplier is higher in open than in the closed-economy.

A decrease in labour taxes also lowers the prices of domestically produced goods but results in a lower GDP multiplier than in the closed-economy setup. There are two main reasons behind it. First, wages are sticky therefore a drop in labour taxes is not passed through so quickly to the marginal costs (and prices) as an equivalent drop in capital

[34] For the open economy model we generate four Markov chains of length 750,000.The acceptance ratios are around 0.27. In the open-economy scenario we use additionally price of private consumption and investment, price of public consumption and investment, nominal exchange rate and volume of export. Data are detrended with their linear trends.

[35] We select the prior distribution for the price stickiness, price indexation, and markup related parameters in the import and export markets analogously to the domestic producers. The priors on the remaining parameters are set as in Adolfson *et al.* (2008). We set the elasticity of substitution between domestic and imported public investment to 1.5. Finally, we set the import-shares in aggregate public and private consumption and public and private investment to match the data from the input-output analytical tables for the UK. The shares of imports in consumption investment and public consumption equal 22 per cent, 32 per cent and 11 per cents respectively. The share of imports in public investment is set to 16 per cent.

taxes. Second, a decrease in capital taxes implies an increase in income of Ricardian households who smooth consumption. In contrast a decrease in labour taxes leads to an increase of income for both types of households, and non-Ricardian households spend it instantly on consumption goods and services which also puts upward pressure on prices. Therefore, the real exchange rate depreciation and an increase in export are smaller than in the case of capital taxes. This, combined with the fact that part of the stimulus is diverted indirectly through the import channel, implies that the GDP multiplier is lower than in the closed-economy specification. In the case of consumption taxes and public spending instruments the GDP multipliers are lower in the case of open-economy. The effect is stronger for public consumption and investment because a fraction of the stimulus is directly diverted from the economy. Also, the drop in the public investment multiplier is relatively greater as the share of stimulus diverted from the economy is higher for this fiscal instrument.

5.3 Zero lower bound on nominal interest rate

Table **??** presents also the results for the situation in which we impose a zero lower bound on the nominal interest rate.[36] In general the results presented are consistent with McKay and Reis (2016) who show that the automatic stabilizers are more effective during a zero lower bound episode.[37] The zero lower bound on the nominal interest rate intensifies the stimulus in the case of public expenditure and consumption taxes. The reason is that all four instruments stimulate the economy through the demand side and therefore lead to a higher inflation. At the same time, the nominal interest rate remains constant which implies that the real interest rate drops with higher inflation which stimulates significantly the private expenditure. In the case of capital and labour income taxes inflation decreases. Therefore, holding the nominal interest rate at a constant level results in an increase of the real interest rate. This motivates Ricardian households to cut on the current expenditure and save. In the open-economy specification, the implications of the zero lower bound on the nominal interest rate are similar to that in closed-economy. An expansionary fiscal policy conducted with spending instruments and consumption taxes becomes more efficient, whereas that conducted with income taxes becomes less efficient.

6 Conclusions

This paper analyses the implications of fiscal policy in the UK economy in an estimated DSGE model over the period from 1987:Q2 to 2011:Q1. The parameter estimates indicate that public investment, consumption and capital income taxes play the most important role in controlling for the government debt over the sample period. Additionally, capital income taxes and government investment characterise significant procyclical response to GDP.

Our results show that independently whether we introduce public consumption into

[36] We obtain the results by holding the nominal interest rate at the zero level by ten quarters.

[37] McKay and Reis (2016) however do not look at the effectiveness of individual fiscal stabilizers, what we do in this paper.

the utility of households or not, or whether we consider closed or open-economy setup, public consumption and public investment are the most effective fiscal instruments in the short-run, whereas capital income tax and the public investment are such instruments in the longer horizon. Public transfers yield relatively lower multipliers when compared with the remaining fiscal policy instruments. The implication of the these results is that cuts in government investment are the most harmful for the economy.

A zero lower bound on the nominal interest rate changes the results considerably. It increases the effectiveness of consumption taxes and public expenditure instruments independently whether we consider closed or open economy. On the other hand, income taxes become the least effective instruments to stimulate the economy. The implication of this result is that when nominal interest rate is at the zero lower bound, cuts conducted with spending instruments or consumption taxes are the most harmful for the economy, whereas cuts conducted with income taxes are the least harmful for the economy.

Finally, we show that nominal and real frictions play an important role in the transmission channel of fiscal policy. In particular we observe that non-Ricardian households tend to make fiscal policy more effective. At the same time nominal rigidities (sticky prices and wages) increase the effectiveness of public spending and consumption taxes and decrease that of income taxes.

References

[1] Adjemian, S., Bastani, H., Juillard, M., Mihoubi, F., Perendia, G., M., Villemot, S. (2011) Dynare: reference manual, version 4, *Dynare Working Papers*, 1, CEPREMAP.

[2] Adolfson, M.; Laséen, S.; Lindé, J; Villani, M (2008) Empirical Properties Of Closed and Open-Economy DSGE Models Of The Euro Area, *Macroeconomic Dynamics*, vol. 12(S1), pp. 2-19.

[3] Ascari, G., Rankin, N. (2013) The effectiveness of government debt for demand management: Sensitivity to monetary policy rules, *Journal of Economic Dynamics and Control*, vol. 37(8), pp. 1544-1566.

[4] Batini, N., Harrison, R., Millard, S. P. (2003) Monetary policy rules for an open economy, *Journal of Economics Dynamics and Control*, vol. 27(11-12), pp. 2059–2094.

[5] Baxter, M., King, R. G. (1993) Fiscal policy in general equilibrium, *American Economic Review*, vol. 83(3), pp. 315-334.

[6] Benigno, P., Woodford, M. (2003) Optimal monetary and fiscal policy: a linear-quadratic approach, *NBER Macroeconomics Annual 2003*, vol. 18, pp. 271–333.

[7] Bhattarai, K. (2007) Welfare impacts of equal-yield tax experiment in the UK economy, *Applied Economics*, vol. 39(12), pp. 1545-1563.

[8] Bhattarai, K., Whalley, J. (1999) Role of labour demand elasticities in tax incidence analysis with heterogeneity of labour, *Empirical Economics*, vol. 24(4), pp. 599-620.

[9] Bouakez, H., Rebei , N. (2007) Why Does Private Consumption Rise After A Government Spending Shock?, *Canadian Journal of Economics*, vol. 40(3), pp. 954–979.

[10] Brewer, M., Francesconi, M., Gregg, P., Grogger, J. (2009) Feature: in-work benefit

reform in a cross-national perspective: introduction, *The Economic Journal*, vol. 119(535), pp. F1-F14.
[11] Burnside, C., Eichenbaum, M., Fisher, J. D. M. (2004) Fiscal shocks and their consequences, *Journal of Economic Theory,* vol. 115(1), pp. 89-117.
[12] Calvo, G. A. (1983) Staggered prices in a utility-maximizing framework, *Journal of Monetary Economics*, vol. 12(3), pp. 383-398.
[13] Campbell, J. Y., Mankiw, N. G. (1989) Consumption, income, and interest rates: reinterpreting the time series evidence, *NBER Macroeconomics Annual 1989*, vol. 4, pp. 185–216.
[14] Canova, F., Pappa, E. (2011) Fiscal policy, pricing frictions and monetary accommodation, *Economic Policy*, vol. 26(68), pp. 555-598.
[15] Cardi, O. (2010) A note on the crowding-out of investment by public spending, *Macroeconomic Dynamics*, vol. 14(4), pp. 604-615.
[16] Christiano, L. J., Eichenbaum, M., Evans, C. (2005) Nominal rigidities and the dynamic effects of a shock to monetary policy, *Journal of Political Economy*, vol. 113(1), pp. 1-45.
[17] Christiano, L., Eichenbaum, M., Rebelo, S. (2011) When is the government spending multiplier large?, *Journal of Political Economy*, vol. 119(1), pp. 78- 121.
[18] Cloyne, J. (2013) Discretionary Tax Changes and the Macroeconomy: New Narrative Evidence from the United Kingdom. *American Economic Review*, vol. 103(4), pp. 1507-1528.
[19] Coenen, G., Straub, R. (2005) Does government spending crowd in private consumption? Theory and empirical evidence from the euro area, *International Finance*, vol. 8(3), pp. 435-470.
[20] Coenen, G., Straub, R., Trabandt, M. (2013) Gauging the effects of fiscal stimulus packages in the euro area, *Journal of Economic Dynamics and Control*, 37(2), pp. 367-386.
[21] Cogan, J. F., Cwik, T., Taylor, J. B., Wieland, V. (2010) New Keynesian versus old Keynesian government spending multipliers, *Journal of Economic Dynamics and Control*, vol. 34(3), pp. 281-295.
[22] Di Cecio, R., Nelson, E. (2007) An estimated DSGE model for the United Kingdom, *Federal Reserve Bank of St Louis Review*, vol. 89(4), pp. 215-231.
[23] Dixon, H., D., Rankin, N. (1994) Imperfect Competition and Macroeconomics: A Survey, *Oxford University Press*, vol. 46(2), pp. 171-199.
[24] Doan, T., Litterman, R., Sims, Ch. (1984) Forecasting and Conditional Projections Using Realistic Prior Distributions, *Econometric Reviews*, vol. 3(1), pp. 1-100.
[25] Drautzburg, T., Uhlig, H. (2015) Fiscal Stimulus and Distortionary Taxation, *Review of Economic Dynamics*, vol. 18(4),pp. 894-920.
[26] Edge, R. M., Laubach, T., Williams, J. C. (2003) The responses of wages and prices to technology shocks, *Working Papers in Applied Economic Theory*, no. 21, Federal Reserve Bank of San Francisco.
[27] Eggertsson, G., B. (2011) What fiscal policy is effective at zero interest rates?, *NBER Macroeconomics Annual 2010*, 25, pp. 59-112.

