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NOMINAL RIGIDITIES AND WAGE-PRICE DYNAMICS IN ESTIMATED DSGE MODEL: APPLICATION FOR THE CZECH ECONOMY

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NOMINAL RIGIDITIES AND WAGE-PRICE DYNAMICS IN ESTIMATED DSGE MODEL: APPLICATION FOR THE CZECH ECONOMY

Abstract:

The goal of this paper is to examine importance of nominal rigidities – especially of wages and prices – in the Czech economy. As a tool, DSGE model of open economy with nominal rigidities is used. The model is estimated on data of the Czech economy using Bayesian techniques. The model is evaluated in terms how it fits the data and the dynamical properties of the model are studied. The emphasis is put on wage-price dynamics. Next, the relative importance of nominal rigidities is examined using sensitivity analysis. The conclusion is that wages are more rigid than prices and thus wage rigidity and price rigidity are interchangeable. This outcome should be taken into consideration for forming of monetary policy by the central bank and modelling of behaviour of the Czech economy.

Abstrakt:

Cílem této práce je prozkoumat význam nominálních rigidit – obzvláště mezd a cen – v české ekonomice. Jako nástroj je použit DSGE model otevřené ekonomiky s nominálními rigiditami. Model je odhadnut na datech české ekonomiky pomocí Bayesovských technik. Poté je model zhodnocen podle toho, jak vystihuje data, a jsou studovány jeho dynamické vlastnosti. Důraz je kladen na dynamiku mezd a cen. Pomocí analýzy citlivosti je zkoumán relativní význam nominálních rigidit. Z výsledků vyplývá, že mzdy jsou rigidnější než ceny a tedy, že mzdová a cenová rigidita nejsou vzájemně zaměnitelné. Tyto závěry by měl být zohledněny při uskutečňování monetární politiky centrální bankou a pro modelování chování české ekonomiky.

Recenzoval:
Ing. Petr Harasimovič, M.A.

1. INTRODUCTION

1.1. Motivation

The primary objective of monetary authority is to maintain price stability. The central banks usually use model framework for analysis of the economy and governing its policy. Their model approach is based on New Keynesian paradigm of which main features are various types of nominal rigidities. These rigidities can stem from wages or prices. Erceg et. al (2000) show for the baseline New Keynesian model with sticky prices that the optimal monetary policy completely stabilizes the price level and the output gap in reaction to shocks. Thus the central bank is able to replicate flexible price equilibrium allocation without welfare losses. When only wages are sticky, the natural allocation is also attainable, but requires full stabilization of nominal wages. When both prices and wages are sticky the natural equilibrium can no longer be attained. More importantly, monetary policy that focuses exclusively on stabilizing price inflation, as most central banks do, is suboptimal. The policy should be aimed at appropriate weighted average of price and wage inflation to mitigate welfare losses relative to the optimal policy. These weights are functions of structural model parameters that describe preferences and technologies. Some of these parameters express degree of price or wage stickiness. Thus the importance of nominal rigidities, especially of wages and prices, has significant impact for pursuance of monetary policy and its stabilization effects.

1.2. Background

Nominal rigidities are the cornerstone of models with label New Keynesian economics.[1] Methodologically, they build on the Real Business Cycle (RBC) theory that has origins in the seminal papers of Kydland and Prescott (1982) and Prescott (1986). Both theories are based on optimizing behaviour of agents (firms and households), both include rational expectations and clearing markets. As a tool, Dynamic Stochastic General Equilibrium (DSGE) models are extensively used for macroeconomic analysis. They are calibrated or estimated and used for simulation and evaluation of model economies.

However, New Keynesian approach introduces several new aspects such as monopolistic competition and nominal rigidities which give rise to short run non-neutrality of monetary policy. Contrary to RBC theory where monetary factors do not play significant role, central bank in " New Keynesian world" can influence the real interest rate (through controlling nominal interest rate) and subsequently other real variables. But in the long run, all prices and wages adjust and economy returns to its natural equilibrium. New Keynesian models are not only in the center of academic research, but they are also widely used in central banks and other institutions for forming and evaluating of economic policy.

Today's economies are open economies and they should be modelled in that way. DSGE models with market imperfections and nominal rigidities that are extended to open economy are referred to as New Open Economy Macroeconomics (NOEM). This new class of models originates from Obstfeld and Rogoff (1995). But their 'Exchange Rate Dynamics Redux' model assumes stickiness in prices that lasts only for one period. Recent DSGE models in NOEM tradition are more realistic. They assume that rigidity lasts for more than one period and allow stickiness in both

[1]Nice introduction and overview of New Keynesian models provides Gali (2008).

prices and wages. The question whether wages are more rigid than prices or other way around remains a matter of empirical testing and can be country specific.

There is number of empirical studies on relative importance of price and wage stickiness, for various countries using various estimation techniques. The results show quite mixed picture. Bergin (2003) uses maximum likelihood for estimation of the model with price and wage rigidities that are introduced in the form of adjustment cost. He tests restricted models with flexible wages and/or prices relatively to the benchmark model with both types of rigidies for Australia, Canada and the UK. He concludes that nominal rigidities are key elements of the NOEM models in all three countries. Regarding relative importance, price rigidity is more important than wage rigidity. The version of model that assumes flexible prices is rejected for all three countries, while the version with flexible wages is rejected only for Australia. Contrary to Bergin, other authors introduce nominal stickiness in the form of Calvo contracts implying that both rigidities are present from the beginning. Then the relevant question is which of the contracts lasts longer and accounts best for model fit. Ambler et al. (2003) combine GMM and SMM[2] for estimation of DSGE model for Canada. Their model assumes Calvo pricing mechanism for domestic prices, import prices and wages and the estimation results indicate that wage contracts last longer than price contracts. Smets and Wouters (2003) estimate DSGE model for Euro area using Bayesian techniques. Relative importance of nominal rigidities says in favour of price stickiness. Adolfson et al. (2005) use ritcher model with more nominal (and real) rigidities and estimate it also on Euro data using Bayesian methods. Their results confirm findings of Smets and Wouters. Rabanal and Rubio-Ramirez (2005) also report that sticky wages models for the Euro area are rejected by the data. Christiano et al. (2005) estimate DSGE model for US economy by minimizing a measure of the distance between the model and empirical impulse response function. The length of Calvo contracts were quite similar but subsequent quantitative analysis shows that sticky wages play a crucial role in the model's performance while sticky prices play only limited role for good fit of the model. Del Negro and Schorfheide (2008) argue that some degree of price rigidity is needed to describe US data but the whole issue is much more complex and the results may be influenced by the choice of priors for parameters and data sets. Finally, Maih (2005) found out for Norwegian economy that wage contracts last longer than price contracts but adjustment to stochastic shocks is faster for wages than for prices.

1.1. Czech data evidence

Cyclical behaviour of the real wage is crucial in helping to discriminate between theories of business cycle. It can also help to determine the source of nominal rigidity. Cyclical behaviour of the real wage in the Czech economy is not typical. The business cycle and the correlation function of labor productivity and the real wage is depicted in Figure 1 (left hand side).[3] Both time series are obtained by Christiano and Fitzgerald (2003) band pass filter.[4] The values of cross-correlation coefficient indicate that the real wage is rather acyclical. Correlation coefficient is not statistically significant except of the lead of five periods. This negative value of

[2]Generalized method of moments (GMM) and Simulated method of moments (SMM).

[3]Labor productivity is calculated as ratio of GDP and number of workers, the real wage is nominal wage divided by CPI.

[4]The business cycle fluctuations are defined as those between six and thirty two quarters, same as in Agresti and Mojon (2005).

correlation coefficient can be explained by looking on the cyclical behaviour over time. There is evident procyclical behaviour at the beginning of the sample period, but from 2000 the real wage behaves countercyclicaly. Right hand side of Figure 1 shows the same characteristics for shortened sample. The correlation coefficient confirm strong countercyclical behaviour of the real wage lagging the cycle of output (per worker) by three periods.

The real wage is usually found to be procyclical or acyclical in other countries.[5] Turning to the theories of business cycle fluctuations, stylized fact of countercyclical real wage is in favour of Keynesian model with sticky wages rather than sticky prices, as it is illustrated in e.g. Romer (2006). However, Romer uses only simple static model. The lagging behaviour of the real wage suggests that staggered wage contracts embedded into dynamic model should be appropriate feature of model of the Czech economy. Next, there are many other factors at play, e.g. various types of shocks, transmission mechanisms, openness of the economy and also mutual relationship between wages and prices (wage-price spiral). This is quite complex issue which also says in favour of using model approach with dynamics.

1.2. The goal of the paper

The research question of this paper is whether wages are more sticky than prices or more broadly which type of nominal rigidities is the most important for modelling of the Czech economy. The objective is not only to estimate parameters that captures degree of nominal rigidity but also to investigate wage and price dynamics.

To provide answer to this question, the DSGE model of open economy with nominal rigidities on various markets is used. The model is estimated on Czech data using Bayesian techniques. The behaviour of model is studied along several dimensions including impulse responses, variance decomposition or sensitivity analysis, with emphasis put on relative importance of wage and price stickiness and their joint dynamics.

The reminder of the paper is organized as follows. Section 2 describes the DSGE model used for the analysis, its derivation from optimization problems of agents, and symmetric equilibrium of the model. Next steps before estimation are log-linearization around the steady-state and solution of the system using state-space form. Section 3 deals with data, their transformation and estimation methodology. Section 4 presents and discusses results of the estimation. The model is evaluated in terms how it fits the data before the dynamical properties of the model are studied. Some other model implications regarding exchange rate pass-through and wage-price dynamics are covered in this section as well. Section 5 focuses on sensitivity analysis. The relative importance of nominal rigidities is tested via marginal likelihood and vector autocorrelation functions. Finally, the issue whether wage rigidity and price rigidity are interchangeable is examined. Section 6 concludes with prospects for further research.

2. THE MODEL

The model is borrowed from Maih (2005), extended (especially by export market rigidities) and adjusted for Czech economy condition. The inspiration for extension

[5] See e.g. Romer (2006), Kydland and Prescott (1990) or Stock and Watson (1998)

was found in Adolfson et al. (2005). Similar models are used in papers of Ambler et al. (2003) or Smets and Wouters (2003).

The model differs from Maih (2005) in several aspects. The money are assumed endogenous and are not explicitly modeled within the (money-in-the-utility) framework. Second, the prices of export intermediate goods are assumed sticky and are modeled in Calvo style. Resulting Phillips curve introduces new channel of slow price adjustment. and can improve fit of the model. Some additional amendments relates to specific features of the Czech economy or estimation procedure. The interest rate rule is modified; besides interest rate smoothing includes only deviation of inflation from target and output gap. This specification is more in accordance with regime of monetary policy of the Czech National Bank. Next, elasticity of substitution across differentiated foreign (imported) intermediate goods is time-varying and is subject to shock. Introduction of markup shock to import prices allows to use additional time series for estimation and thus to draw more information from data.

The derivation of the model is similar to Maih's work, but for readers convenience and several modifications, I present it in this section.

2.1. Households

The model consist of continuum of households indexed on interval $i \in (0,1)$. Households is endowed with a differentiated labor skill. They are choosing a consumption plan and also chooses wage rate plan for all $\tau = t, t+1, t+2, t+3, \ldots$ to maximize an expected discounted infinite stream of utility of the form

$$E_t \sum_{\tau=t}^{\infty} \beta^{\tau-t} Z_{c,\tau} \left[\frac{1}{1-\rho} (C_\tau(i) - habC_{\tau-1})^{1-\rho} - \frac{1}{1+\nu} Z_{ls,\tau} h_\tau(i)^{1+\nu} \right]$$

where E_t is the conditional expectations operator,[6] $\beta \in (0,1)$ is the discount factor, $C_\tau(i)$ is consumption, $h(i)$ denotes hours worked by the household, $Z_{c,t}$ is consumption preference shifter (or aggregate preference shock that is common to all households) and $Z_{ls,t}$ is labor supply shock. $\rho \geq$ is the constant relative risk aversion coefficient or the inverse of the elasticity of intertemporal substitution, $\nu > 0$ is the inverse of the (Frisch) elasticity of labor supply with respect to the real wage and $hab \in [0,1)$ is external habit persistence in the previous period's aggregate consumption. [7]

The household's budget constraint is given by

$$P_t C_t(i) + \frac{B_t(i)}{R_t} + \frac{S_t B_t^*(i)}{R_t^* rp_t} + T(i) \leq B_{t-1}(i) + S_t B_{t-1}^*(i) + W_t(i) h_t(i) + P_t D_t(i) \quad (1)$$

[6] $E_t x_{t+1} = E(x_{t+1} | \Omega_t)$ denotes expectation of variable x_{t+1} made under information set Ω_t available in time t.

[7] This form of habit formation is called "catching up with Johneses" . It is motivated by explaining empirical fact of hump-shaped gradual response of consumption and inflation to shocks. For more details see e.g. Fuhrer (2000) or Ljungqvist and Uhlig (2000).

The right hand side of equation (1) expresses sources, the left hand side is usage of the sources. P_t is price level in the economy and hence $P_t C_t(i)$ denotes nominal consumption of the household. $B_t(i)$ and $B_t^*(i)$ are domestic-currency and foreign-currency bonds respectively purchased at time t, S_t is nominal exchange rate quoted as domestic currency per unit of foreign currency. R_t and R_t^* denote the gross nominal domestic and foreign interest rates between t and $t+1$, respectively. rp_t measures risk premium that reflects departures from uncovered interest parity condition. $T_t(i)$ are taxes paid to government (or transfers when T_t is negative). $W_t(i)$ is nominal wage rate and thus $W_t(i)h_t(i)$ is wage income from supplying $h(i)$ units of labor (hours worked) to the various intermediate goods-producing firms. Households own all firms thus they receive $D_t(i)$ units of consumption good as dividends from equities of intermediate goods-producing firms.

The households can carry wealth between periods using domestic and foreign bonds. Domestic bonds are denominated in the domestic currency and foreign bonds are denominated in the foreign currency. At the beginning of the period t the bonds mature and provide B_{t-1} and $S_t B_{t-1}^*(i)$ additional units of consumption. The household decide to buy B_t new units of domestic bonds at the cost $1/R_t$ and B_t^* new units of foreign bonds at the cost $1/(R_t^* rp_t)$. The endogenous (gross) risk premium rp_t captures that international financial markets are incomplete. It is negative function that depends on the ratio of foreign bond to domestic output.[8]

$$rp_t = \exp\left[-\psi \frac{S_t B_t^*}{P_t Y_t} + \log(Z_{rp,t})\right] \tag{2}$$

where Y_t is the aggregate level of output, B_t^* is the aggregate foreign bonds holdings and $Z_{rp,t}$ is a shock to the risk premium. This function has following properties, $rp_{t'} < 0$ and $rp_t(0) = 1$. If $B_t^* < 0$, domestic households are charged a premium to the foreign interest rate, if $B_t^* > 0$ they receive a lower interest return on their international savings. If there are no bonds, the risk premium is equal to one.

Each household chooses consumption $C_t(i)$, and portfolio that consist of domestic and foreign bonds, $B_t(i)$ and $B_t^*(i)$. The first order conditions for these optimization problems are:

$$Z_{c,t}[C_t(i) - habC_{t-1}]^{-\rho} = \Lambda_t(i) P_t \tag{3}$$

[8]This ratio ensures stationary dynamic path for domestic consumption and wealth and thus a unique steady state.

$$\Lambda_t(i) = \beta R_t E_t[\Lambda_{t+1}(i)] \quad (4)$$

$$R_t S_t E_t[\Lambda_{t+1}(i)] = R_t^* rp_t E_t[\Lambda_{t+1}(i) S_{t+1}] \quad (5)$$

where Λ_t is Lagrange multiplier connected with budget constraint in time t. Equation (4) is standard Euler equation. It states that households want to equalize expected marginal utilities across time periods taking into account relationship between (subjective) time preference factor and market rate of return on savings. Equation (5) is risk-adjusted uncovered interest parity condition. Its meaning is the same, the household only adds into consideration possibility of investing into foreign assets.

The household is endowed with differentiated labor skill that offers in monopolistically competitive labor markets. Labor services of households are imperfect substitutes and thus the households can choose their nominal wage subject to demand imposed by the firms. The households set their nominal wage rate and stand ready to supply the quantity of labor demanded for that wage by firms. However, not all households are able to select their wage rate each period. Result of this wage setting implies existence of nominal rigidities that are modeled in the form of Calvo (1983) contracts. In each period, there is a constant probability δ_w that a worker is not able to re-adjust her wage. If the workers do not have opportunity to reset their wages, these wages are adjusted by wage inflation from previous period as a result of indexation

$$W_{t+1}(i) = \pi_{w,t-1} W_t$$

where

$$\pi_{w,t} = \frac{W_t}{W_{t-1}} \quad (6)$$

Similarly, there is a probability $1-\delta_w$ that the household will be able to change her wage. Then the worker takes into account that she may not re-optimize her wage in the next periods. Thus, she indexes her wage to (price) inflation and technology growth so that her wage $\tau - t$ periods after the wage is set as

$$W_\tau(i) = \left(\prod_{k=t}^{\tau-1} \pi_k \pi_{zy,k} \right) W_t^{new}(i)$$

where $W_t^{new}(i)$ is the wage set in time t that remains fixed until the next opportunity for wage setting, and where

$$\pi_t = \frac{P_t}{P_{t-1}} \quad (7)$$

$$\pi_{zy,t} = \frac{Z_{yt}}{Z_{y,t-1}} \quad (8)$$

where Z_{yt} is the level of technology in the economy in time t.

As the markup for workers that revise their wages should be positive in the steady state, we must impose restriction that the time-varying elasticity of substitution across different types of labor, θ_{wt} is greater than unity. The worker who sets new wage solves optimization problem

$$\max_{W_t^{new}(i)} E_t \sum_{\tau=t}^{\infty} (\beta\delta_w)^{\tau-t} \left[-\frac{Z_{ls,\tau}}{1+\nu} h_\tau(i)^{1+\nu} \right]$$

subject to budget constraint (1) for $\tau = t, t+1, \ldots, \infty$ and labor demand from aggregator [9]

$$h_\tau(i) = \int_0^1 h_\tau(i,j)dj = \left[\frac{W_\tau(i)}{W_\tau} \right]^{-\theta_{w,\tau}} h_\tau(j)$$

This optimization results in the following first order condition

$$E_t \sum_{\tau=t}^{\infty} (\beta\delta_w)^{\tau-t} \left[-\frac{\theta_{w,t} Z_{c,\tau} Z_{hs,\tau} h_\tau^{\nu+1}}{W_t^{new}(i)} + \Lambda_\tau \left(\prod_{k=t}^{\tau-1} \pi_k \pi_{zy,k} \right) (\theta_{w,\tau} - 1) h_\tau \right] = 0. \quad (9)$$

The negative term in equation (9) is the marginal disutility of labor effort (additional hours worked) and the positive term is the marginal revenue from slight increase of the wage rate. In the optimum, the expected sums of those expressions should be equal. At the resulting wage rate, the workers are ready to supply any amount of labor demanded from firms.