[28] Erceg, C. J., Henderson, D. W., Levin, A. T. (2000) Optimal monetary policy with staggered wage and price contracts, *Journal of Monetary Economics*, vol. 46(2), pp. 281-313.

[29] Erceg, Ch. J., Guerrieri, L., Gust, Ch. (2006) Expansionary fiscal shocks and the US trade deficit, *International Finance*, vol. 8(3), pp. 363-397.

[30] Faccini, R., Millard, S. P., Zanetti, F. (2011) An estimated DSGE model for the United Kingdom, *Bank of England Working Paper*, no. 408.

[31] Forni, L., Monteforte, L., Sessa, L. (2009) The general equilibrium effects of fiscal policy: estimates for the euro area, *Journal of Public Economics*, vol. 93(3-4), pp. 559-585.

[32] Fuhrer, J. (2000) Habit formation in consumption and its imptications for monetary-policy models, *American Economic Review*, vol. 90(5), pp. 367-390.

[33] Gali, J., Lopez-Salido, J. D., Valles, J. (2007) Understanding the effects of government spending on consumption, *Journal of the European Economic Association*, vol. 5(1), pp. 227-270.

[34] Gelman, A., Gilks, W. R., Roberts, G. O. (1997) Weak convergence and optimal scaling of random walk metropolis algorithms, *The Annals of Aplied Probability*, vol. 7(1), pp. 110-120.

[35] Harrison, R., Nikolov, K., Quinn, M., Ramsay, G., Scott, A., Thomas, R. (2005) The Bank of England Quarterly Model, London: Bank of England.

[36] Harrison, R., Oomen, O. (2010) Evaluating and estimating a DSGE model for the United Kingdom, *Bank of England Working Paper*, no. 433, Bank of England.

[37] Holly, S., Weale, M. (2000) *Econometric Modelling: Techniques and Applications*, Cambridge University Press.

[38] Jha, S., Mallick, S. K., Park, D., Quising, P. F. (2014) Effectiveness of countercyclical fiscal policy: Evidence from developing Asia, *Journal of Macroeconomics*, vol. 40(2014), pp. 82-98.

[39] Juillard, M., Karam, P., Laxton, D., Pesenti, P. (2006) Welfare-based monetary policy rules in an estimated DSGE model of the US economy, *Working Paper Series*, no. 0613, European Central Bank.

[40] Jones, J. B. (2002) Has fiscal policy helped stabilize the postwar U.S. economy?, *Journal of Monetary Economics*, vol. 49(2002), pp. 709-746.

[41] Keynes, J. M. (1936) *The general theory of employment, interest and money*, MacMillan and Cambridge University Press.

[42] Leeper, E.,Walker,T. B.,Yang, S. C. S. (2010a) Government investment and fiscal stimulus in the short and long runs, *Journal of Monetary Economics* vol. 57(8), pp. 1000-1012.

[43] Leeper, E. M., Plante, M., Traum, N. (2010b) Dynamics of fiscal financing in the United States, *Journal of Econometrics*, vol. 156(2), pp. 304-321.

[44] Lopez-Salido, J. D., Rabanal, P. (2006) Government spending and consumption-hours preferences, *Working Paper Series*, 02/2006.

[45] Mankiw, N. (2000) The savers-spenders theory of fiscal policy, *American Economic Review, vol.* 90(2), pp.120-125.

[46] McKay, A., Reis, R. (2016) The role of automatic stabilizers in the U.S. business cycle, *Econometrica*, vol. 84(1),pp. 141194.

[47] Meade, J. (1978), The structure and reform of direct taxation: report of a committee chaired by Professor J. E. Meade for the Institute for Fiscal Studies, London : George Allen & Unwin.

[48] Mendoza, E. G., Razin, A., Tesar, L. L. (1994) Effective tax rates in macroeconomics. Cross-country estimates of tax rates on factor incomes and consumption, *Journal of Monetary Economics*, vol. 34(1994), pp. 297-323.

[49] Millard, P. S. (2011) An estimated DSGE model of energy, costs and infation in the United Kingdom, *Bank of England Working Paper No. 420*, Bank of England.

[50] Mirrlees, J. A. (1971) An exploration in the theory of optimum income taxation, *Review of Economic Studies*, vol. 38(114), pp. 175-208.

[51] Mirrlees J. A, S., Besley, T., Blundell, R., Bond, S., Chote, R., Gammie,M., Johnson, P., Myles, G., Poterba, J. (2010) *Dimensions of tax design: the Mirrlees review*, Oxford: Oxford University Press.

[52] Mountford, A., Uhlig, H. (2009) What are the effects of fiscal policy shocks?, *Journal of Applied Econometrics*, vol. 24(6), pp. 960-992.

[53] Perotti, R. (2005) Estimating the effects of fiscal policy in OECD countries, *Proceedings*, Federal Reserve Bank of San Francisco.

[54] Ramey, V. A. (2011) Can government purchases stimulate the economy?, *Journal of Economic Literature*, vol. 49(3), pp 673-685.

[55] Ramey, V. A. (2012) Government spending and private activity, *NBER Chapters, in: Fiscal Policy after the Financial Crisis,* National Bureau of Economic Research.

[56] Ramsey, F. P. (1927) A contribution to the theory of taxation, *The Economic Journal,* vol. 37(145), pp. 47-61.

[57] Ratto, M., Roeger, W., In't Veld, J. (2009) QUEST III: An estimated open-economy DSGE model of the euro area with fiscal and monetary policy, *Economic Modelling*, vol. 26(1), pp. 222-233.

[58] Romer, C., D., Romer, D. H. (2010) The Macroeconomic Effects of Tax Changes: Estimates Based on a New Measure of Fiscal Shocks, *American Economic Review*, vol. 100(3), pp. 763-801.

[59] Schmitt-Grohe, S., Uribe, M. (2006) Optimal fiscal and monetary policy in a medium-scale macroeconomic model, *NBER Macroeconomics Annual 2005*, vol. 20, pp. 383-462.

[60] Smets, F., Wouters, R. (2003) An estimated dynamic stochastic general equilibrium model of the euro area, *Journal of the European Economic Association*, vol. 1(5), pp. 1123-1175.

[61] Smets, F., Wouters, R. (2007) Shocks and frictions in US business cycles: a Bayesian DSGE approach, *American Economic Review*, vol. 97(3), pp. 586-606.

[62] Stahler, N., Thomas, C. (2012) FiMod A DSGE model for fiscal policy simulations, *Economic Modelling*, vol. 29(2), pp. 239-261.

[63] Traum, N., Yang, S.-C.S. (2015) When Does Government Debt Crowd Out Investment?, *Journal of Applied Econometrics*, vol. 30(1), pp. 24-45.

[64] Villemot, S. (2011) BVAR models "a la Sims" in Dynare, *Dynare documentation*, Dynare

[65] Woodford, M. (1996) Control of the public debt: a requirement for price stability, *NBER Working Paper*, no. 5684, National Bureau of Economic Research.

[66] Woodford, M. (2003) *Interest and prices: foundations of a theory of monetary policy*, Princeton University Press, Princeton and Oxford.

A Data description, prior and posterior distribution

In order to estimate the benchmark model, twelve data series are used: GDP, consumption, investment, wages, inflation, hours, government consumption, government investment, effective consumption, labour and capital tax rates, and transfers. The data are from the Bank of England (BoE) and Office for National Statistics (ONS) webpages, and cover period from 1987:Q2 to 2011:Q1. While some of the data series can be obtained directly from the ONS, other including effective tax rates, and transfers were calculated closely following Mendoza *et al.* (1994), Jones (2002), and Leeper *et al.* (2010). To derive the effective tax rates on labour income, $\left(\tau^l\right)$, and capital income, $\left(\tau^k\right)$, firstly the average tax rate on income, $\left(\tau^i\right)$ is calculated . The reason for it is that the ONS does not distinguish between labour and capital income taxes.