In equilibrium, there is a fraction $1-\delta_w$ of workers that changes their wages at time t. The expected time between wage adjustments, or equivalently, the number of periods for that the wage reamains fixed is $\frac{1}{1-\delta_w}$.[10] For example, if $\delta_w = 0.75$ then the wages are not changed for one year.

This structure of labor market implies that households are heterogeneous and their labor income and thus consumption and assets holdings may differ. To ensure identical consumption in equilibrium, we assume that households have access to state contingent security markets which provides them full insurance against idiosyncratic shocks in labor income. Consumption will be same for all households in equilibrium and only the wage rate and labor supply will differ.

2.2. Production side of the economy

The production structure of the economy is depicted in Figure 2. Monopolistically competitive markets are depicted by dashed lines. There are three types of firms in the model economy: continuum of intermediate goods producing firms, continuum of exporting firms that give brand names to intermediate goods and various aggregators. Domestic intermediate firms uses labor and capital as factors of

[9]Labor demand function is solution of aggregator's labor packing problem and is defined later.
[10]The time between wage adjustments follows a geometric distribution.

production. Part of domestic intermediate goods is exported and the other part together with imported intermediate goods is used for production of final goods. Final goods is either consumed by households and government or used as capital input in production of intermediate goods. Optimization problem of these firms is described in following subsections.

2.2.1. Domestic intermediate goods

There is continuum of domestic intermediate goods firms indexed on interval $j \in (0,1)$. The firm producing good $Y_{H,t}(j)$ has following production function:

$$Y_{Ht}(j) = Z_{yt}^{\psi} h_t(j)^{\psi} K_t^{1-\psi} \tag{10}$$

where Z_{yt} is a productivity shock, $K_t = Y_t - C_t - G_t$ is part of final goods that is not consumed (capital) and ψ is labor intensity of production function.[11]

Domestic firm chooses level of labor and capital (for given prices) to minimize its cost of production

$$\min_{h_t(j), K_t} W_t h_t(j) + P_t K_t$$

subject to production function (10). The first order conditions of optimization problem are

$$W_t = \psi \Xi_t(j) \frac{Y_{Ht}(j)}{h_t(j)} \tag{11}$$

$$P_t = (1-\psi) \Xi_t(j) \frac{Y_{Ht}(j)}{K_t} \tag{12}$$

where the Lagrange multiplier Ξ_t expresses the marginal cost of production. Then these two equations imply following relationship $W_t h_t(j) + P_t K_t = \Xi_t(j) Y_{Ht}(j)$.[12] The real profits, $D_t(j)$, made by domestic intermediate goods firm j are

$$P_t D_t(j) = P_{Ht}(j) Y_{Ht}(j) - W_t h_t(j) - P_t K_t \tag{13}$$

Firms operate in monopolistically competitive markets. They produce differentiated goods (imperfect substitutes) and thus are able to influence their prices. These characteristics of markets allow firms to gain non-zero profits in equilibrium.

[11] The model does not assume existence of capital in usual terms. Final good is perishable and cannot be stored into next period. Therefore it is used in production in the same period. I will denote it by K_t as capital even it does not correspond to usual definition. This specification comes from Ambler et al. (2003) and has following reason: first, without final goods in the production function, the response of the real wage to demand shocks is too highly countercyclical. Second, the presence of intermediates in the production function for domestic goods affects the correlation between the nominal exchange rate and domestic inflation.

[12] The output is sum of remunerations to production factors.

The price setting problem for domestic intermediate goods producing firm is analogous to that of households for wage-setting. With probability δ_h the firm is not allowed to reoptimize and its price is updated according to the scheme

$$P_{H,t+1}(j) = \pi_{h,t-1} P_{Ht}(j)$$

with

$$\pi_{h,t} = \frac{P_{Ht}}{P_{Ht-1}} \tag{14}$$

Fraction $1-\delta_h$ of firms that can adjust prices set the new prices ($P_{H,t}^{new}$) as a result of following optimization problem:

$$\max_{P_{Ht}^{new}(j)} E_t \left\{ \sum_{\tau=t}^{\infty} (\beta\delta_h)^{\tau-t} \left(\frac{\Lambda_\tau P_\tau}{\Lambda_t P_t} \right) \frac{1}{P_\tau} [P_{H\tau}(j) - \Xi_\tau(j)] Y_{H\tau}(j) \right\}$$

subject to demand that faces from aggregator

$$Y_{H\tau}(j) = \left(\frac{P_{H\tau}(j)}{P_{H\tau}} \right)^{-\theta_{h\tau}} Y_{H\tau},$$

where the newly set price is indexed to inflation in the previous period

$$P_{H,\tau}(j) = \Pi_{k=t}^{\tau-1} \pi_{h,k} P_{Ht}^{new}(j)$$

and $\beta^{\tau-t} \dfrac{\Lambda_\tau P_\tau}{\Lambda_t P_t}$ is stochastic discount factor that is derived from Euler equation for domestic bonds. Households are owners of domestic firms and every agent has access to a complete contingent asset market which implies a unique market discount factor.

The first order condition is

$$E_t \left\{ \begin{array}{c} \sum_{\tau=t}^{\infty} (\beta\delta_h)^{\tau-t} \left(\frac{\Lambda_\tau P_\tau}{\Lambda_t P_t} \right) P_{Ht}^{new}(j)^{-\theta_{h\tau}-1} \times \\ \left[(\theta_{h\tau}-1) P_{Ht}^{new}(j) \Pi_{k=t}^{\tau-1} \pi_{hk} - \theta_{h\tau} \Xi_\tau(j) \right] \left(\frac{\Pi_{k=t}^{\tau-1} \pi_{hk}}{P_{H\tau}} \right)^{-\theta_{h\tau}} \frac{Y_{H\tau}}{P_\tau} \end{array} \right\} = 0 \tag{15}$$

2.2.2. Importers

Analogously, the economy imports a continuum of foreign intermediate goods on the unit interval. There is monopolistic competition in the market for imported intermediates which are imperfect substitutes. For the sake of simplicity the price in the foreign economy is assumed to be flexible. Thus foreign intermediate goods firms set their prices as a markup over foreign marginal costs. The elasticity of substitution across foreign intermediate goods, $\theta_f t$, is assumed to be same in both countries. With additional assumption that foreign goods imported by firms can be also consumed directly by foreigners, the price of imported goods abroad is the foreign consumer price index in equilibrium. Finally, the Home discount factor is used to discount the profits of foreign intermediate goods firms. Again, each firm faces probability $1-\delta_f$ that it can change its price. The newly set price is solution to the following optimization problem

$$\max_{P_{Ft}^{new}(j^*)} E_t\left\{\sum_{\tau=t}^{\infty}(\beta\delta_f)^{\tau-t}\left(\frac{\Lambda_\tau P_\tau}{\Lambda_t P_t}\right)\frac{1}{P_\tau}[P_{F\tau}(j^*)-S_t\Xi_\tau^*(j^*)]\,Y_{F\tau}(j^*)\right\}$$

subject to demand from aggregator

$$Y_{F\tau}(j^*)=\left(\frac{P_{F\tau}(j^*)}{P_{F\tau}}\right)^{-\theta_f}Y_{F\tau}$$

where $P_\tau^*(j^*)=\dfrac{\theta_{ft}}{\theta_{ft}-1}\Xi_\tau^*(j^*)$, and each firm ignores impact of its price setting decision on the price index. The firms take into consideration past inflation of foreign intermediate goods and make indexation to newly set price

$$P_{F,\tau}(j^*)=\Pi_{k=t}^{\tau-1}\pi_{f,k}P_{Ft}^{new}(j^*)$$

where

$$\pi_{f,t-1}=\frac{P_{Ft}}{P_{Ft-1}}. \tag{16}$$

The first order condition of their optimization problem is

$$E_t\left\{\begin{matrix}\displaystyle\sum_{\tau=t}^{\infty}(\beta\delta_f)^{\tau-t}\left(\frac{\Lambda_\tau P_\tau}{\Lambda_t P_t}\right)P_{Ft}^{new}(j)^{-\theta_{f\tau}-1}\times\\ \left[(1-\theta_{f\tau})P_{Ft}^{new}(j)\Pi_{k=t}^{\tau-1}\pi_{fk}+\theta_{f\tau}S_\tau\Xi_\tau^*(j)\right]\left(\dfrac{\Pi_{k=t}^{\tau-1}\pi_{fk}}{P_{F\tau}}\right)^{-\theta_{f\tau}}\dfrac{Y_{F\tau}}{P_\tau}\end{matrix}\right\}=0 \tag{17}$$

Other firms that do not have opportunity to change the price follows pricing rule given by

$$P_{F,t+1}(j^*)=\pi_{f,t-1}P_{Ft}$$

2.2.3. Exporters

Exporting firm buy domestic composite goods and differentiate it by brand naming. Then, they sell the continuum of differentiated goods at monopolistically competitive markets in the foreign economy. Each exporting firm j faces the following demand for its product [13]

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[13] $\zeta>0$ is scale parameter which is expected to be small. In steady state it corresponds to the share of exports of domestic country in the total demand of the foreign country.

$$Y_{X\tau}(j)=\zeta\left(\frac{P_{X\tau}(j)}{P_{X\tau}}\right)^{-\theta_x}Y_{X\tau} \tag{18}$$

Export price $P_{X\tau}(j)$ is invoiced in local currency of the export market, $Y_{X\tau}$ denotes total demand of exported intermediate goods and θ_x is price elasticity of exports.

Existence of product differentiation and monopolistic competition in the foreign market allow firms to influence prices of their goods. It is again modeled in the Calvo setup. Exporting firms that do not have opportunity to reset their prices follow pricing rule and index it to last period (export price) inflation.

$$P_{X,t+1}(j)=\pi_{x,t-1}P_{Xt}$$

with

$$\pi_{x,t}=\frac{P_{Xt}}{P_{Xt-1}} \tag{19}$$

Other part of firms that have opportunity to reset prices (with probability $1-\delta_x$) solve optimization problem

$$\max_{P_{Xt}^{new}(j)} E_t\left\{\sum_{\tau=t}^{\infty}(\beta\delta_x)^{\tau-t}\left(\frac{\Lambda_\tau P_\tau}{\Lambda_t P_t}\right)\frac{1}{P_\tau^*}\left[P_{X\tau}(j)-\frac{\tilde{\Xi}_\tau}{S_t}(j)\right]Y_{X\tau}(j)\right\}$$

subject to demand function (18). Marginal cost for exporting firm $\tilde{\Xi}_t$ is actually the price of domestic composite good P_{Ht}. The firms take into account that there might not be a chance to optimally change in next period. They index the newly set price to inflation of export goods

$$P_{X,\tau}(j)=\Pi_{k=t}^{\tau-1}\pi_{x,k}P_{Xt}^{new}$$

The first order condition of optimization problem is

$$E_t\left\{\begin{array}{c}\sum_{\tau=t}^{\infty}(\beta\delta_x)^{\tau-t}\left(\frac{\Lambda_\tau P_\tau}{\Lambda_t P_t}\right)P_{Xt}^{new}(j)^{-\theta_{x\tau}-1}\times\\ \left[(1-\theta_{x\tau})P_{Xt}^{new}(j)\Pi_{k=t}^{\tau-1}\pi_{xk}+\theta_{x\tau}\frac{\tilde{\Xi}_\tau}{S_\tau}(j)\right]\left(\frac{\Pi_{k=t}^{\tau-1}\pi_{xk}}{P_{X\tau}}\right)^{-\theta_{x\tau}}\frac{Y_{X\tau}}{P_\tau^*}\end{array}\right\}=0 \tag{20}$$

2.2.4. Aggregators

There are several aggregators on various positions of production process. One aggregator demands differentiated types of labor from households, make bundels and sells them to intermediate good producing firms. Another aggregators assemble differentiated domestic and foreign intermediate goods to make composite goods. Final aggregator packs domestic and foreign composite goods to make final good that is distributed among private and government consumption and production of home intermediates. The aggregators are benevolent and they do not make any profit. Their optimization problem are described in following subsections.

Labor packing

The aggregator demands differentiated domestic labor inputs from households. Each worker i posses different skill type and thus acts as monopolistic supplier of labor $h_t(i,j)$ to firm j. The aggregator bundles together those different types of labor and supplies them to each (domestic) intermediate goods firm. The composite labor has following form:

$$h_t(j) = \left[\int_0^1 h_t(i,j)^{\frac{\theta_{wt}-1}{\theta_{wt}}} dj \right]^{\frac{\theta_{wt}}{\theta_{wt}-1}}$$

where θ_{wt} is elasticity of substitution between different labor skills. This implies labor demand

$$h_t(i,j) = \left[\frac{W_t(i)}{W_t} \right]^{-\theta_{wt}} h_t(j)$$

The number of workers is large so that each of them ignores impact of her wage setting decision on the aggregate wage index which is defined as

$$W_t = \left[\int_0^1 W_t(i)^{1-\theta_{w,t}} di \right]^{\frac{1}{1-\theta_{wt}}}$$

Domestic and Foreign composite goods

The aggregator assembles imperfectly substitutable intermediate goods from all firms producing domestic intermediate goods. The constant returns to scale (CRS) technology is expressed as:

$$\left[\int_0^1 Y_{Ht}(j)^{\frac{\theta_{ht}-1}{\theta_{ht}}} dj \right]^{\frac{\theta_{ht}}{\theta_{ht}-1}} \geq Y_{Ht}$$

where $\theta_{ht} > 1$ is time-varying elasticity of substitution across differentiated domestic intermediates. The aggregator solve cost minimization problem which results in demand for each good j given by

$$Y_{Ht}(j) = \left(\frac{P_{Ht}(j)}{P_{Ht}} \right)^{-\theta_{ht}} Y_{Ht}$$

and with zero profit condition the price index is defined as

$$P_{Ht} = \left[\int_0^1 P_{Ht}(j)^{1-\theta_{ht}} di \right]^{\frac{1}{1-\theta_{ht}}}$$

Each firm j takes the aggregate price in the market P_{Ht} and the overall production Y_{Ht} as given and independent of its own decision.

The domestic composite intermediate good is used in the production of final good or it is exported

$$Y_{Ht} = Y_{Ht}^{d} + Y_{Xt}. \tag{21}$$

The aggregator of foreign intermediate goods solves an analogous problem. CRS production function is given by

$$\left[\int_0^1 Y_{Ft}(j)^{\frac{\theta_{ft}-1}{\theta_{ft}}} dj\right]^{\frac{\theta_{ft}}{\theta_{ft}-1}} \geq Y_{Ft}$$

where $\theta_{ft} > 1$ is time-varying elasticity of substitution across differentiated foreign intermediates. Optimization problem with zero-profit condition implies demand function of the form

$$Y_{Ft}(j^*) = \left(\frac{P_{Ft}(j^*)}{P_{Ft}}\right)^{-\theta_{ft}} Y_{Ft}$$

and price index

$$P_{Ft} = \left[\int_0^1 P_{Ft}(j)^{1-\theta_{ft}} di\right]^{\frac{1}{1-\theta_{ft}}}$$

Again, each firm j^* ignores impact of its price setting decision on the price index.

Finished goods production

The final good Y_t is produced by competitive firm (aggregator) that uses domestic and foreign (composite) intermediate goods Y_{Ht}^{d} and Y_{Ft} as inputs subject to constant-returns-to-scale technology:

$$\left(\frac{Y_{Ht}^{d}}{\gamma}\right)^{\gamma}\left(\frac{Y_{Ft}}{1-\gamma}\right)^{1-\gamma} \geq Y_t$$

She buys intermediate goods Y_{Ht}^{d} and Y_{Ft} at nominal prices P_{Ht} and P_{Ft} respectively, and sells final good Y_t at nominal price P_t. Her profit maximization problem can be described as follows:

$$\max_{Y_{Ht}^d, Y_{Ft}} [P_t Y_t - P_{Ht} Y_{Ht}^d - P_{Ft} Y_{Ft}]$$

subject to the production function. The first order conditions are:

$$Y_{Ht}^d = \gamma \frac{P_t}{P_{Ht}} Y_t \qquad (22)$$

$$Y_{Ft} = (1-\gamma) \frac{P_t}{P_{Ft}} Y_t \qquad (23)$$

and with assumption of zero profit the final good price P_t is given by:

$$P_t = (P_{Ht})^{\gamma} (P_{Ft})^{1-\gamma} \qquad (24)$$

The final good is used for domestic consumption C_t, government consumption G_t and in the production of domestic intermediate goods K_t

$$Y_t = C_t + G_t + K_t.$$

2.3. Government

The government budget constraint in the economy is given by

$$P_t G_t = \int_0^1 T_t(i) di \qquad (25)$$

where G_t is government consumption and T_t denotes lump-sum taxes from households. The government budget is balanced in every period. The government spending is subject to random shocks that is defined by equation 2 in next text.

2.4. Monetary policy

The behaviour of monetary authority (central bank) is described by an instrument rule. Central bank adjust the short term interest rate (more precisely, the deviation of nominal interest rate from its steady state value R_t / R_t^{ss}) in response to deviations of CPI inflation from the inflation target and the output gap. We also allow for interest rate smoothing. This type of modified Taylor rule performs empirically quite well and could be regarded as good approximation of optimizing behaviour of central bank. Monetary policy reaction function has following form

$$\left(\frac{R_t}{R_t^{ss}}\right)^4 = \left(\frac{R_{t-1}}{R_t^{ss}}\right)^{4\alpha} \left[\left(\frac{P_{t+3}}{P_{t-1}(\pi_t^T)^4}\right)^{\omega_\pi} \left(\frac{y_{ht-1}}{y_h}\right)^{\omega_y}\right]^{(1-\alpha)} \times Z_{mp,t} \qquad (26)$$

where

$$R_t^{ss} = \frac{\pi_{zy}}{\beta}\pi_t^T \tag{27}$$

$$y_{ht} = \frac{Y_{Ht}}{Z_{yt}} \tag{28}$$

π_t^T is inflation target which is subject to shocks, $Z_{mp,t}$ is shock to interest rate rule.

2.5. Domestic stochastic processes

There are ten exogenous domestic shocks in the model for which law of motion need to be specified. They are $Z_{ct}, Z_{yt}, Z_{ls,t}, Z_{mp}, \pi_t^T, Z_{rp}$, θ_{ht}, θ_{ft}, θ_{wt} and Z_{gt} where the last one comes from definition

$$Z_{gt} = \frac{G_t}{Z_{yt}} \tag{29}$$

The law of motion of shocks is modelled as autoregressive processes

$$\ln(Z_{c,t}) = \rho_{zc}\ln(Z_{c,t-1}) + \varepsilon_{Z_{c,t}} \tag{30}$$

$$\ln(\pi_{zy,t}) = (1-\rho_{zy})\ln(\pi_{zy}) + \rho_{zy}\ln(\pi_{zy,t-1})\varepsilon_{Z_{yt}} \tag{31}$$

$$\ln(Z_{ls,t}) = (1-\rho_{zls})\ln(Z_{ls}) + \rho_{zls}\ln(Z_{ls,t-1}) + \varepsilon_{Z_{ls,t}} \tag{32}$$

$$\ln\left(\frac{\pi_t^T}{\pi^T}\right) = \rho_{\pi^T}\ln\left(\frac{\pi_{t-1}^T}{\pi^T}\right) + \varepsilon_{Z_{\pi_t^T}} \tag{33}$$

$$\ln(Z_{rp,t}) = \rho_{rp}\ln(Z_{rp,t-1}) + \varepsilon_{Z_{rp,t}} \tag{34}$$

$$\left(\frac{\theta_{ht}}{\theta_{ht}-1}\right) = (1-\rho_{\theta_h})\left(\frac{\theta_h}{\theta_h-1}\right) + \rho_{\theta_h}\left(\frac{\theta_{ht-1}}{\theta_{ht-1}-1}\right) + \varepsilon_{Z_{\theta_{ht}}} \tag{35}$$

$$\left(\frac{\theta_{ft}}{\theta_{ft}-1}\right) = (1-\rho_{\theta_f})\left(\frac{\theta_f}{\theta_f-1}\right) + \rho_{\theta_f}\left(\frac{\theta_{ft-1}}{\theta_{ft-1}-1}\right) + \varepsilon_{Z_{\theta_{ft}}} \tag{36}$$

$$\left(\frac{\theta_{wt}}{\theta_{wt}-1}\right)=(1-\rho_{\theta_w})\left(\frac{\theta_w}{\theta_w-1}\right)+\rho_{\theta_w}\left(\frac{\theta_{wt-1}}{\theta_{wt-1}-1}\right)+\varepsilon_{Z_{\theta_{wt}}} \tag{37}$$

$$\ln(Z_{g,t})=(1-\rho_{zg})\ln(Z_g)+\ln(Z_{g,t-1})+\varepsilon_{Z_{g,t}} \tag{38}$$

where the AR parameters are restricted as $\rho_{zc},\rho_{zy},\rho_{zls},\rho_{zrp}$, $\rho_{\pi^T},\rho_{\theta_h},\rho_{\theta_f},\rho_{\theta_w}$, $\rho_{yg}\in[0,1)$. Shock to monetary policy is assumed i.i.d. to be distinguishable from inflation target shock

$$\ln(Z_{mp,t})=\varepsilon_{Z_{mp,t}}. \tag{39}$$

2.6. Foreign economy

Foreign economy is represented by exogenous process and is identified separately. Thus the domestic economy cannot influence foreign economy. Given that the Czech Republic is a small country, it is quite realistic assumption. Foreign sector is modeled as three-equation structural vector autoregression (SVAR) model which includes equation for output, inflation and gross nominal interest rate, respectively. The system of equations can be written as:

$$A_0 x_t = A_1 x_{t-1} + F\varepsilon_t \tag{40}$$

where

$$x_t=\begin{pmatrix}\ln\left(\frac{Y_t^*}{y^*}Z_{yt}\right)\\ \ln\left(\frac{P_t^*}{\pi^* P_{t-1}^*}\right)\\ \ln\left(\frac{R_t^*}{R^*}\right)\end{pmatrix}\quad \varepsilon_t=\begin{pmatrix}\varepsilon_{y_t^*}\\ \varepsilon_{\pi_t^*}\\ \varepsilon_{R_t^*}\end{pmatrix}\sim N(0,1)$$

and where y^*, π^* and R^* are values representing steady states of the variables.

This system resembled reduced form of basic New Keynesian model. First equation (for output) can be thought of as aggregate demand of IS curve, second equation (for inflation) is aggregate supply or Phillips curve and the last equation (for interest rate) represents monetary policy reaction function. The productivity shock in foreign economy is assumed to be same as in domestic country.

To identify the SVAR model we must impose some restrictions (which already follows from ordering of the variables). The output does not respond contemporaneously to both inflation and interest rate and inflation does not react contemporaneously to interest rate. It means that matrix A_0 is lower triangular. With those restrictions, there are only three free parameters in A_0 matrix and also in F matrix, which is diagonal.

$$A_0 = \begin{pmatrix} 1 & 0 & 0 \\ \rho_{\pi^* y^*} & 1 & 0 \\ \rho_{R^* y^*} & \rho_{R^* \pi^*} & 1 \end{pmatrix} \qquad F = \begin{pmatrix} \sigma_{y^*} & 0 & 0 \\ 0 & \sigma_{\pi^*} & 0 \\ 0 & 0 & \sigma_{R^*} \end{pmatrix}$$

2.7. Macroeconomic equilibrium and solution

The symmetric equilibrium of the economy allows to drop the indices (i, j) and express all variables in per capita (or aggregate) term. The wage index and the aggregate prices for domestic and foreign intermediates and exports are

$$W_t = \left[\delta_w (\pi_{wt-1} W_{t-1})^{1-\theta_{wt}} + (1-\delta_w) W_t^{new(1-\theta_{wt})}\right]^{\frac{1}{1-\theta_{wt}}} \tag{41}$$

$$P_{Ht} = \left[\delta_h (\pi_{ht-1} P_{Ht-1})^{1-\theta_{ht}} + (1-\delta_h) P_{Ht}^{new(1-\theta_{ht})}\right]^{\frac{1}{1-\theta_{ht}}} \tag{42}$$

$$P_{Ft} = \left[\delta_f (\pi_{ft-1} P_{Ft-1})^{1-\theta_{ft}} + (1-\delta_f) P_{Ft}^{new(1-\theta_{ft})}\right]^{\frac{1}{1-\theta_{ft}}} \tag{43}$$

$$P_{Xt} = \left[\delta_x (\pi_{xt-1} P_{Xt-1})^{1-\theta_{xt}} + (1-\delta_x) P_{Xt}^{new(1-\theta_{xt})}\right]^{\frac{1}{1-\theta_{xt}}} \tag{44}$$

Symmetry also implies that domestic bonds holdings for every home agent are zero

$$B_t = 0 \tag{45}$$

The equilibrium of the economy consists of 34 sequences of endogenous variables $B_t, B_t^*, C_t, D_t, G_t, \Lambda_t$, $h_t, P_{Ft}^{new}, P_{Ht}^{new}, P_{Xt}^{new}, P_{Ft}, P_{Ht}, P_{Xt}, P_t$, π_t, π_{wt}, $\pi_{ht}, \pi_{ft}, \pi_{xt}$, π_{zyt}, $R_t, R_t^{ss}, rp_t, S_t, T_t, W_t, W_t^{new}, \Xi_t, Y_{Ht}^d, Y_{Ht}, Y_{Ft}, Y_{Xt}$, Y_t, y_{ht}. The equilibrium implies that (i) households maximize their utility (ii) firms maximize profits or minimize their costs, (iii) markets are cleared for each asset and each good and (iv) the resource constraints are satisfied. The endogenous variables are driven by 13 stochastic shocks $Z_{ct}, Z_{yt}, Z_{ls,t}$, Z_{mp}, π_t^T, Z_{rp}, θ_{ht}, θ_{ft}, θ_{wt}, $Z_{gt}, P_t^*, Y_t^*, R_t^*$. There is 47 sequences of variables and thus 47 equations are needed to solve the system. These are the equations numbered from (1) to (45) where (40) is actually a set of three equations.

The model is too complex and does not have an analytical (closed form) solution. It possible to get only approximate solution that is derived from numerical simulation of model log-linearized around its steady state. However, in equilibrium some of the variables contain unit root that comes from the technology shock Z_{yt} (equation (31)) and from foreign inflation (second equation in (40)). Under such conditions the log-linearization is not accurate. The stochastically detrended variables π_t, π_{wt},

$\pi_{ht}, \pi_{ft}, \pi_{xt}, \pi_{zy,t}$, y_{ht} remain stationary. The nonstationary variables are put into stationary form using following transformations:

$$b_t \equiv \frac{B_t}{P_t Z_{yt}}, b_t^* \equiv \frac{B_t^*}{P_t^* Z_{yt}}, w_t \equiv \frac{W_t}{P_t Z_{yt}}, \ w_t^{new} \equiv \frac{W_t^{new}}{W_t}, c_t \equiv \frac{C_t}{Z_{yt}}$$

$$Z_{g,t} \equiv \frac{G_t}{Z_{yt}}, d_t \equiv \frac{D_t}{Z_{yt}}, \lambda_t \equiv \frac{\Lambda_t}{P_t Z_{yt}}, p_{ht} \equiv \frac{P_{Ht}}{P_t}, p_{ft} \equiv \frac{P_{Ft}}{P_t}$$

$$p_{xt} \equiv \frac{P_{Xt}}{P_t^*}, p_{ht}^{new} \equiv \frac{P_{Ht}^{new}}{P_{Ht}}, \xi \equiv \frac{\Xi_t}{P_t}, y_t \equiv \frac{Y_t}{Z_{yt}}$$

$$y_{ft} \equiv \frac{Z_{Ft}}{Z_{yt}}, y_{xt} \equiv \frac{Y_{xt}}{Z_{yt}}, y_{ht}^d \equiv \frac{Y_{Ht}^d}{Z_{yt}}, \pi_t^* \equiv \frac{P_t^*}{P_{t-1}^*}, y_t^* \equiv \frac{Y_t^*}{Z_{yt}}.$$

After these transformations of the variables one can derive stationary form of the system, compute steady state and solve it. The steady state behaves as an atractor or equilibrium to which the system converges when any deviation occurs. Those deviations comes from innovations in the shocks processes (equation (30) to (38)). The aim of the analysis is to study dynamics of the system around the steady state, therefore the log-linearized form of the system is computed. The log-linearized system is presented in Appendix A. The variables are expressed as deviation from steady state, $\hat{x} \equiv \log(\frac{x_t}{x})$, where for any variable x_t, the variable without time index x denotes steady state and $\hat{x}_t$ is log-linear approximation. The log-linearized system includes, besides other equations, four hybrid New Keynesian Phillips curves: for wage inflation (A.15), for domestic prices inflation (A.16) and for import prices and export prices inflation (A.17 and A.18). These equations capture rigid behaviour of (nominal) prices.

The system is transferred into state-space representation and is solved using Blanchard and Kahn (1980) procedure or its modification outlined in Klein (2000). State-space form consists of transition equation (46) and measurement equation (47).

$$\mathsf{S}_{t+1} = \Phi_{\mathsf{S}} \mathsf{S}_t + \Phi_{\varepsilon} \varepsilon_{t+1} \tag{46}$$

$$f_t = \Phi_f \mathsf{S}_t + \eta_t \tag{47}$$

$$\varepsilon_t = \begin{bmatrix} \varepsilon_{Z_{c,t}} & \varepsilon_{Z_{g,t}} & \varepsilon_{Z_{ls,t}} & \varepsilon_{\theta_{ht}} & \varepsilon_{\theta_{ft}} & \varepsilon_{\theta_{wt}} & \dots \\ \varepsilon_{Z_{yt}} & \varepsilon_{Z_{rp,t}} & \varepsilon_{\pi_t^T} & \varepsilon_{Z_{mp,t}} & \sigma_{y^*}\varepsilon_{y_t^*} & \sigma_{\pi^*}\varepsilon_{\pi_t^*} & \sigma_{R^*}\varepsilon_{R_t^*} \end{bmatrix}$$

where S_t is vector of state variables and f_t is vector of flow variables, ε_t is vector of innovations to shocks and η_t is vector of measurement errors for which hold

$E(\varepsilon_t \varepsilon_t') = V$ and $E(\eta_t \eta_t') = \widetilde{R}$. The vector of state variables includes all the predetermined variables ($\hat{R}_{t-1}, \hat{b}^*_{t-1}, \hat{p}^*_{t-1}, \hat{c}_{t-1}, \hat{w}_{t-1}, \hat{p}_{ht-1}, \hat{p}_{ft-1}, \hat{p}_{xt-1}, \hat{\pi}_{wt-1}$, $\hat{\pi}_{ht-1}, \hat{\pi}_{ft-1}$, $\hat{\pi}_{xt-1}, \hat{y}_{ht-1}$) and the exogenous variables ($\hat{Z}_{ct}, \hat{Z}_{ls,t}$, $\hat{\pi}^T_t, \hat{Z}_{mp}, \hat{Z}_{rp}$, $\hat{\theta}_{ht}$, $\hat{\theta}_{ft}$, $\hat{\theta}_{wt}$, $\hat{Z}_{gt}, \hat{\pi}_{zyt}, \hat{y}^*_t, \hat{\pi}^*_t, \hat{R}^*_t$). The vector of flow variables contains ($\hat{d}_t, \hat{h}_t, r\hat{p}_t, \hat{R}^{ss}_t$, $\hat{\xi}_t, \hat{y}_{xt}, \hat{y}_{ft}, \hat{y}^d_{ht}, \hat{y}_t$, $\hat{\pi}_{ct}, \hat{\pi}_{YHt}, \hat{\pi}_t, \hat{\pi}_{wt}$, $\hat{\pi}_{ht}$, $\hat{\pi}_{ft}, \hat{\pi}_{xt}, \hat{\lambda}_t, r\hat{e}r_t, \hat{s}_t$) where three auxiliary variables were added for estimation purposes. They are the growth rate of consumption $\hat{\pi}_{ct}$, the growth rate of production of intermediate goods $\hat{\pi}_{Y_H t}$ and the real exchange rate $r\hat{e}r_t$.

Elements in matrices Φ_S of format (13×13), Φ_ε of format (13×13) and Φ_f of format (19×13) are nonlinear functions of the structural parameters of the model. They do not have analytical solution and thus numerical procedures must be involved to derive it.[14] The requirement of unique solution imposes some restrictions on the parameter space that also cannot be expressed analytically. The unique solution requires that the Blanchard-Kahn condition must be satisfied, i.e. the number of the predetermined variables must be equal to the number of stable eigenvalues of the system, which can be calculated only numerically.

3. EMPIRICAL STRATEGY

3.1. Variables selection

The model includes thirteen exogenous shocks that drive behaviour of the endogenous variables. The parameters of the model cannot be estimated using more than thirteen observable variables. Trying so, the stochastic singularity problem can arise as discussed e.g. in Ireland (2004). It means that the covariance matrix of the data becomes singular and the maximum likelihood estimation breaks down. This is caused by fact that the model predicts deterministic relationship between some endogenous variables but this relationship does not need to hold in the data.

As the number of variables used for estimation is limited, the estimation results can be influenced by choice of them. Therefore the choice of variables has to be restricted to those of direct interest. Specifically, the choice should be motivated by the research question about dynamics of wages and prices within the DSGE model. The variables should help to identify parameters describing nominal rigidity and also parameters of the shocks that directly affects behaviour of wages and prices. The following thirteen variables were chosen to match their empirical counterparts: wage inflation (π_{wt}), inflation in prices of domestic intermediates (π_{ht}), inflation of imported goods (π_{ft}), CPI inflation (π_t), consumption growth (π_{Ct}), production

[14] E.g. Blanchard and Kahn (1980) or Klein (2000).

growth $(\pi_{Y_H t})$, the labor input (h_t), the real exchange rate (rer_t), government expenditures (Z_{gt}), nominal interest rate (R_t), foreign inflation (π_t^*), foreign demand (Y_t^*) and foreign nominal interest rate (R_t^*).

3.2. Taking theoretical variables to the data

Theoretical variables do not need to have exact definition in terms of observable variables. Therefore some compromises and amendments of observable variables must be made to conform the theoretical model. This issue is particularly important because answer to the question, whether wages are more rigid than prices or vice versa, is very sensitive to the exact definition of wage and price indices.

The data used for empirical analysis are quarterly, spanning period from 1996:Q1 to 2007:Q4. Time series are obtained from databases of the Czech Statistical Office (CZSO), the Czech National Bank (CNB) and the European Central Bank (ECB).[15] The data are seasonally adjusted from source or adjusted by Kalman filter-smoother. Domestic output (Y_t) is measured by gross domestic product, final consumption expenditures of households is empirical counterpart for consumption (C_t). Government expenditures (G_t) are measured by final consumption expenditures of government. Labor input (h_t) is represented by number of worked hours. The consumer price index (P_t) has same definition as empirical measure, total wages and salaries correspond to wage rate (W_t) in the model. Prices of imported goods (P_{Ft}) is expressed by import price index. The gross nominal interest rate (R_t) is measured by 3 months Prague Inter Bank Offered Rate (PRIBOR). Nominal exchange rate S_t is exchange rates against the ECU/Euro. As the CZSO do not have records of producer prices from domestic sources, the best proxy variable for prices of domestic intermediate goods (P_{Ht}) is implicit price deflator of gross domestic product which excludes, by definition, prices of imported goods. Foreign sector is represented by Eurozone that includes 12 countries. Foreign demand (Y_t^*) is measured by gross domestic product, price level (P_t^*) by deflator of final consumption of households and NPISHs and nominal interest rate (R_t^*) is 3 months EURIBOR. The aggregate variables (C_t, G_t, Y_{Ht}, h_t and Y_t^*) are divided by total employment to obtain per worker values.[16]

The model is estimated in stationary form, thus the observable variables should be tranformed into stationary form to match the theoretical counterparts. Most of the variables are expessed as growth rates, thus first differences (of logarithms) were calculated. This procedure applies for all types of inflation and consumption and

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[15]Appendix B deals with data sources in more detail.

[16]Usual approach is to divide the aggregate variables by working age population to get per capita values. However, the model assumes that all people in the economy work, the expression of variables per worker is more appropriate.

output growth. These time series were also demeaned where the mean of time series corresponds to steady state value.

Another approach was chosen for other variables. First, there is structural break in hours worked during year 2001 that can be ascribed to demographical changes which are not captured by model. To circumvent this problem, the Hodrick-Prescott (HP) filter[17] was used for estimation of smooth trend that was then extracted. Hours worked are then expressed as gap (deviation from trend). Second, there is downward trend in the real exchange rate which is common in all transition countries. It is usually explained by catch-up effect (or Balassa-Samuelson effect).[18] Simply said, increase in productivity causes increase of relative prices of nontradable goods (to tradable goods). It subsequently induces increase in the overall price level and hence appreciation of the real exchange rate. The paper does not treat tradable and nontradable goods in the model framework and thus is not capable to explain this phenomenon. Again Hodrick-Prescott filter was used to detrend data series of the real exchange rate. Third, nominal interest rate exhibits peak in 1997 and then downward trend. Calculated mean of the series indicates that nominal interest rate has been under its equilibrium value since 2000. This does not correspond to view of the Czech central bank. Therefore HP filter was used for extraction of smooth trend (that expresses steady state) to get more interpretable time series. The processes for exogenous variables are estimated separately. Government spendings are assumed to follow AR(1) process. Foreign sector is modeled as SVAR(1) which should remind basic New Keynesian gap model. The corresponding series (government spendings, foreign output, foreign inflation rate and foreign nominal interest rate) are detrended by Hodrick-Prescott filter and expressed in gap form.