The average income tax rate:

$$\tau^i = \frac{IT + OCT}{W + PI + GOS + MI} \tag{39}$$

where IT denotes income taxes paid by households (HHLDs) and non-profit institutions serving households (NPISHs) [QWMQ]; OCT stands for other current taxes paid by HHLDs & NPISHs [NVCO]; W denotes wages and salaries of HHLDs & NPISHs [QWLW]; PI denotes property income of HHLDs & NPISHs [QWME]; GOS denotes gross operating surplus of HHLDs & NPISHs [QWLS]; MI stands for gross mixed income of HHLDs & NPISHs [QWLT];

The effective labour tax rate:

$$\tau^l = \frac{(W + 0.5 * MI) * \tau^i + ESC}{W + ESC} \tag{40}$$

where ESC stands for employers social contributions of HHLDs & NPISH [QWLX]; (denominator comprises compensations of employees)

The effective capital tax rate:

$$\tau^k = \frac{(PI + GOS + 0.5 * MI) * \tau^i + (ITG + OCTG - IT - OCT) + CT + OTP}{OS} \tag{41}$$

where ITG stands for current taxes on income received by general government (GG) [NMZJ]; $OCTG$ stands for other current taxes received by the GG [NVCM]; CT denotes capital taxes of HHLDs & NPISHs [NSSO]; OTP stands for other taxes on production [NMYD];OCT stands for other current taxes OS stands for gross operating surplus of the whole economy;

The effective consumption tax rate:

$$\tau^c = \frac{TTP}{C - TTP} \tag{42}$$

where TTP stands for total taxes on products (GG) [NVCC]; C stands for final consumption expenditure of HHLDs & NPISHs.

Transfers:

$$TR^M = TR_t + \left[TC_t^M + TL_t^M + TK_t^M - TRes_t\right] \tag{43}$$

where $\left[TC_t^M + TL_t^M + TK_{t-1}^M - TRes_t\right]$ is a tax residual. TR_t represents the sum of: social benefits other than social transfers in kind (GG) [NNAD], other current transfers (GG) [NNAN], subsidies (GG) [NMRL], total capital transfers (GG) [NNBC]. $TC_t^M + TL_t^M + TK_t^M$ denotes total tax revenue. $TRes_t$ represents total resources and totals sum of: gross operating surplus (GG) [NMXV], total taxes on production and import received (GG) [NMYE], other taxes on production (GG) [NMYD], property income received (GG) [NMYU], current taxes on income and wealth (GG) [NMZL], total social contributions (GG) [NMZR], other current transfers (GG) [NNAA], total capital transfers receivable (GG) [NNAY].

Public inv.: government gross fixed capital formation [RPZG];

Public cons.: total final consumption expenditure by general government [NMRP];

GDP: government investment+government consumption+private consumption+private investment;

Private inv.: total gross fixed capital formation [NPQS]- government investment;

Private cons.: final consumption by households [ABJQ]+ final consumption by non-profit institutions [HAYE]

Hours: Actual hours worked, Labour Force Survey [YBUS];

Wages: {Compensation of employees [DTWM]+0.5*(Mixed income [ROYH])} / (Hours worked);

Inflation: first difference of GDP deflator [YBHA/ABMI]

For the open economy specification, we additionally use the following data:

Export: export of goods and services[IKBH]

Private consumption price inflation: first difference of private consumption deflator [(ABJQ+HAYE)/ (ABJR+HAYO)]

Private investment price inflation.: first difference of private investment deflator [(NPQS-RPZG)/ (NPQT-DLWF)]

Public cons. price inf.: first difference of public consumption deflator [NMRP/NMRY]

Public inv. price inf.: first difference of public investment deflator [RPZG/DLWF]

Nominal exchange rate: Quarterly average effective exchange rate index, Sterling (XUQABK67)

Definition of variables:

$$X = ln\left(\frac{x}{pop}\right) * 100 \tag{44}$$

where x = government investment, government consumption, transfers, GDP, private consumption, private investment, hours, export; and pop is defined as all persons aged 16 and over table A02 [Labour Force Survey Summary]. As in Leeper (2010) all data are detrended with their linear trend. We estimates the model also on the data detrended with Hodrick -Prescott filter(Canova (1998) shows many drawbacks of using the Hodrick-Prescot filter as detrending method). In general we can say that multipliers calculated with the model in which parameters were estimated with the data detrended with Hodrick-Prescott filter tend to be lower than in the case when linear detrending method is applied. In the majority of the cases the difference is less than 0.1 and never greater than 0.16, for cumulative multipliers at Q1, Q4, Q12, Q20.

On-line Appendix for Macroeconomic Impacts of Fiscal Policy Shocks in the UK: A DSGE Analysis

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1 Log-linearized system of equations for the closed-economy

This section presents a log-linearized system of equations. The variables without subscript t denote the steady-state values, whereas a hat over a variable denotes its log-deviations from the steady-state.

1.1 Households:

$$\hat{C}_{nr,t}= \left(1-\tau^{l}\right)\frac{wL}{\left(1+\tau^{c}\right)C_{nr}} * \left(\hat{w}_{t}^{\tau}+\hat{L}_{t}-\frac{\tau^{l}}{1-\tau^{l}}\hat{\tau}_{t}^{l}\right)+\frac{TR}{\left(1+\tau^{c}\right)C_{nr}}\widehat{TR}_{t}-\frac{\tau^{c}}{1+\tau^{c}}\hat{\tau}_{t}^{c} \tag{1}$$

$$\hat{C}_{r,t}=\frac{E_{t}\hat{C}_{r,t+1}}{1+h}+\frac{h\hat{C}_{r,t-1}}{1+h}-\frac{1}{\sigma_{c}}\frac{1-h}{1+h}E_{t}\left[R_{t}-\hat{\pi}_{t+1}+\frac{\tau^{c}}{1+\tau^{c}}\left(\hat{\tau}_{t}^{c}-E_{t}\hat{\tau}_{t+1}^{c}\right)+\hat{\varepsilon}_{t+1}^{B}-\hat{\varepsilon}_{t}^{B}\right] \tag{2}$$

$$\hat{Q}_{t}= -\hat{R}_{t}+E_{t}\hat{\pi}_{t+1}+\frac{1}{1-\delta+\left(1-\tau^{k}\right)r_{k}}E_{t}\left[(1-\delta)\hat{Q}_{t+1}+r_{k}\left(1-\tau^{k}\right)\left(\hat{r}_{k,t+1}-\frac{\tau^{k}}{1-\tau^{k}}\hat{\tau}_{t+1}^{k}\right)\right] \tag{3}$$

$$\hat{I}_{t}=\frac{\hat{Q}_{t}}{\phi\left(1+\beta\right)}+\frac{\hat{I}_{t-1}}{1+\beta}+\frac{\beta E_{t}\hat{I}_{t+1}}{1+\beta}+\frac{1}{1+\beta}E_{t}\left(\beta\hat{\varepsilon}_{t+1}^{I}-\hat{\varepsilon}_{t}^{I}\right) \tag{4}$$

$$\hat{u}_{t}=\frac{1}{\kappa}\left[\hat{r}_{k,t}-\frac{\tau^{k}}{\left(1-\tau^{k}\right)}\hat{\tau}_{t}^{k}\right] \tag{5}$$

$$\hat{K}_{t}= (1-\delta)\hat{K}_{t-1}+\delta\hat{I}_{t} \tag{6}$$

$$\begin{aligned}\hat{w}_{t}=&\frac{\beta}{1+\beta}E_{t}\hat{w}_{t+1}+\frac{1}{1+\beta}\hat{w}_{t-1}+\frac{\beta}{1+\beta}E_{t}\hat{\pi}_{t+1}-\frac{1+\beta\gamma_{w}}{1+\beta}\hat{\pi}_{t}+\\&+\frac{\gamma_{w}}{1+\beta}\hat{\pi}_{t-1}-\frac{1}{1+\beta}\frac{\left(1-\beta\varpi^{w}\right)\left(1-\varpi^{w}\right)}{\left(1+\frac{(1+\varsigma_{w})\sigma_{l}}{\varsigma_{w}}\right)\varpi^{w}}\left(X_{t}^{w}+\varepsilon_{t}^{w}\right)\end{aligned} \tag{7}$$

$$X_{t}^{w}= \hat{w}_{t}-\sigma_{l}\hat{L}_{t}-\frac{1}{1-b}\left(\hat{C}_{r,t}-b\hat{C}_{r,t-1}\right)-\frac{\tau^{l}}{1+\tau^{l}}\hat{\tau}_{t}^{l}+\hat{\varepsilon}_{t}^{L}-\frac{\tau^{c}}{1+\tau^{c}}\tau_{t}^{c} \tag{8}$$

$$\hat{\pi}_{c,t}= \hat{\pi}_{t}+\frac{\tau^{c}}{1+\tau^{c}}\left(\hat{\tau}_{t}^{c}-\hat{\tau}_{t-1}^{c}\right) \tag{9}$$

1.2 Firms:

$$\hat{Y}_{t} = \varphi_{y}\left[\hat{\varepsilon}_{t}^{A}+\alpha\hat{K}_{t-1}+\alpha\hat{u}_{t}+\left(1-\alpha\right)\hat{L}_{t}+\sigma_{g}\hat{K}_{g,t-1}\right] \tag{10}$$

$$\hat{L}_{t} = \hat{u}_{t}+\hat{r}_{t}+\hat{K}_{t-1}-\hat{w}_{t} \tag{11}$$

$$\widehat{mc}_{t} = \left(1-\alpha\right)\hat{w}_{t}+\alpha\hat{r}_{t}-\hat{\varepsilon}_{t}^{A}-\sigma_{g}\hat{K}_{g,t-1} \tag{12}$$

$$\hat{\pi}_{t} = \frac{\beta}{1+\beta\gamma_{p}}E_{t}\hat{\pi}_{t+1}+\frac{\gamma_{p}}{1+\beta\gamma_{p}}\hat{\pi}_{t-1}+\frac{\left(1-\beta\varpi\right)\left(1-\varpi\right)}{\varpi\left(1+\beta\gamma_{p}\right)}\left(\widehat{mc}_{t}+\hat{\varepsilon}_{t}^{P}\right) \tag{13}$$