After transformation of the time series used for estimation test for presence of unit root was proceeded to ensure that the series are stationary.[19] Table 1 summarizes results of the test. One could reject the null hypothesis of a unit root for nominal interest rate, all types of inflation, the real exchange rate and consumption growth at significance level of 1 %. On the other hand hours worked and output growth were found to be $I(1)$. Despite the fact that all theoretical variables are assumed to be stationary, these two time series were used for estimation without any additional transformation. However, to mitigate the nonstationarity problem, measurement errors were added to the measurement equation for these two variables. In the state-space representation of the system, measurement errors are stacked in vector η_t in equation (47).

Foreign nominal interest rate was also found to be $I(1)$, but this time series is used in separate estimation using ordinary least squares (OLS) method. Even if the parameters of the foreign sector model can be biased, I belive that it does not have important influence for estimation results of the main model.

[17]Hodrick and Prescott (1997)
[18]Balassa (1964), Samuelson (1964)
[19]Augmented Dickey-Fuller test was used.

3.3. Estimation methodology

A combination of three methods -- calibration, maximum likelihood and Bayesian estimation -- is used for identification of structural parameters of the model. Several parameters are kept fixed throughout the estimation procedure. Some of them relates to steady state values of the observed variables, therefore they are calibrated to match their sample mean. Some parameters are calibrated just for the reason to reduce the number of parameters for estimation.

The state-space form representation of the log-linearized system allows to use Kalman filter algorithm for estimation of the model parameter via maximum likelihood. The maximization of the likelihood is sometimes difficult in large systems due to overparametrization. The likelihood is flat in some directions and parameters can take corner solution. Next, the iteration process do not need to find global maximum of likelihood function. Those problems can be partly eliminated using Bayesian approach. It combines the likelihood with some prior information on the distribution of the parameters to form the posterior density function of those parameters. The prior density of the parameters give a shape or curvature to the likelihood function which makes the optimization algorithm more stable. The prior information downweights the likelihood function in the regions that are implausible or in dissonance with economic theory or other empirical studies. Prior information can be acquired from microeconomic studies or from results of estimation of similar macromodels. They can be also based on expertize analysis or personal judgement that reflect strong beliefs about economic behaviour even if the raw data does not carry such information. This kind of expediency allows to introduce information from outside of the modelling framework. It is initial guess of the value of each parameter and associated uncertainty that is held a priori. Then the uncertainty of the guess is reduced by means of likelihood function to arrive at the posterior. Hence, the Bayesian approach can be thought of as a combination of maximum likelihood and calibration methods.

According to Bayes' rule the posterior density $p(\Theta \mid y)$ is related to the prior density $p(\Theta)$, the likelihood function $p(y \mid \Theta)$ and marginal data density $p(y)$,

$$p(\Theta \mid y) = \frac{p(y \mid \Theta)\, p(\Theta)}{p(y)}$$

where Θ is unknown vector of parameters and y denotes data. As we are interested in unknown parameters Θ which are not involved in $p(y)$, this term can be ignored. Then, the posterior is proportional to likelihood times prior

$$p(\Theta \mid y) \propto p(y \mid \Theta)\, p(\Theta).$$

The formula shows that the Bayesian approach to estimation in some sense tries to pull the estimates of parameters to the values possessing prior information while the maximum likelihood approach pulls those parameters to the values with good fit of the model. In the end, one should get estimates that are plausible from the economic point of view and also fit well empirically.

There is important distinction between Bayesian and classical approach to inferences. The classical approach considers parameters as fixed (and unknown) and the observed data are treated as realizations of some stochastic (data generating) process. The goal is whether the data could be generated by particular model given certain values of parameters. On the other hand, the Bayesian approach treat parameters as random variables, while the observed data are fixed. This simple theoretical concept offers broad range of possibilities including e.g. model comparison based on model probabilities.

To make inferences about the parameters, one needs to compute moments of posterior distribution. The posterior distribution does not have analytical solution, therefore numerical solution using stochastic simulation is employed. This sampling procedure uses Random Walk Chain Metropolis-Hastings algorithm. It is kind of Markov Chain Monte Carlo (MCMC) algorithm that draws sample parameters from a candidate density with equal weights but do not accepts all candidates. The candidates draws are chosen according to acceptance probability. Finally, moments of the function of interest are obtained thought Monte-Carlo integration of the simulated values.[20]

All the computations regarding Bayesian estimation are done using Dynare toolbox (see Juillard (2004)) in Matlab software.

4. ESTIMATION RESULTS

The estimation process for maximization of the posterior distribution is computationally demanding: the model is solved for each observation in each iteration of the optimization procedure for the likelihood function. It can be partly simplified by estimating some parameters separately. It is possible for those shock processes that directly involve observable variables, namely government spending shocks and the foreign sector. Those two sets of parameters are estimated by ordinary least squares method; government spending as simple AR(1) process, foreign sector as SVAR model. Treating foreign sector as exogenous is reasonable assumption. The Czech Republic is small open economy; it behaves as price taker on the world market and cannot affect the world variables. As shown by Musil (2008) there are not important differences between modelling of behaviour of the Czech economy with endogenous or exogenous foreign sector.

4.1. OLS estimation

As mentioned above, the parameters of government spending shock and foreign sector are estimated separately given that corresponding shock processes involve observables. The productivity shock (Z_{yt}) that is unobservable is assumed to be included in both government spendings (G_t) and foreign demand (Y_t^*). To remove it from observable variables, the time series of government spending and the foreign demand are detrended using Hodrick-Prescott filter. The same procedure was applied to foreign inflation and foreign nominal interest rate.

The results of estimation is shown in Table 2 and 3.[21] The government spending shock is not very persistent, the value of AR parameter is 0.58. The innovation to shock is also quite modest with standard deviation of nearly 2 %.

The variables in SVAR model for foreign sector are lagged by only one period. Number of lags was chosen according to information criterions; whereas AIC implied

[20] More details about the algorithm can be found in Koop (2003).

[21] For the sake of transparency, parameters pertaining to foreign sector are quoted in matrix notation.

two lags, and SBC and HQ implied one lag. The matrix pertaining to independent variables (without lag), A_0, is lower triangular. This restriction is imposed from identification purposes and is based on Choleski decomposition. All parameters in matrix A_0 have correct signs, $\rho_{\pi^* y^*}$ is negative (-0.0716) and thus confirm positive relationship between inflation and output gap in the reduced form of Phillips curve. Parameters $\rho_{R^* y^*}$ and $\rho_{R^* y^*}$ are also negative (-0.0869 and -0.0549, respectively) and also correctly describe positive relationship between nominal interest rate and inflation and output gap in the interest rate rule. Matrix of lagged variables A_1 is quite sparse because some of the parameters were not statistically significant. Negatively signed parameter that catches relationship between contemporary inflation and lagged output is difficult to interpret. However, its value is less than value of $\rho_{\pi^* y^*}$ thus the positive impact of contemporary output gap overweights. Other statistically significant parameters in A_1 are correctly signed. Standard deviation of innovations to individual equations are shown on diagonal of matrix F. The influence of shock to interest rate rule is negligible, only 0.05 %. It implies that behaviour of (foreign) nominal interest rate is almost perfectly explained by inflation and output gap. Standard errors in demand equation and Phillips curve equation are around 0.2 %.

4.2. Calibration

Because number of variables used for estimation is limited, not all the parameters can be estimated precisely. As it is common in the literature, the accuracy of the estimation is increased if some parameters are kept fixed throughout the estimation. Usually, the parameters are calibrated to match their long-run averages in the data or they are set at " reasonable" values based on some prior knowledge from other empirical studies. Most of calibrated parameters relates only to model's steady state. The calibrated parameters are summarized in Table 4.

The shock processes with the steady state different from unity (zero in log-linearized model) cause that the steady state of the whole model is not uniquely defined. Therefore ten additional conditions regarding steady states are needed to add. (i) Output, consumption and government spendings should grow at the same rate in the steady state. This growth rate is equal to the growth rate of technology. However, the data shows that this assumption is not maintained. The output growth rate is similar to growth rate in consumption, 1.0079 and 1.0075, respectively.[22] The growth rate of government spendings is only 1.0045. Against this background, the steady-state gross growth rate of technology is calibrated to π_{zy} = 1.005 which is roughly 2 % on annual basis. This choice comes from necessary condition that β, the time preference parameter, must be less than one. As shown below, the growth rate of technology together with the real interest rate implies the value of β. Thus, this choice has rather pragmatic reasoning. Another justification is that the model does not take into consideration population growth. The calibrated value can be thought of as mixture of technology growth and population growth which was

[22]The growth rate is expressed as quarter-on-quarter.

actually negative in the Czech Republic. The lower value of π_{zy} is reasonable compromise. (ii) and (iii) The steady state level of elasticity of substitution across different types of domestic and foreign intermediate goods, θ_h and θ_f, are both set to 8, which implies a gross steady state markup of 1.143. [23] There are not any microeconomic studies of these elasticities for the Czech data. Value for these parameters were simply borrowed from Maih (2005) for Norwegian economy. Same approach was chosen for (iv) the steady state level of the elasticity of substitution across different types of labor input, θ_w, which is set to 6, implying gross steady state markup of 1.2.

Generally, it is quite difficult to pin down the values of elasticity of substitution (especially for foreign intermediates) because lack of enough empirical evidence. Those elasticities appear only in the steady state of the model which makes impossible to identify them econometrically. The value of likelihood is independent of those parameters. It may be worth exploring the impact of different values of those elasticities on the results of the estimations and implications for the model's dynamics. Sensitivity analysis is a possible approach, but this paper does not deal with this issue and leaves it for further research. (v) The steady state level of inflation target, π^T, is set to the sample mean of CPI inflation. The Czech National Bank has been operating in regime of inflation targeting since January 1998 which covers almost the whole data sample used for the estimation and offers possibility to use official measure of inflation target. However, the ways of inflation target announcements was altered several times, they were discontinuous and also the targeting variable changed during the time. The mean of CPI inflation is better proxy for the inflation target. (vi) The steady state level of foreign inflation, π^*, is set to the sample mean of consumer prices inflation in Eurozone, (vii) the steady state level of the foreign gross nominal interest rate, R^*, is set to match the sample mean of EURIBOR. $(viii)$ For determination of the steady state level of detrended foreign output, y^*, the paper uses fact of constant export-to-output ratio which can be computed from the data, $k_x = x/y$;[24] (ix) the stationary model also implies constant government spending-to-output ratio, k_g (again calculated from data), which can be used for computing of the steady state level of detrended government spendings $Z_g = k_g y$. (x) The model implies that discount factor, β, is related to the steady state real interest rate by following formula: $\frac{R}{\pi} = \frac{\pi_{zy}}{\beta}$. With calibrated

[23] markup = $\frac{\theta_h}{\theta_h - 1}$

[24] Even if the model implies constancy of export-to-output ratio, it does not hold in Czech data. There is increasing trend of this ratio. Alternatively, it is possible to use consumption-to-output ratio as Maih (2005) did.

value of π_{zy} and steady state real interest rate calculated from data,[25] the discount factor is equal to 0.9993.

The elasticity of intertemporal substitution $\frac{1}{\rho}$ is set to 1 because that is the only value for which the model is consistent with a balanced growth path. This is a consequence of the additively separable parametrization of the utility function as shown e.g. by King, Plosser and Rebelo (1988). Necessary condition for the identification of shocks is to have as many observable variables as the number of shocks. However, this condition is not sufficient. Both labor supply and wage markup shocks enter the system through and only through the wage Phillips curve, as can be seen in equation (A.15). Without any further assumption about how those two shocks are correlated, none of them can be identified. The paper assumes wage markup shocks to be persistent and labor supply shocks to be only temporary. This identification assumptions implies that labor supply shock is i.i.d. $(\rho_{zls} = 0)$ while wage markup shocks follow autoregressive processes.

4.3. Bayesian estimation

4.3.1. The prior distribution

This section deals with setting of priors of the parameters before Bayesian estimation. Priors can be thought of as beliefs about the likely location of the structural parameters in the parameter space. Some regions of that parameter space are not in accordance with the theory or model equilibrium. The priors are chosen so as to preclude those regions and thus restrict the parameters to lie within the boundaries specified by the theory. Table 5 reports estimated parameters together with parameters' domain, distribution, prior mean and the standard deviation reflecting the uncertainty about prior beliefs.

For parameters that lie between 0 and 1, beta distribution is used. The prior mean of the habit persistence parameter (hab) is set to 0.7, which is value commonly used in the literature. Its prior standard derivation is set to 0.1. The prior mean for γ is set to 0.2669 so that $(1-\gamma)$ matches the average import-to-output ratio calculated from data. The prior mean for the persistence parameters $(\rho_{\pi^T}, \rho_{Z_{ls}}, \rho_{Z_{rp}}, \rho_{Z_y}, \rho_{\theta_h}, \rho_{\theta_f}, \rho_{\theta_w})$ is set to 0.4 with standard deviation .1. Smets and Wouters (2003), Maih (2005) or Adolfson et al. (2005) use higher values of priors for autoregressive coefficients of the shocks, usually 0.85. Higher persistence of shocks can usually improve the fit of the model. However, I decided to choose lower prior values of AR parameters based on discussion with experts from the Czech National Bank. The reasoning is as follows. When the shock hits the economy, the agents usually do not assume that the shock is persistent and will last for many periods. This is quite relevant assumption especially for the Czech economy that has experienced many structural changes during the transformation process and people expect variable economic environment. Excessively persistent shocks could misleadingly catch some important features of the economy that are under our

[25]Sample mean of the real interest rate is 2.3% on an annual basis.

interest. Following Adolfon et al. (2005) the prior for smoothing parameter of interest rate in the monetary policy reaction function (α) is set to 0.80 with a standard deviation of 0.05. High degree of interest rate smoothing of the Czech central bank was also found e.g. in Musil (2008).

Stickiness in wages and prices reflects frictions in goods and labor markets that causes propagation of exogenous shocks into the real part of economy. Parameters expressing degree of nominal rigidity are closely related to our research question. Even if the data experience of the Czech economy suggests that nominal wages are more sticky than prices the prior mean is set to same value. It allows us to reveal ultimate conclusion without influences caused by prior setting. The Calvo parameters for imported intermediates (δ_f), domestic intermediates (δ_h) exported intermediate composite good (δ_x) and wages (δ_w) are all set to 0.75, which implies that contracts change on average every 4 quarters. Standard deviation of 0.10 means that contracts can vary between 3 and 6 quarters.[26]

For parameters that are assumed to be positive, such as the standard deviations of the shocks, σ, inverted gamma distribution is used. The prior mean for standard deviations of the shock processes is set to 0.01. The prior mean for the standard deviations of the measurement errors is set to 0.01 for both hours worked (h) and output growth (π_{Y_H}). The paper allows measurement errors only in these two variables because they contain unit root, as disscused above. There are no measurement errors on the other variables because they are stationary processes.

The inverted gamma distribution is also used for the risk premium parameter φ. This parameter is assumed to be positive but small, the prior mean was set to 0.01. For two parameters, the price elasticity of exports (θ_x) and the Frisch elasticity of labor supply ($\frac{1}{\nu}$) that are assumed positive and larger, gamma distribution is chosen. The prior mean for the price elasticity is set to 0.8 with standard deviation 0.05. The Frisch elasticity of labor supply is quite controversial and is usually calibrated. References in Maih (2005) report values that vary from 1/3 to 1, depending on the study. Since there is not any study about labor supply elasticity for the Czech economy, the paper uses Maih's prior values: mean of ν is set to 3 and standard deviation to 1.

The remaining parameters are the coefficients of the monetary policy reaction function for which the normal distribution is chosen. The parameter that describes reaction of central bank to inflation (ω_π) has prior 1.70 and standard deviation 0.1. Weight of reaction to output gap (ω_y) is assumed much smaller, the prior mean is set to 0.1 and standard deviation to 0.05.

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[26]Average length of contracts comes from formula: $\frac{1}{1-\delta}$.

4.3.2. The posterior distribution

The joint posterior distribution of the vector of parameters is obtained in two steps by using numerical algorithms. First, the posterior mode and Hessian matrix evaluated at the mode are computed by standard numerical optimization routines (Christopher Sims' csminwel function). The likelihood function is computed first by solving the model and then using the Kalman filter. Figure 4 and 5 shows the curvature of the objective function at the mode for each estimated parameter. The algoritm did not find evident minimum for parameters α and δ_w thus they are not properply identified. Then, there is a second step that generates samples from joint posterior distribution to carry out Bayesian inferences. Specifically, Random Walk Chain Metropolis-Hastings algorithm is used. The algorithm starts from the mode and generates 1,000,000 draws from the posterior distribution. 50 % of replications are discarded so as to avoid influence of initial conditions. The moments of the posterior distribution are computed through Monte-Carlo integration of the remaining draws. The average acceptance probability of candidates was 0.32. Markov Chain Monte Carlo diagnostics were used for convergence verification of the algorithm.

Figure 6 and 7 shows prior distribution (grey line) and posterior distribution (black line) together with posterior mode (dashed green line) for each of the estimated parameters. Table 4 shows the results from the Bayesian estimation. The structural parameters and their domain are presented in the first and second column. The third up to the fifth column summarizes moments of the prior distribution. The mode and the standard deviation of the posterior maximization are reported in the sixth and seventh column. The eighth column shows the posterior mean together with the 5th and 95th percentile of the posterior distribution (ninth and tenth column). The last two columns thus constitute the 90 % confidence interval.

Let us start interpretation of the results with the parameters describing preferences of households. The habit formation (hab) seems not so important, its posterior mean is 0.6937, lower than the prior value. The mean of the Frisch labor supply elasticity (inverse of υ) is $\frac{1}{2.7062}$ which indicates that labor adjust quite slowly to the real wage movements. However, this estimated value should be taken with care because time series of hours worked was found nonstationary and enter the estimation with measurement error.

The estimated Calvo parameters (δ_f, δ_h, δ_w, δ_x) express degree of nominal rigidities and are key element in answering the research question. The estimated Calvo parameters express degree of nominal rigidity. The average duration of wage contracts is nearly 7 quarters and that of price contracts for domestic intermediates is only 1.7 quarters.[27] It indicates that wages adjust more sluggishly than domestic prices. More importantly, according to this measure, wages are the most rigid and domestic prices are the most flexible nominal prices. Calvo parameters (and contracts duration) for other nominal variables lie between these two values. Average duration of price contracts for imported intermediates is 4 quarters and for exported intermediates 2.7 quarters. The point estimate of Calvo parameter for

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[27] Average duration of contract is calculated using formula $\frac{1}{1-\delta}$.

domestic prices deviated from the prior value more than three times the standard deviation. However, this result turned out to be robust outcome of the estimation procedure. Parameter γ expresses openness of the economy. More precisely $(1-\gamma)$ should capture share of imports to output. Posterior mean of γ is 0.1629 which indicates much higher openness than the prior value. Labor share in the production function, parameter ψ, was estimated to 0.6498. It is quite reasonable value, as the capital share[28] is usually calibrated to one third. However, it is higher than value obtained from other sources; e.g. Hloušek (2007) reports average labor share 0.59, calculated as total labor cost to gross value added.

The monetary policy reaction function shows very high interest rate smoothing. Mean of the parameter corresponding to the lagged interest rate, α, is 0.8972. This value seems to be too high in comparison with rhetoric of the Czech National Bank about inflation targeting as the main strategy. However, similar values were found by Musil (2008), and other authors. Weights on inflation and output in the reaction function, ω_{π} and ω_{yh}, are very similar to the priors; emphasis on inflation targeting is sixteen times higher than on output stabilization. But as can be seen from Figure 7 these two parameters were not identified appropriately from the data. The difference between the prior and the posterior distribution was negligible which indicates that the parameters are rather calibrated than estimated.

The price elasticity of export function, θ_x, is rather high compared to the prior mean. Risk premium was estimated to about 2 % p. q. Such high value should be attributed mainly to the financial crisis in 1997.

Looking at the autoregressive parameters of the shocks, the most persistent shock is the risk premium shock (ρ_{zrp} = 0.5719). On the other hand, the least persistent are the shocks to price markup of imported intermediates (ρ_{θ_f} = 0.1705) and markup of domestic intermediates (ρ_{θ_h} = 0.3151). Other autoregressive shock processes exhibit inertia not far from the prior value.

Looking at the volatility of the shocks, labor supply shock and shock to markup of imported intermediates are the most volatile ($\sigma_{Z_{ls}}$ = 0.1415, σ_{θ_f} = 0.1321.) Quite substantial is also wage markup shock, σ_{θ_w}. Productivity shock and monetary policy shock are the least volatile, σ_{Z_y} and $\sigma_{Z_{mp}}$ respectively. The measurement error of output growth is relatively small, measurement error of hours worked is more substantial but still acceptable. Their impact on the overall fit of the model could be considered as negligible.

4.4. Assessing the fit

Although the DSGE model has firm economic foundations, it may have problems to replicate the data, because it is too stylized. The assessing of the fit of the model is carried out along three dimensions. Firstly, the fitted series are visually compared

[28] Complement to one, $(1-\psi)$.

with the observed series. Secondly, the volatility and the autocorrelations implied by the model are compared with the statistics calculated from the data. And thirdly, estimated unobserved shocks should reflect important events in the Czech economy.

4.4.1. Filtered vs. observed variables

Figure 8 provides qualitative fit of the DSGE model to the data. Observed time series (solid line) can be compared with the one-period-ahead forecast obtained from Kalman filter (dashed and dotted line). Filtered and smoothed variables are computed at the mean of the posterior distribution. Overall fit of the model is more or less satisfactory at the first sight. Nominal interest rate and CPI inflation has the best fit. Nominal interest rate can be perfectly measured, the result is in accordance with what one would assume. Other filtered variables mostly record the right direction, however their volatility is smaller. But not always, the model predicted more significant drop in consumption growth at the end of 90's than the data shows. Model behaviour of wage inflation is in accordance with the data from 2000 or so. Time series of output growth and hours worked were introduced with the measurement error and thus poor fit of these model variables can be ascribed to this fact. Prediction of hours worked looks like being lagged, especially in the mid of the sample period. Very significant differences are in inflation of import prices. This variable was introduced without measurement error, however the algorithm returned quite substantial measurement error and filtered import inflation closely to CPI inflation. This is the most severe problem of the model fit, however I belive that its implications for wage-price dynamics is not so critical and it does not influence the principal research question in important way.

4.4.2. Unconditional second-order moments

Common practice in the Real Business Cycle literature for model evaluation is comparison of model statistics (mostly variances and correlations) with statistics from the data. Here, I focus only on the volatility and autocorrelations (not cross-correlation) of the variables used for Bayesian estimation. Table 7 presents standard deviations computed from the data and the theoretical standard deviation predicted by the model (for the estimated vector of parameters). As the table shows, the most volatile variable is the real exchange rate while nominal interest rate is the least volatile. DSGE model succeeded in replication of these magnitudes pretty well. The volatility of output growth is also almost the same. Differences in volatility of hours worked, consumption growth and CPI inflation are not large. However, the model overestimates volatilities in wage inflation and underestimates volatility in import inflation and domestic inflation. Overall fit of the model regarding these statistics is quite satisfactory.

The benchmark for comparison of autocorrelations is unrestricted first order VAR. Figure 9 shows autocorrelations implied by DSGE model (dashed and dotted line) and VAR model (solid line) for the same set of variables as above. The DSGE model replicates autocorrelations of the real exchange rate, domestic inflation and consumption growth quite well, but it fails in other variables. Magnitude of autocorrelation of nominal interest rate is systematically higher than in the data. DSGE also fails to capture short run autocorrelation of CPI inflation and output growth and medium run autocorrelation of labor (hours worked). Autocorrelation functions of VAR and DSGE model only intersect for wage inflation and import inflation at lags of four. All these discrepancies can be caused by the fact that the

VAR is not the process that generates data and that, due to unobserved variables, the DSGE does not have VAR representation.

4.4.3. Kalman smoothed unobserved shocks

Estimates of the unobserved variables (shocks) are presented in Figure 10. The shocks are smoothed by Kalman filter and are also computed at the mean of the posterior distribution. Most of the shocks follow autoregressive processes and their behaviour can be linked with estimated values of AR parameters.[29] The AR coefficients are quite small (around 0.4) and the degree of persistence is not so visible. Risk premium shocks should be the most persistent (ρ_{Zrp} = 0.59), but it is apparent only at the end of time series. Consumption preference shocks and productivity (technology) shocks have similar AR coefficients (ρ_{Zc} = 0.44) and $\rho_{\pi zy}$ = 0.42), but their behaviour is totally different. Productivity shocks look more persistent.

The smoothed shocks can be related to events in the history of the Czech economy. Most of the shocks exhibit higher volatility at the beginning of the sample period. This is certainly connected with the crisis in 1997. This period was characterized by high interest rates which can be detected in monetary policy and risk premium shocks. The recession was characterised by negative output growth which can be ascribed to negative technology shock. Regime of inflation targeting was introduced in January 1998. Period before the transition to this regime and the first year of its functioning is characterized by high volatility of inflation target shock. Higher inflation at the end of 1990s can be associated with domestic prices markup shocks. It must be mentioned that wage and import prices markup shocks are large in terms of volatility compared to other shocks (look at the scale). However, their role in explaining some economic events is limited. They do not exhibit any systematic pattern and looks stationary. Government spendings were also negatively influenced by the recession. But from 2001 onwards, the government budget benefited from growing economy. Economic slowdown in 2002 in the Czech economy can be partly explained by weak foreign demand. Similarly, negative foreign inflation shocks contributed to low (or decrease of) CPI inflation before 2000 and after 2002.

4.5. Dynamical properties of the model

This section studies dynamical characteristics of the model using variance decomposition and impulse response functions.

4.5.1. Variance decomposition

Variation of selected endogenous variables can be decomposed into contribution of each shock using variance decomposition. It enables to infer the importance of the thirteen exogenous shocks in fluctuations of the variables. Table 8 presents unconditional asymptotic variance decomposition, i.e. forecast error variance of the variables in the long run horizon. The considered variables are following: real and nominal interest rate, real exchange rate, CPI inflation, domestic prices and wage inflation, consumption growth, output growth and labor (hours worked). The shocks are divided into three groups. Real shocks include consumption preference shock, technology shock and labor supply shock; nominal shocks are wage markup shock, price markup shocks (of domestic goods and imports), inflation target, risk premium

[29]Monetary policy shock and labor supply shock are i.i.d. and thus are equal to innovations.

and monetary policy shocks. Last group contains shocks in foreign economy and government spending shock.

Foreign shocks have negligible effect for behaviour of selected variables. Only foreign output shock can explain 20 % of the variation of domestic output growth. Government spending shock is also insignificant. On the other hand, the most important shock is shock in markup of import prices. It has substantial effects not only for nominal but also for real variables.

Shock to wage markup, which is assumed to be persistent, is then second most important driving force in variation of hours worked. It comes as no surprise that consumption preference shock explains most of the variation in consumption growth (65 %) and productivity shock of the output growth (nearly 40 %). Risk premium shock has significant impact on movements of the real exchange rate. Its contribution to variation in hours, output growth and nominal interest rate is about 11 %.

Besides import prices markup shock, large part of variation in the domestic prices and wage inflation are explained by (domestic) price markup and wage markup shocks, respectively. Even if labor supply shock was assumed i.i.d. (not persistent) it accounts for almost 11 % in variation of wage inflation.

As it was mentioned above, the import prices markup shock is principal mover in nominal variables, especially in import and CPI inflation (more than 77 and 74 % respectively). It indicates that the Czech economy must confront inflation pressures mostly from abroad. Inflation target and monetary policy shocks are more or less evenly spread among all analysed variables. Their contributions in explaining variation of overall inflation are 4.6 and 7.4 % respectively. It shows that the Czech National Bank pursue good monetary policy.

4.5.2. Impulse response function

The dynamic behaviour of the model can be also studied using impulse response function. The model is hit by one-period unitary shock (innovation) and behaviour of endogenous variables in reaction to that disturbance is simulated. Reported variables are real and nominal interest rate, real exchange rate, CPI inflation, domestic and wage inflation, consumption growth, output growth and labor (hours worked) and, if appropriate, import inflation, imports and exports. In figures from 11 to 23, time horizon (in quarters) is measured on the horizontal axis, the vertical axis expresses percentage deviation of the variable from steady state.[30] The size of the shock is one standard deviation of the stochastic variable. The shocks can be divided into two groups, similarly as in Juillard et al. (2006). Demand shocks produce positive correlation between inflation and real GDP in the short run, while supply shocks imply negative short run correlation between these two variables. Due to this classification, demand shocks considered in this paper are: consumption preference shock ($\hat{Z}_c$), the inflation target shock ($\hat{\pi}^T$), the risk premium shock ($\hat{Z}_{rp,t}$), the monetary policy shock ($\hat{Z}_{mp,t}$) and the imported intermediates price markup shock ($\hat{\theta}_{ft}$) and all shocks in foreign economy ($\hat{y}_t^*$, $\hat{\pi}_t^*$ and $\hat{R}_t^*$). Group of

[30]Used notation is e.g. 0.10 which means 10 %.

supply shocks includes the government spending shock ($\hat{Z}_{g,t}$), the domestic price markup shock ($\hat{\theta}_{ht}$), the wage markup shock ($\hat{\theta}_{wt}$), the technology shock ($\hat{\pi}_{zyt}$), the labor supply shock ($\hat{Z}_{ls,t}$).

Consumption preferences shock [figure 11]

Higher consumption demand increases production and thus demand for labor input. Increased labor demand induces wage inflation which pushes up also prices. Central bank reacts by increasing interest rate. However, increase in inflation is higher and the real interest rate decreases. Real exchange rates depreciates in reaction to the (real) interest rate differential.

Technology shock [figure 12]

The productivity shock is not so persistent as one would expect. Production and consumption increase, part of output (of intermediate goods) is exported. Higher productivity is followed by increase of worked hours which pushes the wages up. However, the total marginal cost of firms decreases (without reducing their profits) and firms can reduce their markups. It lowers domestic inflation. Overall inflation also decreases and the central bank reacts by decrease of nominal interest rate. Decrease of inflation is more significant therefore the real interest rate increases and the real exchange rate appreciates.

Wage markup shock and Labor supply shock [figure 13 and 14]

An increase in wages raises cost of production of domestic intermediates which causes decrease of the demand for labor. Wage inflation is transmitted into price inflation, but only for domestic good. Overall CPI inflation after initial small jump decreases. Central bank lowers interest rate to stabilize the economy, because production is also below its potential. In spite of it the real interest rate increases and the real exchange rate appreciates to satisfy (real) UIP condition. The effects of labor supply shock are qualitatively very similar to the wage markup shock, only the size of deviations is smaller.

Monetary policy shock [figure 15]

The contractionary monetary policy represented by sudden increase in nominal interest rate causes recession in the economy -- drop in output growth and inflation. Decline of inflation is hump shaped because prices are sticky. Combination of high nominal interest rate and fall in inflation implies that the real interest rate rises even more and the real exchange rate appreciates. High real interest rate increases the opportunity cost of consumption which depresses domestic demand as consumers shift their consumption into the future. Weak demand for output forces domestic produces to decrease demand for labor input.

Inflation target shock [figure 16]

Inflation target shock causes initial decrease of nominal interest rate which allows inflation to increase. Decline in the real interest rate is connected with sharp depreciation of the real exchange rate and increase of consumer demand (which is more profitable today than in the future). Higher consumer (and export) demand is satisfied by higher production which leads to increase of hours worked.

Risk premium shock [figure 17]

Risk premium shock induces large exchange rate depreciation (in real terms). It enhances export of intermediates, because they are cheaper for foreigners. The exchange rate depreciation is passed-through into import prices. Import price inflation leads to fall in imports and to increase of the overall inflation. The central bank reacts by increase of interest rate. Even if the real interest rate decreases, consumers do not switch consumption form future towards today. Higher production of output is rather exported than consumed. It follows that the number of hours worked increases.

Government spending shock [figure 18]

Reaction of the economy is quite similar to consumption shock. There is an initial increase in the aggregate output which is produced by employing more labor. However, government spending crowds out private consumption which decreases. All types of inflation increase and follow hump-shaped pattern. Central bank reacts by increasing interest rate. Again, the real interest rate decreases which is accompanied by real exchange rate depreciation.

Domestic price markup shock [figure 19]

An increase in the markup of domestic producers increases domestic and also overall inflation. However, this increase is only one-shot and inflation switches into negative values. The production follows similar but reversed pattern. Labor demand decreased together with wage inflation. To restore the equilibrium in the economy, central bank gradually lowers interest rate. However, as the inflation was below the equilibrium, the real interest rate increased and the real exchange rate appreciated. Appreation has negative effect on exports and higher consumption demand was satisfied by higher imports.

Import price markup shock [figure 20]

An increase in the markup of importers is passed through import inflation into CPI inflation. The amount of imported goods decreases. The central bank reacts to inflation in the economy and increases interest rate. The increase in the nominal interest rate is not sufficient and the real interest rate decreases which makes the real exchange rate to gradually appreciate. Production increases only a little, but allows a rise in worked hours. Consumption is negatively affected by decrease in imports.

Foreign interest rate shock [figure 21]

Shock in foreign interest rate causes (through uncovered interest parity condition) depreciation of the real exchange rate. It enhances domestic production and labor demand. Output is rather exported than consumed by households. Depreciation of the real exchange rate has negative effect on imports because they are more expensive. Expansion in home economy is accompanied by increase in all types of inflation. Central bank reacts by rising nominal interest rate to bring the economy back to equilibrium.

Foreign output and foreign inflation shock [figure 22 and 23]

Shock to foreign output affects home economy through another channels, even if the impacts are quite similar. Part of higher foreign production is imported and consumed in home economy (increase in imports is long-lasting). Increase in output growth is one-shot. Initialy higher labor demand returns to steady state more sluggishly. Inflation in the economy forces central bank to increase nominal interest rate. The real interest rate decreases as the real exchange rate depreciates. Reaction of the economy to the shock in foreign inflation is qualitatively very similar to the shock in foreign output. Exception is volume of imports that responds only temporary for the foreign inflation shock. Quantitatively, the size of deviations is smaller in case of foreign inflation shock.

4.6. Further implications of the model

4.6.1. Implications for exchange rate pass-through

Figure 24 shows how changes in the exchange rate slowly pass-through into domestic prices, import prices and consumer prices. It must be mentioned that all prices and exchange rate are endogenous variables, which means they are interdependent. Adjustment of the prices following changes in exchange rate cannot be interpreted as the exchange rate pulls the prices. The degree of exchange rate pass-through can be inferred from the distance between the line representing nominal exchange rate and the lines of corresponding variables (prices).

Exchange rate is flexible, it usually jumps and then gradually moves to new level. Behaviour of prices is regulated by contracts, thus the prices evolve only gradually. High flexibility of domestic prices is evident in the plots and is consistent with low value of estimated Calvo parameter.

Exchange rate pass-through is very fast in case of monetary policy, inflation target and risk premium shocks. The complete adjustment of all the prices is no longer than fifteen periods.[31] Pass-through into the CPI is faster than into the other prices in response to all shocks. This result is in contrast to findings of Maih (2005) and Ambler et al. (2003). They found out that pass-through to import prices is the quickest.[32] Quite surprising result is that the pass-through is not complete in the long run horizon for domestic prices and even import prices for some types of shocks. It can be explained by fact that domestic prices are quite independent of exchange rate movements and are influenced only indirectly. Or from the other side, some types of shocks have direct impact on domestic prices but exchange rate is subject to other forces. This is certainly the case of domestic prices markup shock, wage markup shock, labor supply shock and technology shock. Following three former shocks, domestic prices initially increases but the nominal exchange rate appreciates. It confirms the view that domestic prices " live their own life" . In case of import prices markup shock, exchange rate and other prices behave similarly, but domestic prices converge to different level in the long run. Why pass-through into import prices is incomplete in the long run for some type of shocks remains puzzle.

Regarding foreign economy shocks, the speed of pass-through for import prices and CPI is quite high (again around fifteen periods) with domestic prices approaching in the long run horizon. Similarly for consumption preference shock. In case of government spending shock, pass-through to all prices is complete after twenty five periods.

[31] The word "complete" is not accurate. There is still small gap between nominal exchange rate and domestic prices, even in the long run. However, I neglect this discrepancy as it can be covered in the confidence interval of impulse responses that are not shown here.

[32] Import prices follow CPI very closely, but there remains small discrepancy between import prices and exchange rate for some types of shocks.

This analysis shows that exchange rate pass-through is conditional on the stochastic shocks which can influence prices and exchange rate in different way.

4.6.2. Implications for wage-price dynamics

The point estimates of Calvo parameters indicates how often the contracts change, but they do not say anything about the dynamics of wages and prices. Again as in the previous subsection, wages and prices are endogenous variables which means that they do not affect each other directly and they are subject to many other influences. Figure 25 shows impulse responses of wages (solid line) and consumer price index (dashed line) in reaction to exogenous shocks. Overall impression is similar to exchange rate pass-through analysis. Behaviour of the variables depends on the type of shock and considered time horizon. Wages and prices behave almost identically in case of monetary policy and inflation target shock. The prices change quicker (lead) than wages for most of the shocks.[33] However, wages are significantly more volatile than prices for labor supply, wage markup and technology shocks. It is intuitive, because these shocks influence the process of wage setting directly. Wages and prices do not need to move in the same direction in the short run. Examples of such behaviour are responses to price markup shock and technology shock. In the case of technology shock, prices and wages diverge even in the long run (wages come to higher and prices to lower level than before the shock). At long run horizon wages and prices do not converge to the qualitatively and quantitatively same level for many shocks. The reasoning can stem from high openness of the Czech economy. Wages are the main component of domestic prices, but large part of CPI is composed of import prices and they are determined on different markets.