1.3 Government:

$$\hat{G}_{rev,t} = \tau^c \frac{C}{Y}\left(\hat{\tau}^c_t + \hat{C}_t\right) + \tau^l \frac{wL}{Y}\left(\hat{\tau}^l_t + \hat{w}_t + \hat{L}_t\right) + \tau^k \frac{r_k K}{Y}\left(\hat{\tau}^k_t + \hat{r}_{k,t} + \hat{u}_t + \hat{K}_{t-1}\right) \tag{14}$$

$$\hat{G}_{rev,t} = R\frac{b}{Y}\left(\hat{R}_{t-1} - \hat{\pi}_t + \hat{b}_{t-1}\right) - \frac{b}{Y}\hat{b}_t + \frac{G}{Y}\hat{G}_t + \frac{IG}{Y}\widehat{IG}_t + \frac{TR}{Y}\widehat{TR}_t \tag{15}$$

$$\hat{K}_{g,t} = (1-\delta)\hat{K}_{g,t-1} + \delta\widehat{IG}_t \tag{16}$$

1.4 Aggregation and market clearing:

$$\hat{Y}_t = \frac{C}{Y}\hat{C}_t + \frac{I}{Y}\hat{I}_t + \frac{G}{Y}\hat{G}_t + \frac{IG}{Y}\widehat{IG}_t + (1-\tau^k)\frac{r_k K}{Y} \times \hat{u}_t \tag{17}$$

$$C\hat{C}_t = (1-\lambda)\, C_r \hat{C}_{r,t} + \lambda C_{nr}\hat{C}_{nr,t} \tag{18}$$

The above equations plus the equations specifying fiscal and monetary policy in the paper (equations (23) – (25), which are already in the log-linear form) comprise the system of equations which is subsequently solved and estimated.

2 Open-economy Model

This section explains the open-economy extension presented in the paper.

2.1 Households

As in the closed-economy the open-economy is populated by ϑ of non-Ricardian households and $(1-\vartheta)$ of Ricardian households.

2.1.1 Ricardian Households

The utility of Ricardian households remains the same as in the closed-economy. The total real disposable income of each Ricardian household consists of: (1) the after tax labour income $\left(1-\tau_t^l\right) w_{r,t}^n L_{r,t}^n$, where $w_{r,t}^n$ represents the real wage rate, and τ_t^l is the effective labour income tax rate; (2) the after tax capital income $\left(1-\tau_t^k\right) r_{k,t} u_t^n K_{r,t-1}^n$, where $r_{k,t}$ denotes the real rate of return on capital, $K_{r,t-1}^n$ denotes the physical stock of capital, and u_t^n is the capital utilisation rate, and τ_t^k is the effective capital income tax rate; [1] (3) the income from profits $Prof_{r,t}^n$; (4) lump-sum government transfers (TR_r^n), (5) the interest income from the domestic government bond holdings $\left(\frac{(R_{t-1}-1)b_{r,t-1}^n}{\pi_t}\right)$, where R_{t-1} denotes the nominal interest rate on a one-period bond; (6) the interests income from holdings of foreign bonds $\frac{(R_{t-1}^*-1)S_t P_{t-1}^* B_{r,f,t-1}^{\tau} risk_{t-1}}{P_t}$ where R_{t-1}^* denotes the nominal interest rate on the one period bond, P_{t-1}^* denotes the foreign price, S_t the nominal exchange rate, $B_{r,f}$ denotes foreign bond holdings, and $risk$ is a premium on the foreign bond holdings as in Adolfson *et al.* (2007) and Benigno (2009).[2] The real disposable income is reduced by a cost of capital utilisation represented by: $\left(1-\tau_t^k\right) a(u_t^n) K_{r,t-1}^n$.

Every period, each Ricardian household n decides on the allocation of its resources between consumption and the accumulation of financial and non-financial assets. The consumption bundle is purchased at a consumer price $P_{c,t}\left(1+\tau_t^c\right)$, where τ_t^c denotes the effective consumption tax rate. The price of investment is given by $P_{i,t}$.The investment is given by a Constant Elasticity of Substitution function: (CES):

$$I_t = \left(a_i^{\frac{1}{s_i}} I_{d,t}^{\frac{s_i-1}{s_i}} + (1-a_i)^{\frac{1}{s_i}} I_{m,t}^{\frac{s_i-1}{s_i}} \right)^{\frac{s_i}{s_i-1}} \tag{19}$$

where $0 < (1-a_i) < 1$ denotes a share of imported consumption or investment, and s_i represents an elasticity of substitution between domestically produced and imported investment good.[3] Finally, net accumulation of financial assets comprises: (1) acquisition of government bonds, $b_t^n - \frac{b_{t-1}^n}{\pi_{t-1}}$; (2) acquisition of

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[1] We assume that $\frac{a''(u_t^n)}{a'(u_t^n)} = \kappa$. Consequently, only the dynamics of the model depend on the parameter κ. In the steady state $u = 1$

[2] $risk_t = \exp\left(-\varkappa\left(aa_t - aa\right) + \eta_t^r\right)$, and $aa_t = \frac{S_t B_{f,t}^{\tau}}{P_t}$ denotes the real aggregate net foreign asset position

[3] The demand for $I_{d,t}$, and $I_{m,t}$ are given by: $I_{d,t} = a_i \left(\frac{P_t}{P_{i,t}}\right)^{-s_i} I_t$ and $I_{m,t} = (1-a_i)\left(\frac{P_{i,m,t}}{P_{i,t}}\right)^{-s_i} I_t$

foreign bonds $\frac{S_t B^n_{f,t}}{P_t} - \frac{S_t B^n_{f,t-1} risk_{t-1}}{P_t}$. The budget constraint takes the following form:

$$\begin{aligned} & p_{i,t} I^n_t + p_{c,t} \left(1+\tau^c_t\right) C^n_{r,t} + \left(b^n_{r,t} - \frac{b^n_{r,t-1}}{\pi_{t-1}}\right) + \left(\frac{S_t B^n_{r,f,t}}{P_t} - \frac{S_t B^n_{r,f,t-1} risk_{t-1}}{P_t}\right) \\ = \; & \left(1-\tau^l_t\right)\left(w^n_{r,t} L^n_{r,t}\right) + \left(1-\tau^k_t\right) r_{k,t} u^n_{r,t} K^n_{r,t-1} - \left(1-\tau^k_t\right) a(u^n_{r,t}) K^n_{r,t-1} + TR^n_{r,t} \\ & + Prof^n_{r,t} + \frac{\left(R_{t-1}-1\right)}{\pi_t} b^n_{r,t-1} + \left(\frac{\left(R^*_{t-1}-1\right) S_t B^n_{r,f,t-1} risk_{t-1}}{P_t}\right) \end{aligned} \tag{20}$$

where $p_{i,t} = \frac{P_{i,t}}{P_t}$ and $p_{c,t} = \frac{P_{c,t}}{P_t}$.

2.1.2 Non-Ricardian Households

The budget constraint of non-Ricardian households is given by:

$$\left(1+\tau^c_t\right) p_{c,t} C^m_{nr,t} = \left(1-\tau^l_t\right) w^m_{nr,t} L^m_{nr,t} + TR^m_{nr,t} \tag{21}$$

The aggregate consumption is given by a CES function:

$$\vartheta C_{nr,t} + (1-\vartheta) C_{r,t} = C_t = \left(a_c^{\frac{1}{s_c}} C_{d,t}^{\frac{s_c-1}{s_c}} + (1-a_c)^{\frac{1}{s_c}} C_{m,t}^{\frac{s_c-1}{s_c}}\right)^{\frac{s_c}{s_c-1}} \tag{22}$$

where $0 < (1-a_n) < 1$ denotes a share of imported consumption or investment, and s_c represents an elasticity of substitution between domestically produced and imported good.[4]

2.1.3 Non-Ricardian Households

The wage market is analogous to the closed-economy setup.

2.2 Firms

In the open-economy output of the competitive producer of the composite good Y_t is converteded one-for-one into the homogenous: private consumption ($C_{d,t}$), private investment ($I_{d,t}$), public consumption ($G_{d,t}$), public investment ($IG_{d,t}$), and export ($EX_{d,t}$).

$$Y_t - \left(1-\tau^k_t\right) a(u_t) K_{t-1} = I_{d,t} + C_{d,t} + IG_{d,t} + G_{d,t} + EX_{d,t} \tag{23}$$

As a result the price of $I_{d,t}, C_{d,t}, IG_{d,t}, G_{d,t}$, and $EX_{d,t}$ is equal to the price of Y_t and is represented by P_t. The setup and optimisation process of the composite good producer and that of monopolistic intermediate producers remains as in the closed-economy.