5. SENSITIVITY ANALYSIS

5.1. Relative importance of wage and price rigidity

This section focuses on assessment of relative importance of nominal rigidities in the model. Special attention is devoted to wage and price rigidity.The subject of interest is comparison of competing models in terms how they fit the data. These competing models assume flexibility in some of the prices or combinations of them. Marginal likelihood based on Bayesian estimation is first measure of fit. Second measure looks at vector autocorrelation function.

5.1.1. Marginal likelihood

Quantitative measure of data fit provides marignal likelihood calculated from Bayesian estimation. The Bayesian estimation overcomes maximum likelihood estimation because it takes into account the uncertainty that comes from the models or the estimates of shocks and parameters.[34] Because the priors play key role in Bayesian estimation and can influence results in important way, it is necessary to set the priors of all estimated parameters for all models to their initial values. It is exceptionally important for the sensitivity analysis.

[33] Leading behaviour is very subtle but is noticeable.

[34] However, as Del Negro and Schorfheide (2008) pointed out standard setting of priors need not be the right guide for discrimination among different theories. They suggest alternative approach for choosing the priors that is based on quasi-likelihood function with the aim of 'levelling the playing field'. However, I believe that this new approach do not have substantial qualitative influence for the results presented here. Nevertheless it could be interesting topic for further research if and how the results are quantitatively different.

The competing models are derived from the benchmark model (with all rigidities) -- they allow flexible prices in particular sector. The term flexibility (or no habit persistence) means that corresponding parameter is set to 0.2.[35]

The analysis considers following specifications: the benchmark model is denoted BM, the model with flexible import prices FIP, the model with flexible domestic prices FDP, the model with flexible wages FW and the model with flexible export prices FEP. Then some combinations with rigidities in two or more sectors are: the model with flexible domestic and export prices FDEP, the model with flexible domestic, import prices and no habit formation FDIPH and model without nominal rigidities FWDIEP.[36]

Table 9 presents estimated parameters of competing models together with Laplace approximation of the log data density. The models are ordered according to the value of log data density which measures fit of the data.

The results of the analysis are quite surprising. The model with flexible domestic prices fits the data better than the richer benchmark model. Also model with assumption of flexible domestic and export prices overtook the benchmark model. With focus on relative importance between price and wage stickiness it is obvious that these rigidities are not interchangeable. Specifically, wage rigidity is more important than price rigidity. It is confirmed both by triumph of FDP model and by poor fit of FW model. It also corresponds to empirical fact that real wages behave countercyclically in the Czech economy.

Next, the results indicate that extension of the model by rigidities in export market (compared to Maih's (2005) original model) has only small effect. Difference between benchmark model and that with flexible export prices is not so significant. The model without nominal rigidities and with only real rigidity (habit in consumption) has the worst fit of all models. It suggests that nominal stickiness is important phenomenon. However, it is not universal for all prices. The most important nominal frictions in the Czech economy are rigidities in wages and import prices.

Interesting fact is how the model parameters compensate the lack of rigidity in particular sector (compared to the benchmark model). The most striking difference is in estimates of Frisch elasticity of labor supply $(1/\upsilon)$ which decreases from 1/2.7062 for the benchmark model to 1/3.9320 for the flexible wage model. It implies that labor supply is more unresponsive to changes in the real wage. In other words, the nominal rigidity in wages is transferred to rigidity in labor supply.

Another structural parameter that is highly volatile for different specifications is γ. It expresses openness of the economy; more precisely $(1-\gamma)$ should capture share of imports to output. However, γ also regards to the price index, it expresses weight of domestic prices in the CPI. Because the nominal time series (inflation of domestic prices, import prices and CPI) are used for estimation this influence is probably more important for the results. Value of γ fluctuates from 0.1629 for the benchmark model (very open economy) up to 0.5128 for flexible import prices model. The

[35]For behaviour of prices it means that the contract is changed once in 1.25 quarters.
[36]Some other specifications as the models with flexible domestic and import prices FDIP plus flexible export prices FDIEP were also analyzed. Their performance to fit the data is not significantly different from FDIPH model, so they are not presented here.

domestic prices thus increased their ability in explaining (rigid) behaviour of CPI index. Low value of 0.094 for flexible wage model shows extreme openness to trade. This result is quite puzzle and can stem from mutual influence of more parameters for this specification.

Autoregressive parameter of shock to import prices is also highly volatile. It increases (from 0.17) to value around 0.52 for all models with flexible import prices. The model tries to explain higher persistence in import prices by shock behaviour.

This approach also enables to assess importance of measurement errors introduced in the estimation. Measurement errors remain quite stable for all specifications of the models; the only exception is measurement error in output growth which slightly increased for models which include flexible import prices. However, in general the results indicate that measurement errors have negligible effect for the fit of the models.

Similar analysis could be applied to shocks and their volatility. The most important shocks (with largest standard deviation) are labor supply shock and markup shocks to import prices and to wages. These shocks also vary most of all which indicates quite high sensitivity to the type of rigidity. It is quite hard to find some stable pattern across the models. However, it seems that higher flexibility of particular prices reduces the standard deviation of relevant shock. This is true e. g. for import prices and shock to their markup.

5.1.2. Vector autocorrelation functions

This section looks at vector autocorrelations of the variables used in Bayesian estimation. This is done for three specifications of the model: flexible domestic prices model and flexible wages model are compared to each other and with reference to the benchmark model. The considered variables are hours worked, output growth, consumption growth and the real exchange rate as the real variables and wage inflation, domestic inflation, import inflation, CPI inflation and nominal interest rate as the nominal variables.

Figure 10 plots correlation up to tenth order of these variables for BM (solid line), FDP (dashed and dotted line) and FW (dotted line) model. Persistence of the variables is shown on the diagonal plots. Autocorrelations implied by FDP are pretty much same as in the BM case for all the variables. FW model shows lower short-run persistence[37] especially for wage inflation (plot(5,5)), but partly also for domestic inflation, consumption and output growth and labor. In the medium run,[38] the persistence of these variables is little bit higher for flexible wage model compared to the benchmark. Looking at the off-diagonal correlations, there are many statistics, but most of them provide similar picture. Flexible domestic prices model matches correlations very closely to the benchmark model. Correlations implied by flexible wages model are usually smaller and sometimes close to zero. Correlation of wage inflation with the nominal variables is an illustrative example (fifth row). Similar pattern shows also correlations of many variables with worked hours (first column). Cross-correlation function of labor with wage inflation and domestic inflation follow hump shaped pattern for FW model, but for FDP and BM it gradually decreases,

[37]Up to 5 periods.
[38]From 5 to 10 periods.

even into negative values (plot(1,5) and (1,6)). Neither FW nor FDP can match medium run correlations of import and CPI inflation with consumption growth that is present in benchmark model (plot (7,3) and (8,3)). Correlation of wage inflation and domestic prices inflation with growth of consumption is different for all models and for all lags (plot (4,3)).

To summarize it, assumption of flexible wages is at odd in matching the statistics of benchmark model. This result further support the view that wage rigidity is more important than price rigidity.

5.2. Is wage and price rigidity interchangeable?

This section further examine whether wage and price rigidity is interchangeable or not. This is done by comparison of impulse responses for different model specification, i.e. with different assumption about nominal rigidity. The considered models are again the benchmark, the flexible wages and the flexible domestic prices model. Figures 11 and 12 show impulse responses of these variables: labor, output growth, consumption growth, CPI and wage inflation, the real interest rate and the real exchange rate, to all shocks except the foreign shocks. The responses are computed using the vector of parameters at the mean of posterior distribution.

The impulses response for the benchmark model (solid line) and flexible domestic prices model (dashed and dotted line) are very similar. Significant differences are evident only for the wage markup and labor supply shock (figure 12, fourth and fifth row). For the latter shock, the variables in benchmark case are more volatile. Differences between flexible wages and the benchmark model are apparent especially in behaviour of hours worked and wage inflation. Under the assumption of wage flexibility, responses of labor are not so hump shaped, return is faster and initial reaction is sometimes opposite than in benchmark case (figure 11, first column). Wage inflation is more volatile, but returns quickly to the equilibrium. Fast adjustment of the variables is characteristic also for many other variables and shocks in flexible wage model. These observations confirm that behaviour of the variables in time is sensitive to the assumptions about the source of nominal rigidity and that wage rigidity is not tantamount to price rigidity.

6. CONCLUSION

This paper examined importance of nominal rigidities in DSGE model of the Czech economy with emphasis on wage-price dynamics. Results of estimation revealed quite clear conclusion. Estimated length of Calvo contracts suggests that wage stickiness is more important than price stickiness. The model approach allowed to investigate the dynamics of wages and prices in more detail. The impulse response funciton showed that adjustment of prices is faster than of wages for many stochastic shocks. Next, prices and wages need not move in the same direction and can converge to different levels. Their joint dynamics depends on type of the shock and considered time horizon. Sensitivity analysis showed that assumption of flexible nominal wages is flawed feature of the model and do not fit data well. On the other hand, model specification with flexible prices are in accordance with the data. It means that rigidity in wages is more important than in prices. Impulse responses for alternative models (with different assumptions about nominal rigidities) illustrated that the source of nominal rigidity has important impacts for behaviour of several variables, especially in the short and medium horizon. It was also confirmed by vector autocorrelations. The price rigidity is thus distinguishable from wage rigidity.

The analysis made in this paper naturaly suggests several ways for further research on both theoretical and empirical level. The model can be extended by investment sector with real rigidity expressed by adjustment cost, as in Adolfson et al. (2005). Another interesting extension could be dividing the production into tradable and nontradable goods, as it is modeled by Musil (2008).

On the empirical level, the sensitivity analysis can be carried out using Global sensitivity analysis (GSA) techniques propagated by Ratto (2008). This approach can more effectively show possible weaknesses of estimation process or relationship between data series and parameters or between structural parameters and parameters of the reduced form. Next, the setting of priors (quasi-likelihood based priors) for Bayesian estimation as suggested DelNegro and Schorfheide (2008) can have quantitative impacts for the result. They are worth to be examined.

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A Stationary log-linearized system

Definition of deviation of variable from trend: $\hat{x} \equiv \log(\frac{x_t}{x})$.

The risk premium

$$r\hat{p}_t = -\varphi rer \frac{b^*}{y}\left(r\hat{e}r_t + \hat{b}_t^* - \hat{y}_t\right) + \hat{Z}_{rp,t} \tag{A.1}$$

The budget constraint

$$\frac{rerb^*}{\pi_{zy}\pi^*}(\beta-1)r\hat{e}r_t + \beta\frac{rerb^*}{\pi_{zy}\pi^*}\hat{b}_t^* =$$

$$p_h y_h \hat{p}_{ht} + p_h y_h \hat{y}_{ht} - y\hat{y}_t + \frac{rerb^*}{\pi_{zy}\pi^*}\left(\hat{b}_{t-1}^* - \hat{\pi}_t^* - \hat{\pi}_{zt} + \beta\hat{R}_t^* + \beta r\hat{p}_t\right) \tag{A.2}$$

The consumption demand

$$\hat{Z}_{C,t} = \frac{\lambda c}{Z_c}\left(\hat{\lambda}_t + \hat{c}_t\right) - \frac{hab\lambda c}{Z_c\pi_{zy}}\left(\hat{\lambda}_t + \hat{c}_{t-1} - \hat{\pi}_{zy,t}\right) \tag{A.3}$$

The Euler equation for domestic bonds

$$\hat{\lambda}_t = \hat{R}_t + E_t(\hat{\lambda}_t) - E_t(\hat{\pi}_{t+1}) - E_t(\hat{\pi}_{zy,t+1}) \tag{A.4}$$

The uncovered interest rate parity condition

$$\hat{R}_t r\hat{e}r_t - E_t(\hat{\pi}_{t+1}) = \hat{R}_t^* + r\hat{p}_t + E_t r\hat{e}r_{t+1} - E_t\hat{\pi}_{t+1}^* \tag{A.5}$$

The home demand for home intermediates

$$\hat{y}_{ht}^d = -\hat{p}_{ht} + \hat{y}_t \tag{A.6}$$

The home demand for foreign intermediates

$$\hat{y}_{ft} = -\hat{p}_{ft} + \hat{y}_t \tag{A.7}$$

The aggregate price or CPI index

$$0 = \gamma\hat{p}_{ht} + (1-\gamma)\hat{p}_{ft} \tag{A.8}$$

Equilibrium condition for the Home production of intermediates

$$\hat{y}_{ht} = \frac{y_h^d}{y_h}\hat{y}_{ht}^d + \frac{y_x}{y_h}\hat{y}_{xt} \tag{A.9}$$

Export demand equation

$$\hat{y}_{xt} = \theta_{xp}(r\hat{e}r_t - \hat{p}_{ht}) + \hat{y}_t^* \tag{A.10}$$

The production function for domestic intermediates

$$\hat{y}_{ht} = \psi\hat{h}_t + (1-\psi)\left(\frac{y}{y-c-g}\hat{y}_t - \frac{c}{y-c-g}\hat{c}_t - \frac{g}{y-c-g}\hat{g}_t\right) \tag{A.11}$$

The labor demand equation

$$\hat{w}_t = \hat{\xi}_t + \hat{y}_{ht} - \hat{h}_t \tag{A.12}$$

The other input (capital) demand equation

$$0 = \hat{\xi}_t + \hat{y}_{ht} - \frac{y}{y-c-g}\hat{y}_t + \frac{c}{y-c-g}\hat{c}_t + \frac{g}{y-c-g}\hat{g}_t \tag{A.13}$$

The profits

$$d\hat{d}_t = p_h y_h(\hat{p}_{ht} + \hat{y}_{ht}) - wh(\hat{w}_t + \hat{h}_t) - y\hat{y}_t + c\hat{c}_t \tag{A.14}$$

The Phillips curve for wages

$$\hat{\pi}_{wt} = \frac{\beta\delta_w}{1+\beta\delta_w}E_t\hat{\pi}_{wt+1} + \frac{1}{1+\beta\delta_w}\hat{\pi}_{wt-1}$$
$$+\frac{(1-\delta_w)(1-\beta\delta_w)}{\delta_w(1+\beta\delta_w)}\left(v\hat{h}_t - \hat{\lambda}_t - \hat{w}_t + \hat{Z}_{C,t} + \hat{Z}_{ls,t} - \frac{1}{\theta_w - 1}\hat{\theta}_{wt}\right) \tag{A.15}$$

The Phillips curve for domestic intermediates' prices

$$\hat{\pi}_{ht} = \frac{\beta\delta_h}{1+\beta\delta_h}E_t\hat{\pi}_{ht+1} + \frac{1}{1+\beta\delta_h}\hat{\pi}_{ht-1} + \frac{(1-\delta_h)(1-\beta\delta_h)}{\delta_h(1+\beta\delta_h)}\left(\hat{\xi}_t - \hat{p}_{ht} - \frac{1}{\theta_h - 1}\hat{\theta}_{ht}\right) \tag{A.16}$$

The Phillips curve for imported goods' prices

$$\hat{\pi}_{ft} = \frac{\beta\delta_f}{1+\beta\delta_f}E_t\hat{\pi}_{ft+1} + \frac{1}{1+\beta\delta_f}\hat{\pi}_{ft-1} + \frac{(1-\delta_f)(1-\beta\delta_f)}{\delta_f(1+\beta\delta_f)}\left(r\hat{e}r_t - \hat{p}_{ft}\right) \tag{A.17}$$

The Phillips curve for exported goods' prices

$$\hat{\pi}_{xt} = \frac{\beta\delta_x}{1+\beta\delta_x}E_t\hat{\pi}_{xt+1} + \frac{1}{1+\beta\delta_x}\hat{\pi}_{xt-1} + \frac{(1-\delta_x)(1-\beta\delta_x)}{\delta_x(1+\beta\delta_x)}\left(\hat{p}_{ht} - \hat{s}_t - \hat{p}_{xt}\right) \tag{A.18}$$

The monetary policy reaction function

$$4\hat{R}_t = 4\alpha\hat{R}_{t-1} +$$
$$+(1-\alpha)\begin{bmatrix} 4\hat{R}_t^{ss} + \omega_y\hat{y}_{ht-1} \\ \omega_\pi E_t(\hat{\pi}_{t+3} + \hat{\pi}_{t+2} + \hat{\pi}_{t+1} + \hat{\pi}_t - 4\hat{\pi}_t^T) \end{bmatrix} + \hat{Z}_{mp,t} \tag{A.19}$$

The steady state for the gross nominal interest rate is

$$\hat{R}_t^{ss} = \hat{\pi}_t^T \tag{A.20}$$

The definition of the real exchange rate

$$r\hat{e}r_t = \hat{s}_t + \hat{p}_t^* - \hat{p}_t \tag{A.21}$$

The definition of foreign inflation rate

$$\hat{\pi}_t^* = \hat{p}_t^* - \hat{p}_{t-1}^* \tag{A.22}$$

The definition of inflation for the aggregate domestic intermediate goods price

$$\hat{\pi}_{ht} = \hat{p}_{ht} - \hat{p}_{ht-1} + \hat{\pi}_t \tag{A.23}$$

The definition of nominal wage growth

$$\hat{\pi}_{wt} = \hat{w}_t - \hat{w}_{t-1} + \hat{\pi}_{zy,t} + \hat{\pi}_t \tag{A.24}$$

The definition of inflation for the aggregate imported intermediate goods price

$$\hat{\pi}_{ft} = \hat{p}_{ft} - \hat{p}_{ft-1} + \hat{\pi}_t \tag{A.25}$$

The definition of inflation for the aggregate exported intermediate goods price

$$\hat{\pi}_{xt} = \hat{p}_{xt} - \hat{p}_{xt-1} \tag{A.26}$$

The consumption preference shock

$$\hat{Z}_{c,t} = \rho_{zc}\hat{Z}_{c,t-1} + \varepsilon_{Z_{c,t}} \tag{A.27}$$

The government spending shock

$$\hat{Z}_{g,t} = \rho_{zg}\hat{Z}_{g,t-1} + \varepsilon_{Z_{g,t}} \tag{A.28}$$

Labor supply shock

$$\hat{Z}_{ls,t} = \rho_{Zls}\hat{Z}_{ls,t-1} + \varepsilon_{Z_{ls,t}} \tag{A.29}$$

Domestic prices markup shock

$$\hat{\theta}_{ht} = \rho_{\theta_h}\hat{\theta}_{ht-1} - \frac{(\theta_h - 1)^2}{\theta_h}\varepsilon_{\theta_{ht}} \tag{A.30}$$

Import prices markup shock

$$\hat{\theta}_{ft} = \rho_{\theta_f}\hat{\theta}_{ft-1} - \frac{(\theta_f - 1)^2}{\theta_f}\varepsilon_{\theta_{ft}} \tag{A.31}$$

Wage markup shock

$$\hat{\theta}_{wt} = \rho_{\theta_w}\hat{\theta}_{wt-1} - \frac{(\theta_w - 1)^2}{\theta_w}\varepsilon_{\theta_{wt}} \tag{A.32}$$

The technology shock

$$\hat{\pi}_{zy,t} = \rho_{zy}\hat{\pi}_{zy,t-1} + \varepsilon_{Z_{y,t}} \tag{A.33}$$

The monetary policy shock

$$\hat{Z}_{mp,t} = \varepsilon_{Z_{mp,t}} \tag{A.34}$$

The risk premium shock

$$\hat{Z}_{rp,t} = \rho_{zrp}\hat{Z}_{rp,t-1} + \varepsilon_{Z_{rp,t}} \tag{A.35}$$

Inflation targeting shock

$$\hat{\pi}_t^T = \rho_{\pi^T} \hat{\pi}_{t-1}^T + \varepsilon_{\pi_t^T} \tag{A.36}$$

Foreign sector's shocks (demand, price, interest rate)

$$A_0 \begin{pmatrix} \hat{y}_t^* \\ \hat{\pi}_t^* \\ \hat{R}_t^* \end{pmatrix} = A(L) \begin{pmatrix} \hat{y}_{t-1}^* \\ \hat{\pi}_{t-1}^* \\ \hat{R}_{t-1}^* \end{pmatrix} + F \begin{pmatrix} \varepsilon_{y_t^*} \\ \varepsilon_{\pi_t^*} \\ \varepsilon_{R_t^*} \end{pmatrix} \tag{A.37}$$

The definition of consumption growth

$$\hat{\pi}_{Ct} = \hat{\pi}_{zy,t} + \hat{c}_t - \hat{c}_{t-1} \tag{A.38}$$

The definition of production growth

$$\hat{\pi}_{YHt} = \hat{\pi}_{zy,t} + \hat{y}_{ht} - \hat{y}_{ht-1} \tag{A.39}$$

The model consists of 41 equations; equation (37) is actually set of three equations. There are 28 endogenous variables (prices and quantities) $\hat{b}_t^*, \hat{p}_t^*, \hat{c}_t, \hat{d}_t, \hat{h}_t, \hat{\lambda}_t$, $\hat{\pi}_{ft}, \hat{\pi}_{xt}$, $\hat{\pi}_{ht}, \hat{\pi}_{wt}, \hat{p}_{ht}, \hat{p}_{ft}, \hat{p}_{xt}$, $\hat{\pi}_{Ct}, \hat{\pi}_{YHt}, \hat{\pi}_t, \hat{R}_{ht}, \hat{R}_t^{ss}$, $r\hat{e}r_t, \hat{s}_t$, $r\hat{p}_t$, $\hat{w}_t, \hat{\xi}_t, \hat{x}_t, \hat{y}_{ft}$, $\hat{y}_{ht}^d, \hat{y}_{ht}, \hat{y}_t$ together with the law of motion of 13 shocks $\hat{Z}_{c,t}, \hat{Z}_{g,t}, \hat{Z}_{hs,t}, \hat{Z}_{rp,t}$, $\hat{Z}_{mp,t}$, $\hat{\pi}_t^T, \hat{\theta}_{ht}, \hat{\theta}_{w,t}$, $\hat{\pi}_{zy,t}, \hat{\pi}_t^*, \hat{R}_t^*$, $\hat{y}_t^*$. (Assuming that $b_t = 0$ for all t, it is dropped out. And given that the paper focuses on the macroeconomic equilibrium $p_{ht}^{new}, p_{ft}^{new}, p_{xt}^{new}$ and w_t^{new} is also dropped.)

B Data description

The data are quarterly, spanning period from 1996:Q1 to 2007:Q4. If the data are not seasonally adjusted from the source, when necessary, Kalman smoother is used for seasonal adjusment.

- Gross domestic product / CZK mil., constant prices of 2000 / seasonally adjusted / CZSO
- Gross domestic product / CZK mil., current prices / seasonally adjusted / CZSO
- Final consumption expenditures of households / CZK mil., constant prices of 2000 / seasonally adjusted / CZSO
- Final consumption expenditures of government / CZK mil., constant prices of 2000 / seasonally adjusted / CZSO
- Exports / Total / CZK mil., constant prices of 2000 / seasonally adjusted / CZSO
- Total employment: hours worked / thousand hours / CZSO
- Total employment: persons / one-job holder / CZSO
- Wages and salaries: total / CZK mil., current prices / CZSO
- Import prices / Index, December 1999 = 100 / CZSO
- Consumer price index / Index, 2005 = 100 / seasonally adjusted / CZSO
- 3-month PRIBOR / per cent p.a. / CNB
- Exchange rates against the ECU/Euro (average) / Not seasonally adjusted data / Czech Koruna / CNB
- Gross domestic product at constant prices, in millions of ECU/EUR at 1995 prices / seasonally adjusted, Euro 12 /ECB
- Total employment / thousands of persons / Seasonally adjusted / Euro 12 / ECB
- Deflator of final consumption of households and NPISHs / Euro 12 / ECB
- 3-month EURIBOR / per cent p.a. / ECB

C Tables and figures

Table 1: Data and their transformation

Variable	Symbol	Transform.	Test of stationarity	Estimated shock
Endogenous data				
labor (hours worked)	h_t	HP filter	$I(1)^{***}$	$Z_{ls,t}$
nominal interest rate	R_t	HP filter	$I(0)^{***}$	$Z_{mp,t}$
CPI inflation	π_t	none	$I(0)^{***}$	π_t^T
domestic inflation	π_{ht}	none	$I(0)^{***}$	$\frac{\theta_{ht}}{\theta_{ht}-1}$
imported inflation	π_{ft}	none	$I(0)^{***}$	$\frac{\theta_{ft}}{\theta_{ft}-1}$
wage inflation	π_{wt}	none	$I(0)^{***}$	$\frac{\theta_{wt}}{\theta_{wt}-1}$
real exchange rate	rer_t	HP filter	$I(0)^{***}$	$Z_{rp,t}$
consumption growth	π_{ct}	none	$I(0)^{***}$	$Z_{c,t}$
output growth	π_{yht}	none	$I(0)^{*}/I(1)^{***}$	$\pi_{zy,t}$
Exogenous data				
government spending	g_t	HP filter	$I(0)^{***}$	$Z_{g,t}$
foreign CPI inflation	π_t^*	HP filter	$I(0)^{***}$	π_t^*
foreign demand	y_t^*	HP filter	$I(0)^{**}$	y_t^*
foreign interest rate	R_t^*	HP filter	$I(1)^{***}$	R_t^*

Test of stationarity is based on Augmented Dickey-Fuller (ADF) test. Maximum number of lags was set to five. Symbols *, **, *** denotes significance level, 10 %, 5 % and 1 % respectively. Data that are not filtered by HP filter are centered around their mean before estimation.

Figure 1: Cyclical behaviour of the real wage

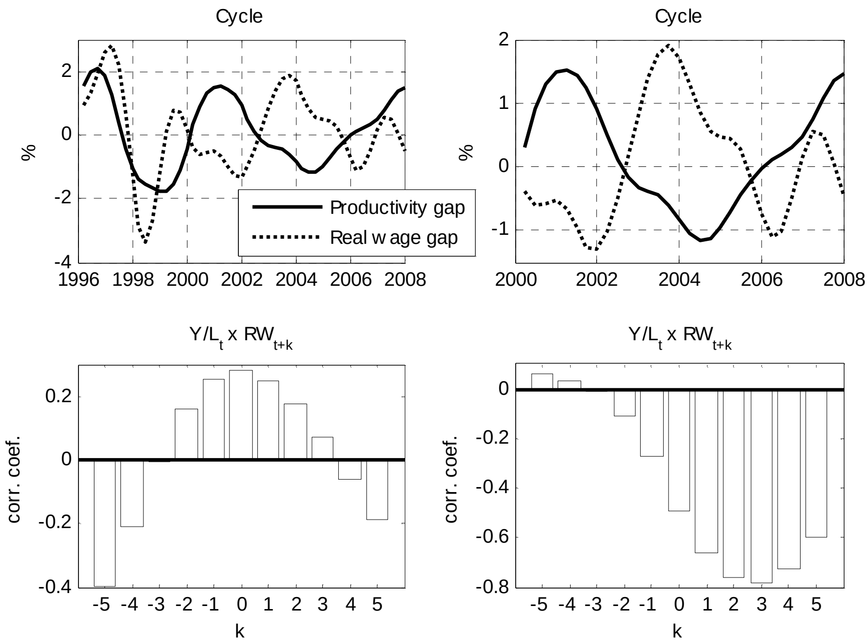


Figure 2: Production side of the economy

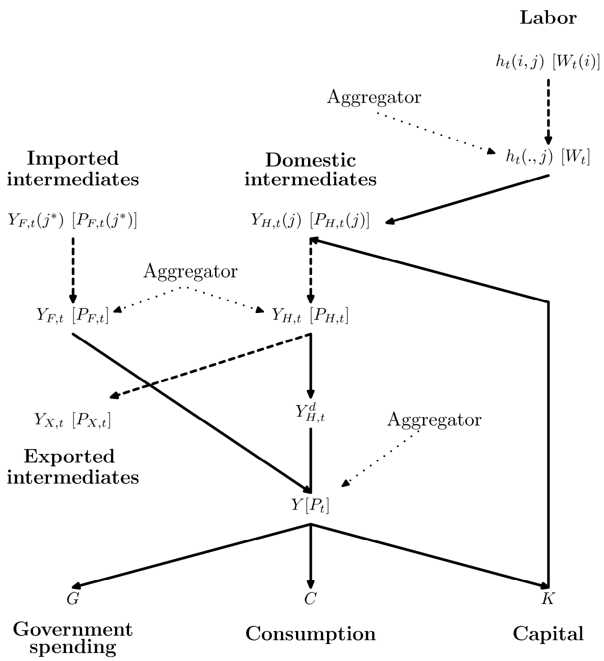


Figure 3: Data for Bayesian estimation

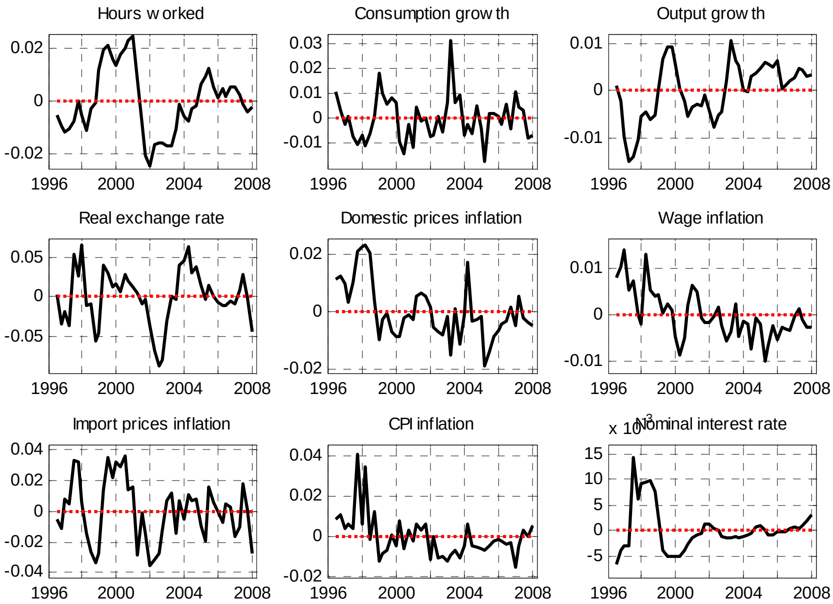


Table 2: Government spending shock

Parameter	estimate	standard deviation
ρ_{zg}	0.5812	0.2886
σ_{z_g}	0.0199	-

Table 3: Foreign sector

$$A_0 x_t = A_1 x_{t-1} + F\varepsilon_t$$

$$A_0 = \begin{pmatrix} 1 & 0 & 0 \\ -0.0716 & 1 & 0 \\ -0.0869 & -0.0549 & 1 \end{pmatrix} \quad A_1 = \begin{pmatrix} 0.8628 & 0 & 0 \\ -0.0618 & 0 & 0 \\ 0.0425 & 0.1095 & 0.6817 \end{pmatrix}$$

$$x_t = \begin{pmatrix} \hat{y}_t^* \\ \hat{\pi}_t^* \\ \hat{R}_t^* \end{pmatrix} \quad F = \begin{pmatrix} 0.0024 & 0 & 0 \\ 0 & 0.0018 & 0 \\ 0 & 0 & 0.0005 \end{pmatrix} \quad \varepsilon_t = \begin{pmatrix} \varepsilon_{y_t^*} \\ \varepsilon_{\pi_t^*} \\ \varepsilon_{R_t^*} \end{pmatrix}$$

Table 4: Calibrated parameters and steady states

Parameter	Symbol	Value
Structural parameters		
Elasticity of intertemporal substitution	$\frac{1}{\rho}$	1
Discount factor	β	0.9993
Labor supply shock persistence	ρ_{zls}	0
Steady state parameters		
Gross growth rate	π_{zy}	1.0050
Export-to-output ratio	k_c	0.6989
Gov. spending-to-output ratio	k_g	0.2167
Inflation target	π_T	1.0104
Real interest rate	$\frac{R}{\pi}$	1.0057
Domestic intermediates' price markup	$\frac{\theta_h}{\theta_h - 1}$	1.1429
Foreign intermediates' price markup	$\frac{\theta_f}{\theta_f - 1}$	1.1429
Wage markup	$\frac{\theta_w}{\theta_w - 1}$	1.2
Foreign gross nominal interest rate	R^*	1.0091
Foreign inflation	π^*	1.0047

Table 5: Parameters

Para-meter	Domain	Density	Prior mean	Std	Description
Nominal rigidities					
δ_f	[0,1)	beta	0.75	0.10	Calvo parameter, import prices
δ_h	[0,1)	beta	0.75	0.10	Calvo parameter, domestic prices
δ_w	[0,1)	beta	0.75	0.10	Calvo parameter, wages
δ_x	[0,1)	beta	0.75	0.10	Calvo parameter, export prices
Miscellaneous					
γ	[0,1)	beta	0.40	0.10	weight of domestic goods in output
φ	R^+	invg	0.06	Inf	risk premium (UIP condition)

Preferences					
hab	[0,1)	beta	0.70	0.05	habit in consumption
υ	R^+	gamm	3.00	1.00	(Frisch) elasticity of labor supply
Monetary policy reaction function					
α	[0,1)	beta	0.75	0.10	interest rate smoothing
ω_π	R^+	norm	1.50	0.10	weight on inflation
ω_{yh}	R^+	norm	0.10	0.05	weight on output
Production and export function					
ψ	[0,1)	beta	0.60	0.05	labor elasticity of production
θ_x	R^+	gamm	0.03	0.02	price elasticity of exports
Shock persistence					
ρ_{π^T}	[0,1)	beta	0.40	0.10	inflation target
ρ_{θ_h}	[0,1)	beta	0.40	0.10	markup in domestic prices
ρ_{θ_f}	[0,1)	beta	0.40	0.10	markup in imported prices
ρ_{θ_w}	[0,1)	beta	0.40	0.10	markup in wages
ρ_{Z_c}	[0,1)	beta	0.40	0.10	preferences
ρ_{Z_y}	[0,1)	beta	0.40	0.10	technology
$\rho_{Z_{rp}}$	[0,1)	beta	0.40	0.10	risk premium
Shock volatility					
σ_{Z_c}	R^+	invg	0.01	Inf	consumption preference shock
$\sigma_{Z_{ls}}$	R^+	invg	0.01	Inf	labor supply shock
$\sigma_{Z_{mp}}$	R^+	invg	0.01	Inf	monetary policy shock
σ_{π^T}	R^+	invg	0.01	Inf	inflation target shock
σ_{Z_y}	R^+	invg	0.01	Inf	technology shock
$\sigma_{Z_{rp}}$	R^+	invg	0.01	Inf	risk premium shock
σ_{θ_h}	R^+	invg	0.01	Inf	markup shock in domestic prices
σ_{θ_f}	R^+	invg	0.01	Inf	markup shock in imported prices
σ_{θ_w}	R^+	invg	0.01	Inf	markup shock in wages
Standard deviation of measurement errors					
π_{yht}	R^+	invg	0.01	Inf	output growth
h_t	R^+	invg	0.01	Inf	labor (hours worked)