[4]The demand for $C_{d,t}$, and $C_{m,t}$ are given by: $C_{d,t} = a_c \left(\frac{P_t}{P_{c,t}}\right)^{-s_c} C_t$ and $C_{m,t} = (1-a_c)\left(\frac{P_{c,m,t}}{P_{c,t}}\right)^{-s_c} C_t$

2.2.1 Importers

Composite producer

There are four homogenous imported goods in the model economy: private consumption ($C_{m,t}$), private investment ($I_{m,t}$), public consumption ($G_{m,t}$), and public investment ($IG_{m,t}$). There are four producers of the homogenous imported goods, each of which specialises in production of one of four homogenous imported goods. The four producers purchase from monopolistic importers differentiated imported consumption and investment goods $N_{m,j,t}$ where $N \in \{C, I, G, IG\}$, $n \in \{c, i, g, ig\}$, and j denotes a particular monopolistic intermediate importer. The homogenous imported good $N_{m,t}$, is produced from differentiated goods, $N_{m,j,t}$, by means of the following CES technology: $N_{m,t} = \left[\int_0^1 N_{m,j,t}^{\frac{\upsilon_{n,m}-1}{\upsilon_{n,m}}} dj\right]^{\frac{\upsilon_{n,m}}{\upsilon_{n,m}-1}}$, where $\upsilon_{n,m} > 0$ denotes the corresponding elasticity of substitution among the differentiated imported goods. The composite firm chooses $N_{m,j,t}$ and maximises profit of the following form:

$$Prof_{n,t} = P_{n,m,t}N_{m,t} - \int_0^1 P_{n,m,j,t}N_{m,j,t}dj \tag{24}$$

The first-order condition results in the demand equation for the output of a monopolistic producer of imported differentiated good j:

$$N_{m,j,t} = \left(\frac{P_{n,m,t}}{P_{n,m,j,t}}\right)^{\upsilon_{n,m}} N_{m,t} \tag{25}$$

Monopolistic producers

The monopolistic importers operate in four different sectors. Each importer specialises in importing only one good N. They buy homogenous goods abroad at P^*, rebrand and sell it to the composite imported goods producer. The companies pay for goods in the foreign currency, therefore, the real marginal cost is represented by: $mc_{n,m,t} = \frac{P_t^* * S_t}{P_{n,m,t}}$. To introduce the incomplete exchange rate pass-through only fraction $0 < (1 - \varpi_{n,m}) < 1$ of importers can adjust prices every period. Those who cannot adjust prices, simply follow an indexation rule $P_{n,m,t} = \left(\frac{P_{n,m,t-1}}{P_{n,m,t-2}}\right)^{\upsilon_{n,m}} P_{n,m,t-1}$. Remaining companies choose $P_{n,m,t}$ to maximise profits subject to the demand presented in equation (7). The resulting first order condition is given by:

$$E_t \sum_{l=0}^{\infty} (\beta\varpi_{n,m})^l \lambda_{t+l} \left[\frac{\tilde{P}_{n,m,t}X_{n,m,tl}}{P_{n,m,t+l}} - \frac{\upsilon_{n,m}}{\upsilon_{n,m}-1} mc_{n,m,t+l}\right] P_{n,m,t+l}N_{m,j,t+l} \tag{26}$$

where $X_{n,m,tl} = \pi_{n,m,t}^{\gamma_{n,m}} \times \pi_{n,m,t+1}^{\gamma_{n,m}} \times ... \times \pi_{n,m,t+l-1}^{\gamma_{n,m}}$ for $l \geqslant 1$, and $X_{n,m,tl} = 1$ for $l = 0$.

2.2.2 Exporters

Composite good producer

The competitive producer of the homogenous export good faces a foreign demand for its output in the form of: $EXP_t = \left(\frac{P_{exp,t}}{P_t^*}\right)^{-f} Y_t^*$, where $P_{exp,t}$ denotes the foreign currency price of the exported good, P_t^* is a foreign price index, and Y_t^* represents a foreign output. The homogenous export good EXP_t, is produced from the differentiated export good, $EXP_{j,t}$, by means of the CES technology: $EXP_t = \left[\int_0^1 EXP_{j,t}^{\frac{\upsilon_x - 1}{\upsilon_x}} dj\right]^{\frac{\upsilon_x}{\upsilon_x - 1}}$, where $\upsilon_x > 0$ denotes the elasticity of substitution among the differentiated export goods. The composite firm chooses $EXP_{j,t}$ and maximises profit:

$$Prof_{exp,t} = P_{exp,t} EXP_t - \int_0^1 P_{exp,j,t} EXP_{j,t} dj \tag{27}$$

The first-order condition results in the demand equation for the output of monopolistic producer j:

$$EXP_{j,t} = \left(\frac{P_{exp,t}}{P_{exp,j,t}}\right)^{\upsilon_x} EXP_t \tag{28}$$

Monopolistic producers

Monopolistic exporters simply buy output (EX_t) from the composite producer of the domestic homogenous good at price P_t, rebrand it, and sell it to the competitive producer of the homogenous export good at a price $P_{exp,t}$. The real marginal cost is therefore represented by:

$$mc_{exp,t} = \frac{MC_{exp,t}}{P_{exp,t} S_t} = \frac{P_t}{P_{exp,t} S_t} \tag{29}$$

To introduce incomplete exchange rate pass-through we let the monopolistic exporters set prices subject to Calvo (1983) frictions. In particular each period a share of companies $0 < \varpi_x < 1$, is not able to reoptimise itsprice. They simply set prices by means of the indexation rule: $P_{exp,j,t} = \left(\frac{P_{exp,t}}{P_{exp,t}}\right)^{\gamma_x} P_{exp,j,t-1}$. The remaining share of companies $(1 - \varpi_x)$, choose price $P_{exp,t}$ and maximise profits subject to equation 10. The resulting first order condition is given by:

$$E_t \sum_{l=0}^{\infty} (\beta \varpi_x)^l \lambda_{t+l} \left[\frac{\tilde{P}_{exp,t} S_{t+l} X_{exp,tl}}{P_{exp,t} S_{t+l}} - \frac{\upsilon_x}{\upsilon_x - 1} mc_{exp,t+l}\right] P_{exp,t} S_{t+l} EXP_{j,t+l} \tag{30}$$

where $X_{exp,tl} = \pi_{x,t}^{\gamma_x} \times \pi_{x,t+1}^{\gamma_x} \times ... \times \pi_{x,t+l-1}^{\gamma_x}$ for $l \geqslant 1$ and $X_{x,tl} = 1$ for $l = 0$.

2.3 Fiscal and Monetary Policy

Monetary policy remains as in the closed-economy model. The government' budget constraint is given by

$$\tau_t^c p_{c,t} C_t + \tau_t^l w_t L_t + \tau_t^k r_{k,t} u_t K_{t-1} + b_t = \left(\frac{R_{t-1}}{\pi_t}\right) b_{t-1} + p_g G_t + p_{ig} IG_t + TR_t \tag{31}$$

Public consumption and investment are represented by a constant elasticity of substitution function (CES):

$$N_t = \left(a_n^{\frac{1}{s_n}} N_{d,t}^{\frac{s_n-1}{s_n}} + (1-a_n)^{\frac{1}{s_n}} N_{m,t}^{\frac{s_n-1}{s_n}} \right)^{\frac{s_n}{s_n-1}} \tag{32}$$

where $n \in \{g, ig\}$ $N \in \{G, IG\}$, and $0 < (1-a_n) < 1$ denotes a share of imported consumption or investment, and s_n represents an elasticity of substitution between domestically produced and imported good.[5]

The public capital accumulation equation is represented by:

$$K_{g,t} = (1-\delta_{k,g})K_{g,t-1} + IG_t \tag{33}$$

2.4 Market Clearing Conditions

The resource constraint is represented by:

$$Y_t - a(u_t)K_{t-1} = I_{d,t} + C_{d,t} + IG_{d,t} + G_{d,t} + EX_{d,t} \tag{34}$$

The current account balance implies that the expenses on the new purchases of foreign assets, $S_t B_{f,t}$, and imports $S_t P_t^* \left(C_{m,t} + I_{m,t} + G_{m,t} + IG_{m,t}\right)$, have to be equal to the income from export, $S_t P_{exp,t} EXP_t$, and previously purchased foreign assets, $S_t B_{f,t-1} R_{t-1}^* risk_{t-1}$.

$$S_t B_{f,t} + S_t P_t^* \left(C_{m,t} + I_{m,t} + G_{m,t} + IG_{m,t}\right) = S_t P_{exp,t} EXP_t + S_t B_{f,t-1} R_{t-1}^* risk_{t-1} \tag{35}$$

[5]demand functions for $N_{d,t}$ and $N_{m,t}$ are:$N_{d,t} = a_n \left(\frac{P_t}{P_{n,t}}\right)^{-s_n} N_{T,t}$ and $N_{m,t} = (1-a_n)\left(\frac{P_{n,m,t}}{P_{n,t}}\right)^{-s_n} N_{T,t}$, where as above $n \in \{g, ig\}$ $N \in \{G, IG\}$

3 Log-linearized system of equations for the open-economy

The names of variables and parameters in the open-economy scenario remain the same as in the closed-economy. The definitions of all new variables and parameters are present at the end of the section.

3.1 Households:

$$\hat{C}_{nr,t}=\frac{\left(1-\tau^{l}\right)wL}{\left(1+\tau^{c}\right)p_{c}C_{nr}}*\left(\hat{w}_{t}^{\tau}+\hat{L}_{t}-\frac{\tau^{l}}{1-\tau^{l}}\hat{\tau}_{t}^{l}\right)+\frac{TR}{\left(1+\tau^{c}\right)p_{c}C_{nr}}\widehat{TR}_{t}-\frac{\tau^{c}}{1+\tau^{c}}\hat{\tau}_{t}^{c}-\hat{p}_{c,t} \tag{36}$$

$$\hat{C}_{r,t}=\frac{E_{t}\hat{C}_{r,t+1}}{1+h}+\frac{h\hat{C}_{r,t-1}}{1+h}-\frac{1}{\sigma_{c}}\frac{1-h}{1+h}E_{t}\left[R_{t}-\hat{\pi}_{c,t+1}+\frac{\tau^{c}}{1+\tau^{c}}\left(\hat{\tau}_{t}^{c}-E_{t}\hat{\tau}_{t+1}^{c}\right)+\hat{\varepsilon}_{t+1}^{B}-\hat{\varepsilon}_{t}^{B}\right] \tag{37}$$

$$\hat{Q}_{t}=-\hat{R}_{t}+E_{t}\hat{\pi}_{t+1}+\frac{1}{1-\delta+\left(1-\tau^{k}\right)r_{k}}E_{t}\left[(1-\delta)\hat{Q}_{t+1}+r_{k}\left(1-\tau^{k}\right)\left(\hat{r}_{k,t+1}-\frac{\tau^{k}}{1-\tau^{k}}\hat{\tau}_{t+1}^{k}\right)\right] \tag{38}$$

$$\hat{I}_{t}=\frac{\hat{Q}_{t}-\hat{p}_{i,t}}{\phi\left(1+\beta\right)}+\frac{\hat{I}_{t-1}}{1+\beta}+\frac{\beta E_{t}\hat{I}_{t+1}}{1+\beta}+\frac{1}{1+\beta}E_{t}\left(\beta\hat{\varepsilon}_{t+1}^{I}-\hat{\varepsilon}_{t}^{I}\right) \tag{39}$$

$$\hat{K}_{t}=(1-\delta)\hat{K}_{t-1}+\delta\hat{I}_{t} \tag{40}$$

$$\hat{u}_{t}=\frac{1}{\kappa}\left[\hat{r}_{k,t}-\frac{\tau^{k}}{\left(1-\tau^{k}\right)}\hat{\tau}_{t}^{k}\right] \tag{41}$$

$$\hat{w}_{t}=\frac{\beta}{1+\beta}E_{t}\hat{w}_{t+1}+\frac{1}{1+\beta}\hat{w}_{t-1}+\frac{\beta}{1+\beta}E_{t}\hat{\pi}_{t+1}-\frac{1+\beta\gamma_{w}}{1+\beta}\hat{\pi}_{t}+$$
$$+\frac{\gamma_{w}}{1+\beta}\hat{\pi}_{t-1}-\frac{1}{1+\beta}\frac{\left(1-\beta\varpi^{w}\right)\left(1-\varpi^{w}\right)}{\left(1+\frac{(1+\varsigma_{w})\sigma_{l}}{\varsigma_{w}}\right)\varpi^{w}}\left(X_{t}^{w}+\varepsilon_{t}^{w}\right) \tag{42}$$

$$X_{t}^{w}=\hat{w}_{t}-\sigma_{l}\hat{L}_{t}-\frac{1}{1-b}\left(\hat{C}_{r,t}-b\hat{C}_{r,t-1}\right)-\frac{\tau^{l}}{1+\tau^{l}}\hat{\tau}_{t}^{l}+\hat{\varepsilon}_{t}^{L}-\frac{\tau^{c}}{1+\tau^{c}}\tau_{t}^{c}-\hat{p}_{c,t} \tag{43}$$

$$\hat{R}_{t}=\left(\hat{S}_{t+1}-\hat{S}_{t}\right)+\hat{R}_{t}^{*}-\varkappa_{a}\hat{a}_{t}+\hat{\varepsilon}_{t}^{R} \tag{44}$$

where $p_{c}=\left[a_{c}+\left(1-a_{c}\right)\left(p_{c,m}\right)^{1-s_{c}}\right]^{\frac{1}{1-s_{c}}}$ and
$p_{i}=\left[a_{i}+\left(1-a_{i}\right)\left(p_{i,m}\right)^{1-s_{i}}\right]^{\frac{1}{1-s_{i}}}$.

3.2 Domestic producers:

$$\hat{Y}_t = \varphi_y \left[\hat{\varepsilon}_t^A + \alpha \hat{K}_{t-1} + \alpha \hat{u}_t + (1-\alpha) \hat{L}_t + \sigma_g \hat{K}_{g,t-1} \right] \tag{45}$$

$$\hat{L}_t = \hat{u}_t + \hat{r}_t + \hat{K}_{t-1} - \hat{w}_t \tag{46}$$

$$\widehat{mc}_t = (1-\alpha) \hat{w}_t + \alpha \hat{r}_t - \hat{\varepsilon}_t^A - \sigma_g \hat{K}_{g,t-1} \tag{47}$$

$$\hat{\pi}_t = \frac{\beta}{1+\beta\gamma_p} E_t \hat{\pi}_{t+1} + \frac{\gamma_p}{1+\beta\gamma_p} \hat{\pi}_{t-1} + \frac{(1-\beta\varpi)(1-\varpi)}{\varpi(1+\beta\gamma_p)} \left(\widehat{mc}_t + \hat{\varepsilon}_t^P \right) \tag{48}$$

3.3 Exporters and importers:

$$\hat{\pi}_{x,t} = \frac{\beta E_t \hat{\pi}_{x,t+1}}{1+\beta\gamma_x} + \frac{\gamma_x \hat{\pi}_{x,t-1}}{1+\beta\gamma_x} + \psi_x \left(\widehat{mc}_{exp,t} + \hat{\varepsilon}_t^X \right) \tag{49}$$

$$\widehat{mc}_{exp,t} = \widehat{mc}_{exp,t-1} + \hat{\pi}_t - \hat{\pi}_{x,t} - \hat{S}_t + \hat{S}_{t-1} \tag{50}$$

$$\hat{\pi}_{c,m,t} = \frac{\beta E_t \hat{\pi}_{c,m,t+1}}{1+\beta\gamma_{c,m}} + \frac{\gamma_{c,m} \hat{\pi}_{c,m,t-1}}{1+\beta\gamma_{c,m}} + \psi_{c,m} \left(\widehat{mc}_{c,m,t} + \hat{\varepsilon}_t^{C,m} \right) \tag{51}$$

$$\widehat{mc}_{c,m,t} = \widehat{mc}_{c,m,t-1} + \hat{\pi}_t^* - \hat{\pi}_{c,m,t} + \hat{S}_t - \hat{S}_{t-1} \tag{52}$$

$$\hat{\pi}_{i,m,t} = \frac{\beta E_t \hat{\pi}_{i,m,t+1}}{1+\beta\gamma_{i,m}} + \frac{\gamma_{i,m} \hat{\pi}_{i,m,t-1}}{1+\beta\gamma_{i,m}} + \psi_{i,m} \left(\widehat{mc}_{i,m,t} + \hat{\varepsilon}_t^{I,m} \right) \tag{53}$$

$$\widehat{mc}_{i,m,t} = \widehat{mc}_{i,m,t-1} + \hat{\pi}_t^* - \hat{\pi}_{i,m,t} + \hat{S}_t - \hat{S}_{t-1} \tag{54}$$

$$\hat{\pi}_{ig,m,t} = \frac{\beta E_t \hat{\pi}_{ig,m,t+1}}{1+\beta\gamma_{ig,m}} + \frac{\gamma_{ig,m} \hat{\pi}_{ig,m,t-1}}{1+\beta\gamma_{ig,m}} + \psi_{ig,m} \left(\widehat{mc}_{ig,m,t} + \hat{\varepsilon}_t^{IG,m} \right) \tag{55}$$

$$\widehat{mc}_{ig,m,t} = \widehat{mc}_{ig,m,t-1} + \hat{\pi}_t^* - \hat{\pi}_{ig,m,t} + \hat{S}_t - \hat{S}_{t-1} \tag{56}$$

$$\hat{\pi}_{g,m,t} = \frac{\beta E_t \hat{\pi}_{g,m,t+1}}{1+\beta\gamma_{g,m}} + \frac{\gamma_{g,m} \hat{\pi}_{g,m,t-1}}{1+\beta\gamma_{g,m}} + \psi_{g,m} \left(\widehat{mc}_{g,m,t} + \hat{\varepsilon}_t^{G,m} \right) \tag{57}$$

$$\widehat{mc}_{g,m,t} = \widehat{mc}_{g,m,t-1} + \hat{\pi}_t^* - \hat{\pi}_{g,m,t} + \hat{S}_t - \hat{S}_{t-1} \tag{58}$$

where $\psi_n = \frac{(1-\beta\varpi_n)(1-\varpi_n)}{\varpi_n(1+\beta\gamma_n)}$ for $n \in \{x; c,m; i,m; ig,m; g,m\}$.

3.4 Government:

$$\hat{G}_{rev,t} = \frac{\tau^c p_c C}{Y} \left(\hat{\tau}_t^c + \hat{p}_{c,t} + \hat{C}_t \right) + \frac{\tau^l w L}{Y} \left(\hat{\tau}_t^l + \hat{w}_t + \hat{L}_t \right) + \frac{\tau^k r_k K}{Y} \left(\hat{\tau}_t^k + \hat{r}_{k,t} + \hat{u}_t + \hat{K}_{t-1} \right) \tag{59}$$

$$\hat{G}_{rev,t} = \frac{Rb}{Y} \left(\hat{R}_{t-1} - \hat{\pi}_t + \hat{b}_{t-1} \right) - \frac{b}{Y} \hat{b}_t + \frac{p_g G}{Y} \left(\hat{p}_{g,t} + \hat{G}_t \right) + \frac{p_{ig} IG}{Y} \left(\hat{p}_{ig,t} + \widehat{IG}_t \right) + \frac{TR}{Y} \widehat{TR}_t \tag{60}$$

$$\hat{K}_{g,t} = (1-\delta) \hat{K}_{g,t-1} + \delta \widehat{IG}_t \tag{61}$$

where $p_g = \left[a_g + (1-a_g)(p_{g,m})^{1-s_g} \right]^{\frac{1}{1-s_g}}$ and
$p_{ig} = \left[a_{ig} + (1-a_{ig})(p_{ig,m})^{1-s_{ig}} \right]^{\frac{1}{1-s_{ig}}}$.

3.5 Foreign assets accumulation equation:

$$\begin{aligned}
\hat{a}_t &= -(1-a_c)\left(\frac{p_{c,m}}{p_c}\right)^{-s_c} C\left(-\widehat{mc}_{x,t}-\hat{p}_{x,t}+C_{m,t}\right) \\
&\quad -(1-a_i)\left(\frac{p_{i,m}}{p_i}\right)^{-s_i} I\left(-\widehat{mc}_{x,t}-\hat{p}_{x,t}+I_{m,t}\right) \\
&\quad -(1-a_g)\left(\frac{p_{g,m}}{p_g}\right)^{-s_g} G\left(-\widehat{mc}_{x,t}-\hat{p}_{x,t}+G_{m,t}\right)+Y_x\left(-\widehat{mc}_{x,t}+\hat{Y}_{x,t}\right) \\
&\quad -(1-a_{ig})\left(\frac{p_{ig,m}}{p_{ig}}\right)^{-s_{ig}} IG\left(-\widehat{mc}_{x,t}-\hat{p}_{x,t}+IG_{m,t}\right)+R\hat{a}_{t-1} \qquad (62)
\end{aligned}$$

3.6 Aggregation and market clearing:

$$\begin{aligned}
\hat{Y}_t &= a_c\left(\frac{1}{p_c}\right)^{-s_c}\frac{C}{Y}\hat{C}_{d,t}+a_i\left(\frac{1}{p_i}\right)^{-s_i}\frac{I}{Y}\hat{I}_{d,t}+a_{ig}\left(\frac{1}{p_{ig}}\right)^{-s_{ig}}\frac{IG}{Y}\widehat{IG}_{d,t} \\
&\quad +a_g\left(\frac{1}{p_g}\right)^{-s_g}\frac{G}{Y}\hat{G}_{d,t}+\frac{Y_x}{Y}\hat{Y}_{x,t}+\left(1-\tau^k\right)\frac{r_{k,c}K_c}{Y}\hat{u}_{c,t} \qquad (63)
\end{aligned}$$

where $Y_x = C_m + I_m + G_m + IG_m = (1-a_c)\left(\frac{p_{c,m}}{p_c}\right)^{-s_c} C + (1-a_i)\left(\frac{p_{i,m}}{p_i}\right)^{-s_i} I + (1-a_g)\left(\frac{p_{g,m}}{p_g}\right)^{-s_g} G + (1-a_{ig})\left(\frac{p_{ig,m}}{p_{ig}}\right)^{-s_{ig}} IG.$

$$C\hat{C}_t = (1-\lambda)\,C_r\hat{C}_{r,t} + \lambda C_{nr}\hat{C}_{nr,t}$$

3.7 Inflation:

$$\hat{\pi}_{c,t} = \frac{a_c}{p_c^{1-s_c}}\left(\hat{\pi}_t-\hat{p}_{c,t-1}\right)+\left(1-\frac{a_c}{p_c^{1-s_c}}\right)\left(\hat{\pi}_{c,m,t}+\hat{p}_{c,m,t-1}-\hat{p}_{c,t-1}\right) \qquad (64)$$

$$\hat{\pi}_{i,t} = \frac{a_i}{p_i^{1-s_i}}\left(\hat{\pi}_t-\hat{p}_{i,t-1}\right)+\left(1-\frac{a_i}{p_i^{1-s_i}}\right)\left(\hat{\pi}_{i,m,t}+\hat{p}_{i,m,t-1}-\hat{p}_{i,t-1}\right) \qquad (65)$$

$$\hat{\pi}_{ig,t} = \frac{a_{ig}}{p_{ig}^{1-s_{ig}}}\left(\hat{\pi}_t-\hat{p}_{ig,t-1}\right)+\left(1-\frac{a_{ig}}{p_{ig}^{1-s_{ig}}}\right)\left(\hat{\pi}_{ig,m,t}+\hat{p}_{ig,m,t-1}-\hat{p}_{ig,t-1}\right) \qquad (66)$$

$$\hat{\pi}_{g,t} = \frac{a_g}{p_g^{1-s_g}}\left(\hat{\pi}_t-\hat{p}_{g,t-1}\right)+\left(1-\frac{a_g}{p_g^{1-s_g}}\right)\left(\hat{\pi}_{g,m,t}+\hat{p}_{g,m,t-1}-\hat{p}_{g,t-1}\right) \qquad (67)$$

3.8 Demands for export, import, and domestically produced goods

$$
\begin{aligned}
C_{m,t} &= -s_c\left(\hat{p}_{c,m,t} - p_{c,t}\right) + \hat{C}_t & (68)\\
I_{m,t} &= -s_i\left(\hat{p}_{i,m,t} - \hat{p}_{i,t}\right) + \hat{I}_t & (69)\\
G_{m,t} &= -s_g\left(\hat{p}_{g,m,t} - \hat{p}_{g,t}\right) + \hat{G}_t & (70)\\
IG_{m,t} &= -s_{ig}\left(\hat{p}_{ig,m,t} - \hat{p}_{ig,t}\right) + \widehat{IG}_t & (71)\\
C_{d,t} &= s_c p_{c,t} + \hat{C}_t & (72)\\
I_{d,t} &= s_i \hat{p}_{i,t} + \hat{I}_t & (73)\\
G_{d,t} &= s_g \hat{p}_{g,t} + \hat{G}_t & (74)\\
IG_{d,t} &= s_{ig} \hat{p}_{ig,t} + \widehat{IG}_t & (75)\\
\hat{Y}_{x,t} &= -s_f \hat{p}_{x,t} + \hat{Y}^*_t & (76)
\end{aligned}
$$

3.9 Relative prices

$$
\begin{aligned}
\hat{p}_{c,t} &= \hat{p}_{c,t-1} + \hat{\pi}_{c,t} - \hat{\pi}_t & (77)\\
\hat{p}_{i,t} &= \hat{p}_{i,t-1} + \hat{\pi}_{i,t} - \hat{\pi}_t & (78)
\end{aligned}
$$

$$
\begin{aligned}
\hat{p}_{ig,t} &= \hat{p}_{ig,t-1} + \hat{\pi}_{ig,t} - \hat{\pi}_t & (79)\\
\hat{p}_{g,t} &= \hat{p}_{g,t-1} + \hat{\pi}_{g,t} - \hat{\pi}_t & (80)\\
\hat{p}_{x,t} &= \hat{p}_{x,t-1} + \hat{\pi}_{x,t} - \hat{\pi}^*_t & (81)\\
\hat{p}_{c,m,t} &= \hat{p}_{c,m,t-1} + \hat{\pi}_{c,m,t} - \hat{\pi}_t & (82)\\
\hat{p}_{i,m,t} &= \hat{p}_{i,m,t-1} + \hat{\pi}_{i,m,t} - \hat{\pi}_t & (83)\\
\hat{p}_{g,m,t} &= \hat{p}_{g,m,t-1} + \hat{\pi}_{g,m,t} - \hat{\pi}_t & (84)\\
\hat{p}_{ig,m,t} &= \hat{p}_{ig,m,t-1} + \hat{\pi}_{ig,m,t} - \hat{\pi}_t & (85)
\end{aligned}
$$

Following Harrison and Oomen (2010) and Millard (2011) we hand-coded the foreign shock processes into the model that was estimated. The shock processes are taken from Millard (2011) and are represented by:

$$
\begin{aligned}
\hat{Y}^*_t &= 0.9061\hat{Y}^*_{t-1} + \hat{\eta}^{y^*}_t; \sigma_{y^*} = 0.0142 & (86)\\
\hat{\pi}^*_t &= 0.8991\hat{\pi}^*_{t-1} + \hat{\eta}^{\pi^*}_t; \sigma_{\pi^*} = 0.0075 & (87)\\
\hat{R}^*_t &= 0.8738\hat{R}^*_{t-1} + \hat{\eta}^{R^*}_t; \sigma_{y^*} = 0.0012 & (88)
\end{aligned}
$$

The above equations plus the equations specifying fiscal and monetary policy in the text (equations (23) – (25)) comprise the system of equations which is subsequently solved and estimated.
Names and description of variables and parameters specific to open economy scenario:
p_c – relative price of private consumption goods,

p_i- relative price of private investment goods,
p_g- relative price of public consumption goods,
$p_{ig}-$ relative price of public investment goods,
$p_{c,m}$ $-$ relative price of imported private consumption goods,
$p_{i,m}-$ relative price of imported private investment goods,
$p_{g,m}-$ relative price of imported public consumption goods,
$p_{ig,m}-$ relative price of imported public investment goods,
π_x- inflation of exported goods,
π_c- inflation of private consumption goods,
π_i- inflation of private investment goods,
π_g- inflation of public consumption goods,
$\pi_{ig}-$ inflation of public investment goods,
$\pi_{c,m}-$ inflation of imported private consumption goods,
$\pi_{i,m}-$ inflation of imported private investment goods,
$\pi_{g,m}-$ inflation of imported public consumption goods,
$\pi_{ig,m}-$ inflation of imported public investment goods,
$S-$ nominal exchange rate,
$\hat{\pi}_t^*-$ rest of the world inflation,
R^*- rest of the world nominal interest rate,
Y^*- rest of the world output
$aa-$ net foreign assets position
$\hat{\varepsilon}_t^R-$ risk premium shock,
$\hat{\varepsilon}_t^X-$ cost push-up shock - export,
$\hat{\varepsilon}_t^{C,m}-$ cost push-up shock - import of private consumption goods,
$\hat{\varepsilon}_t^{I,m}-$ cost push-up shock - import of private investment goods,
$\hat{\varepsilon}_t^{G,m}-$ cost push-up shock - import of public consumption goods,
$\hat{\varepsilon}_t^{IG,m}-$ cost push-up shock - import of public investment goods,
$mc_{exp}-$ marginal cost of exporters,
$mc_{c,m}-$ marginal cost of imported private consumption goods,
$mc_{i,m}-$ marginal cost of imported private investment goods,
$mc_{g,m}-$ marginal cost of imported public consumption goods,
$mc_{ig,m}-$ marginal cost of imported public investment goods,
C_d- demand of households for domestically produced consumption goods,
I_d- demand of households for domestically produced investment goods,
G_d- demand of government for domestically produced consumption goods,
IG_d- demand of government for domestically produced investment goods,
Y_e- demand for exports,
C_m- demand of households for imported consumption goods,
I_m- demand of households for imported investment goods,
G_m- demand of government for imported consumption goods,
IG_m- demand of government for imported investment goods,
ϖ_x- price stickiness export,
γ_x- indexation parameter - export,
$\varpi_{c,m}-$ price stickiness - import of private consumption goods,
$\gamma_{c,m}-$ indexation parameter - import of private consumption goods,
$\varpi_{i,m}-$ price stickiness - import of private investment goods,
$\gamma_{i,m}-$ indexation parameter - import of private investment goods,
$\varpi_{g,m}-$ price stickiness - import of public consumption goods,
$\gamma_{g,m}-$ indexation parameter - import of public consumption goods,

$\varpi_{ig,m}-$ price stickiness - import of public investment goods,
$\gamma_{ig,m}-$ indexation parameter - import of public investment goods,
$\varkappa_a -$ the risk premium parameter related to net foreign assets,
a_c- share of imported consumption in a CES composite of private consumption,
a_i- share of imported investment in a CES composite of private consumption,
a_g- share of imported consumption in a CES composite of public consumption,
$a_{ig}-$ share of imported consumption in a CES composite of public investment,
s_c- the substitution elasticity between foreign and domestic private consumption goods,
s_i- the substitution elasticity between foreign and domestic private investment goods,
s_g- the substitution elasticity between foreign and domestic public consumption goods,
$s_{ig}-$ the substitution elasticity between foreign and domestic public investment goods,
s_f- the substitution elasticity between variety of exports.
$\frac{\upsilon_{c,m}}{\upsilon_{c,m}-1}-$ markup in the private consumption good import sector
$\frac{\upsilon_{i,m}}{\upsilon_{i,m}-1}-$ markup in the private investment good import sector
$\frac{\upsilon_{g,m}}{\upsilon_{g,m}-1}-$ markup in the public consumption good import sector
$\frac{\upsilon_{ig,m}}{\upsilon_{ig,m}-1}-$ markup in the public investment good import sector

4 Prior and Posterior distributions

Figure 1: Prior and Posterior distribution for the benchmark model

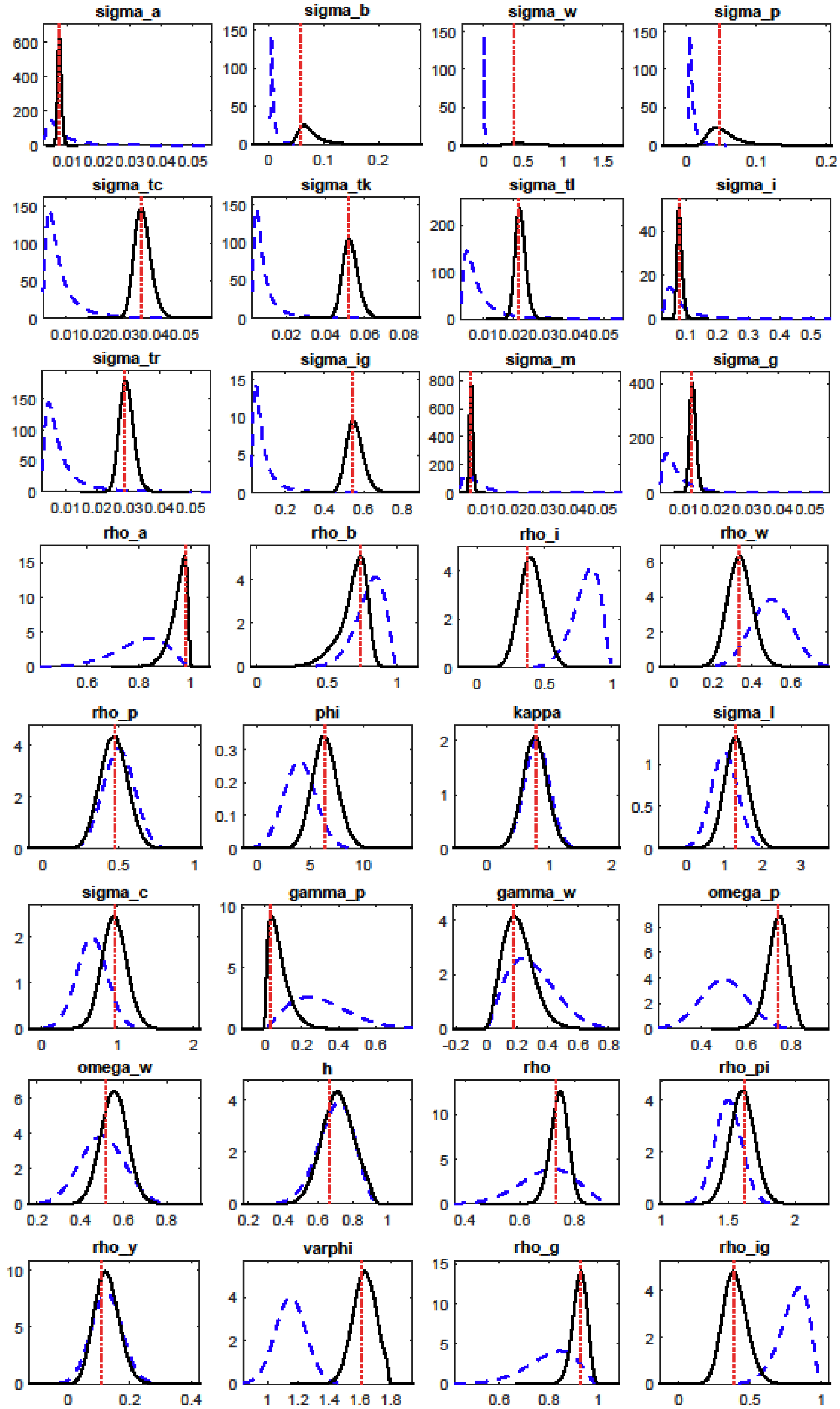

Figure 2: Prior and Posterior distribution for the benchmark model