Figure 4: Check plots

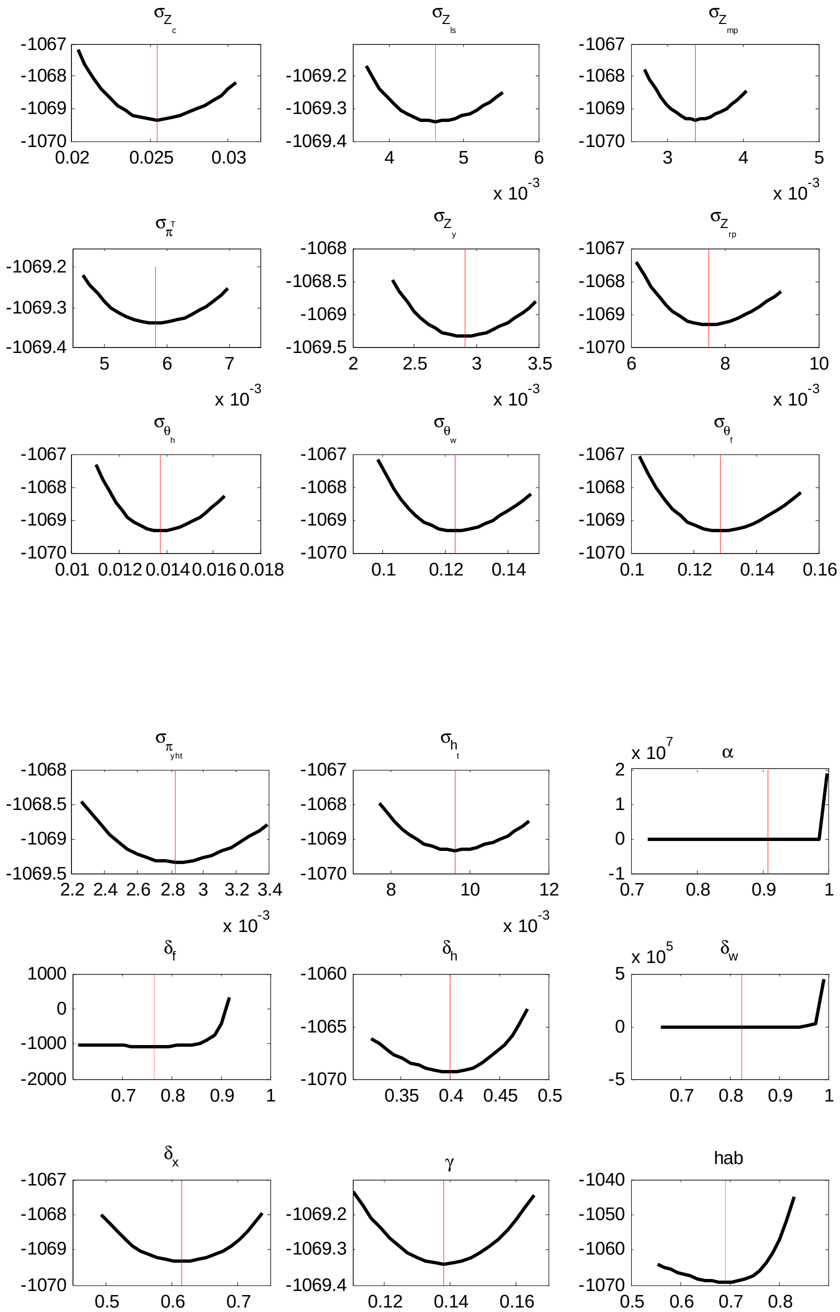


Figure 5: Check plots

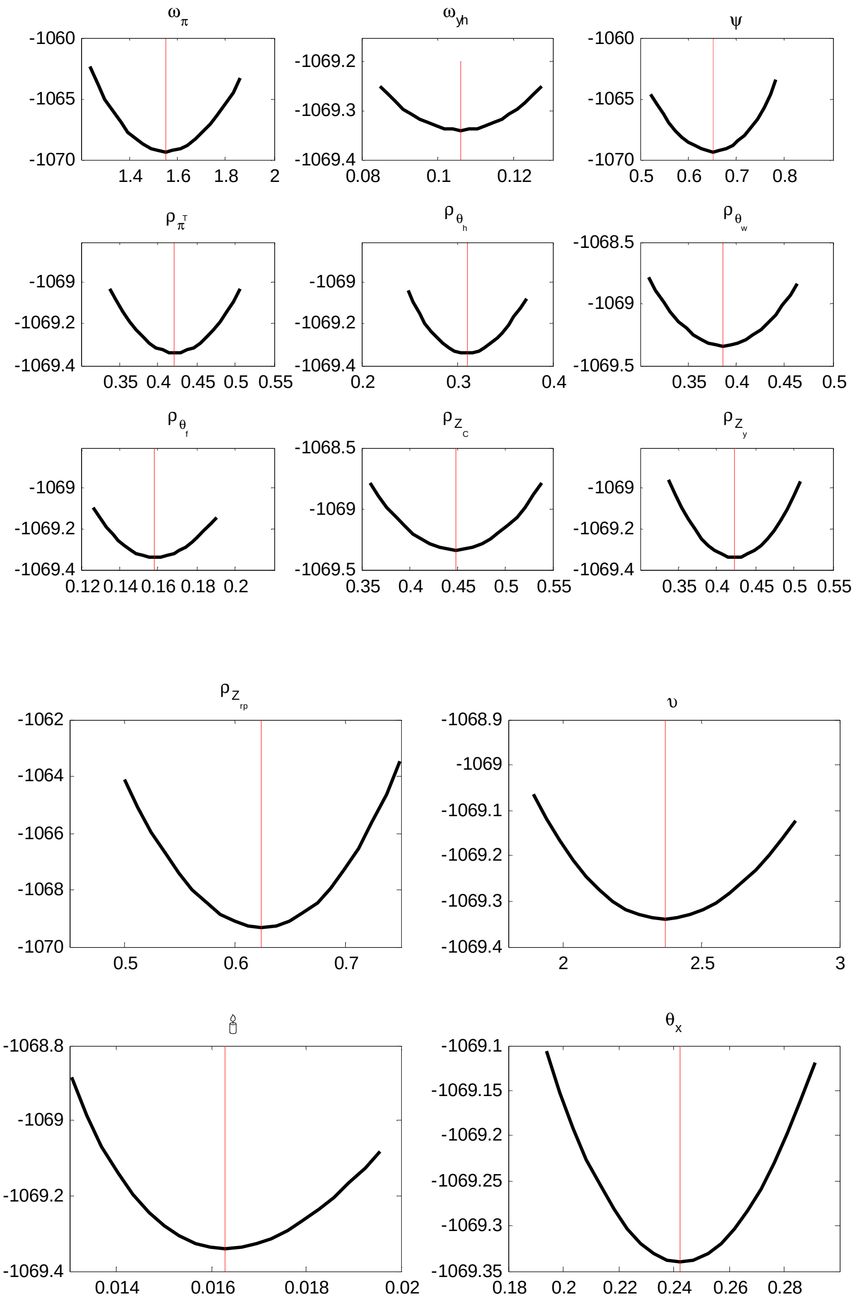


Figure 6: Priors and posteriors

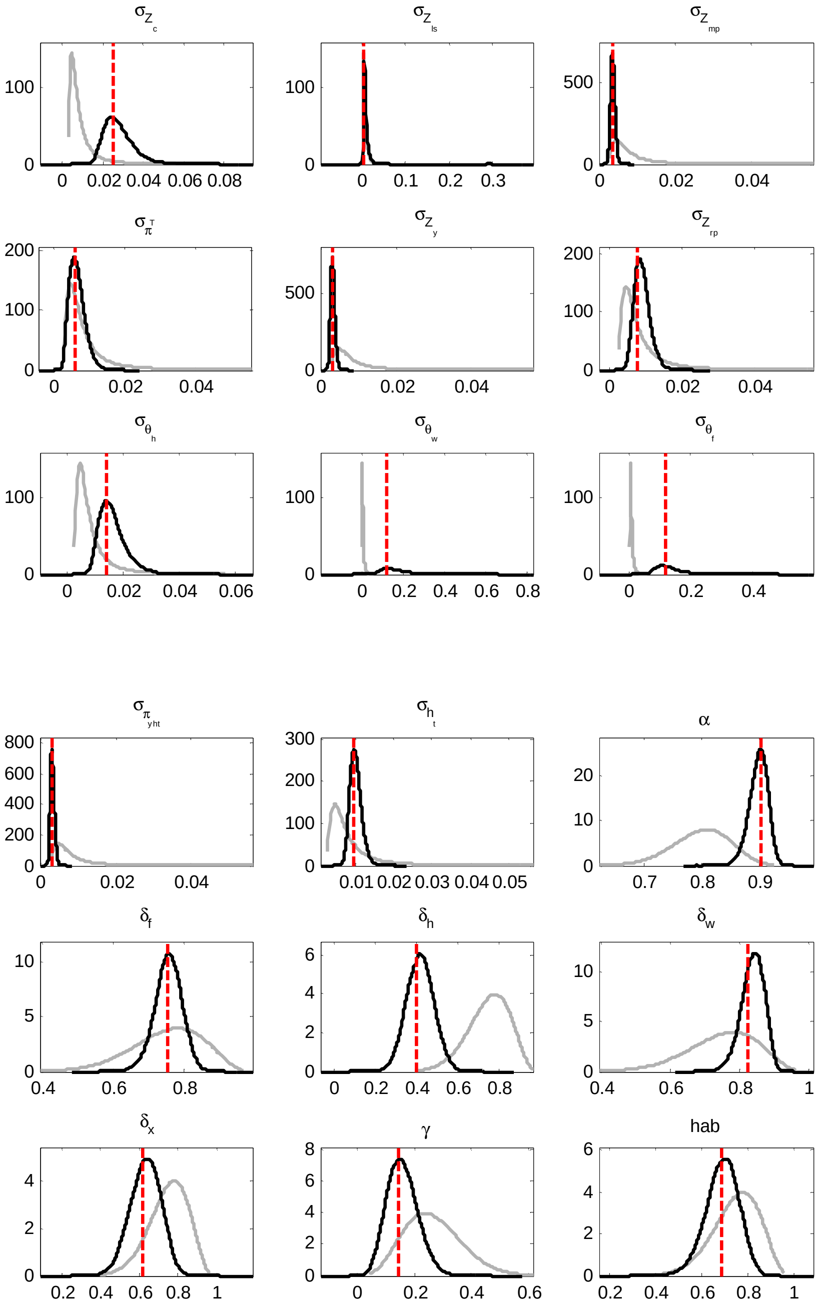


Figure 7: Priors and posteriors

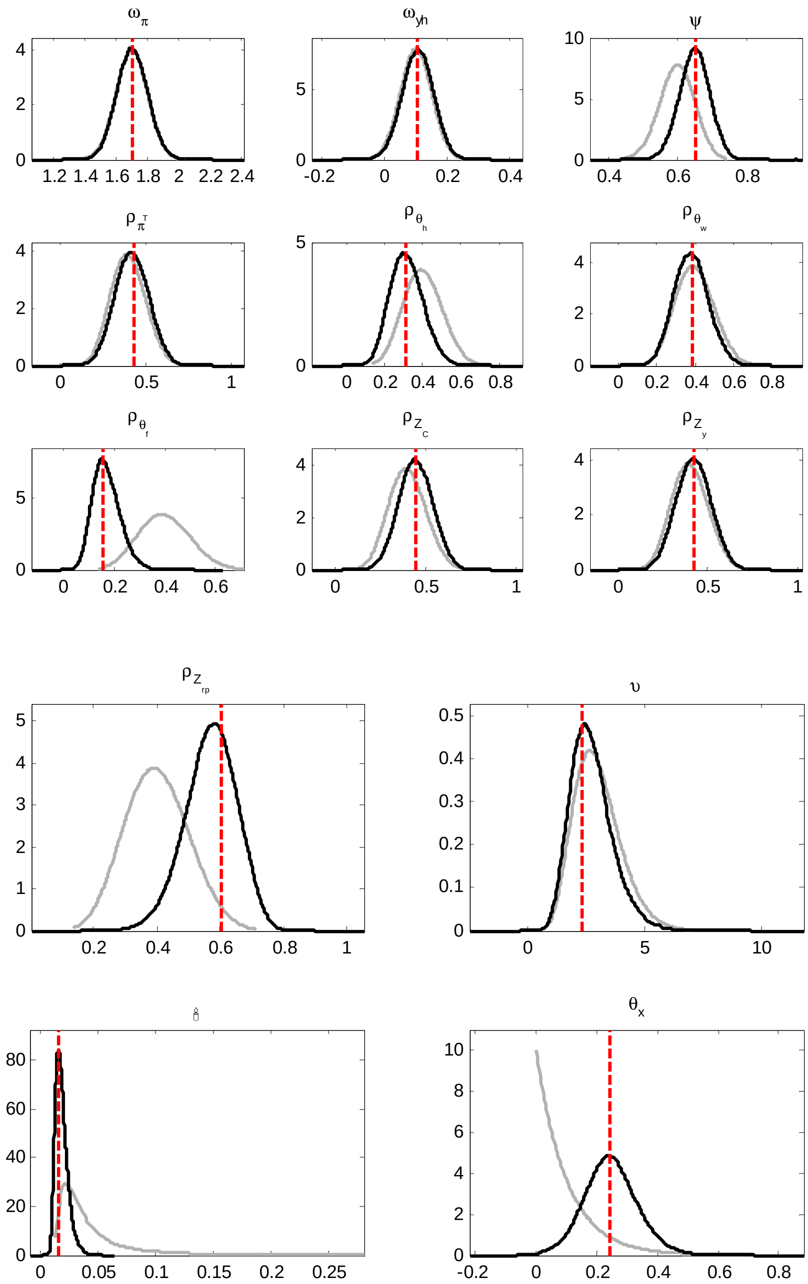


Table 6: Bayesian estimation results

		Prior distribution			Posterior max		Posterior distribution		
	Dom.	Density	Mean	S.D.	Mode	S.D.	Mean	5 %	95 %
Nominal rigidities									
δ_f	[0,1)	beta	0.75	0.10	0.7523	0.0352	0.7530	0.6925	0.8159
δ_h	[0,1)	beta	0.75	0.10	0.4025	0.0653	0.4181	0.3121	0.5263
δ_w	[0,1)	beta	0.75	0.10	0.8258	0.0337	0.8569	0.7860	0.8910
δ_x	[0,1)	beta	0.75	0.10	0.6179	0.0841	0.6329	0.5036	0.7584
Miscellaneous (CPI index, risk premium)									
γ	[0,1)	beta	0.27	0.10	0.1417	0.0529	0.1629	0.0703	0.2426
φ	[0,1)	invg	0.05	Inf	0.0168	0.0045	0.0192	0.0107	0.0272
Preferences									
hab	[0,1)	beta	0.75	0.10	0.6882	0.0710	0.6937	0.5772	0.8081
υ	R^+	gamm	3.00	1.00	2.3532	0.7986	2.7062	1.3035	4.1225
Monetary policy reaction function									
α	[0,1)	beta	0.80	0.05	0.9037	0.0148	0.8972	0.8728	0.9237
ω_π	R^+	norm	1.70	0.10	1.7095	0.0963	1.7026	1.5427	1.8647
ω_{yh}	R^+	norm	0.10	0.05	0.1044	0.0500	0.1070	0.0227	0.1859
Production and export function									
ψ	[0,1)	beta	0.60	0.05	0.6546	0.0428	0.6498	0.5805	0.7222
θ_x	R^+	gamm	0.10	0.10	0.2425	0.0785	0.2500	0.1025	0.3885
Shock persistence									
ρ_{π^T}	[0,1)	beta	0.40	0.10	0.4302	0.1063	0.4184	0.2586	0.5794
ρ_{θ_h}	[0,1)	beta	0.40	0.10	0.3086	0.0915	0.3151	0.1789	0.4577
ρ_{θ_w}	[0,1)	beta	0.40	0.10	0.3846	0.0934	0.3918	0.2348	0.5256
ρ_{θ_f}	[0,1)	beta	0.40	0.10	0.1576	0.0524	0.1705	0.0854	0.2554
ρ_{zc}	[0,1)	beta	0.40	0.10	0.4466	0.0955	0.4440	0.2962	0.5978
ρ_{zy}	[0,1)	beta	0.40	0.10	0.4211	0.1004	0.4193	0.2594	0.5724
ρ_{zrp}	[0,1)	beta	0.40	0.10	0.6019	0.0784	0.5719	0.4409	0.7062
Standard deviation of shocks									
σ_{Z_c}	R^+	invg	0.01	Inf	0.0253	0.0062	0.0281	0.0166	0.0392
$\sigma_{Z_{ls}}$	R^+	invg	0.01	Inf	0.0046	0.0019	0.1415	0.0024	0.0153
$\sigma_{Z_{mp}}$	R^+	invg	0.01	Inf	0.0034	0.0006	0.0036	0.0026	0.0046
σ_{π^T}	R^+	invg	0.01	Inf	0.0059	0.0024	0.0064	0.0029	0.0097
σ_{Z_y}	R^+	invg	0.01	Inf	0.0029	0.0005	0.0031	0.0022	0.0040

$\sigma_{Z_{rp}}$	R^+	invg	0.01	Inf	0.0079	0.0019	0.0091	0.0056	0.0125
σ_{θ_h}	R^+	invg	0.01	Inf	0.0139	0.0039	0.0163	0.0088	0.0235
σ_{θ_w}	R^+	invg	0.01	Inf	0.1223	0.0468	0.0878	0.0659	0.2624
σ_{θ_f}	R^+	invg	0.01	Inf	0.1158	0.0343	0.1321	0.0657	0.1962
Standard deviation of measurement errors									
π_{ht}	R^+	invg	0.01	Inf	0.0028	0.0005	0.0031	0.0022	0.0039
h_t	R^+	invg	0.01	Inf	0.0096	0.0014	0.0102	0.0076	0.0125

Table 7: Standard deviation from the data and from the model

	σ_h	σ_{π_c}	$\sigma_{\pi_{yh}}$	σ_{rer}	σ_{π_h}	σ_{π_w}	σ_{π_f}	σ_{π}	σ_R
Data	1.24	0.87	0.59	3.50	0.99	0.52	1.97	1.05	0.43
Model	1.80	1.10	0.57	3.47	1.22	1.07	1.44	1.34	0.37

Figure 8: Filtered and observed variables

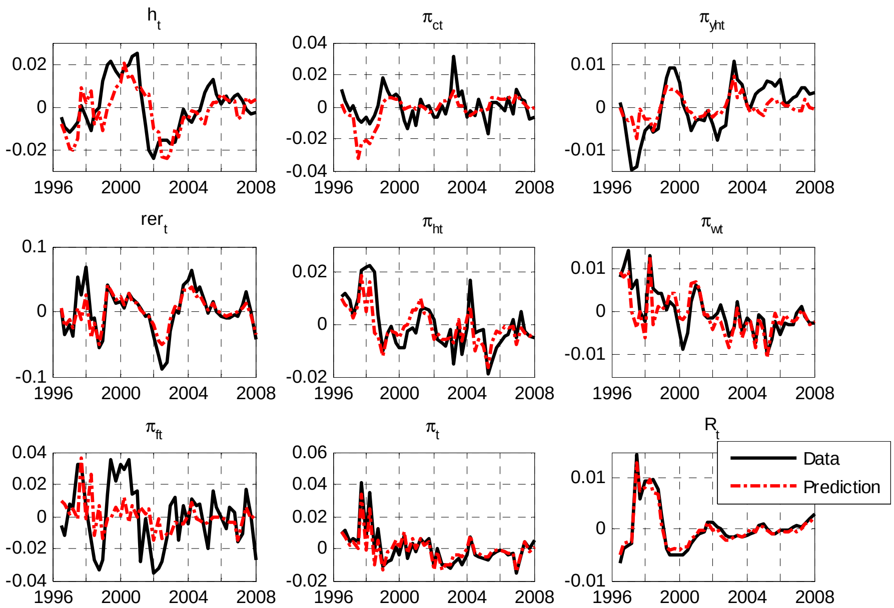


Figure 9: Autocorrelation from VAR and DSGE model

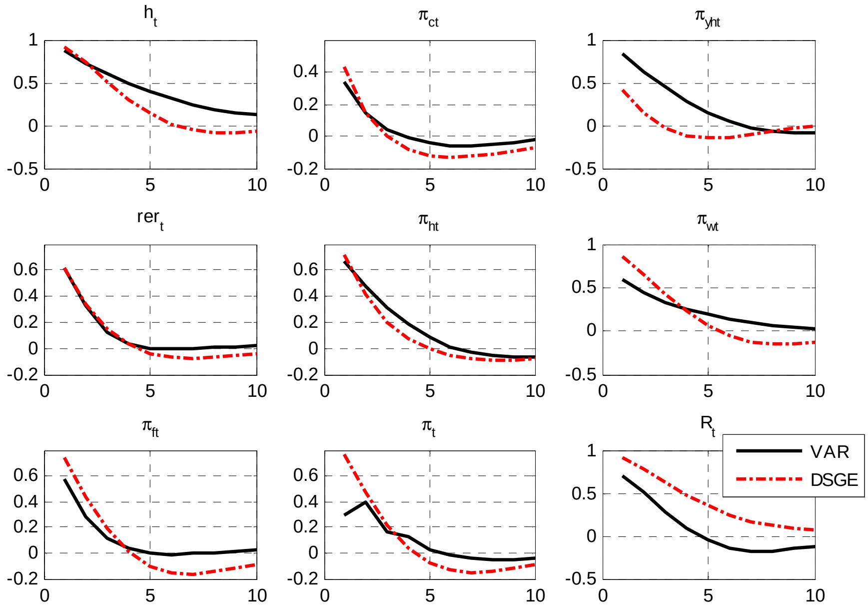
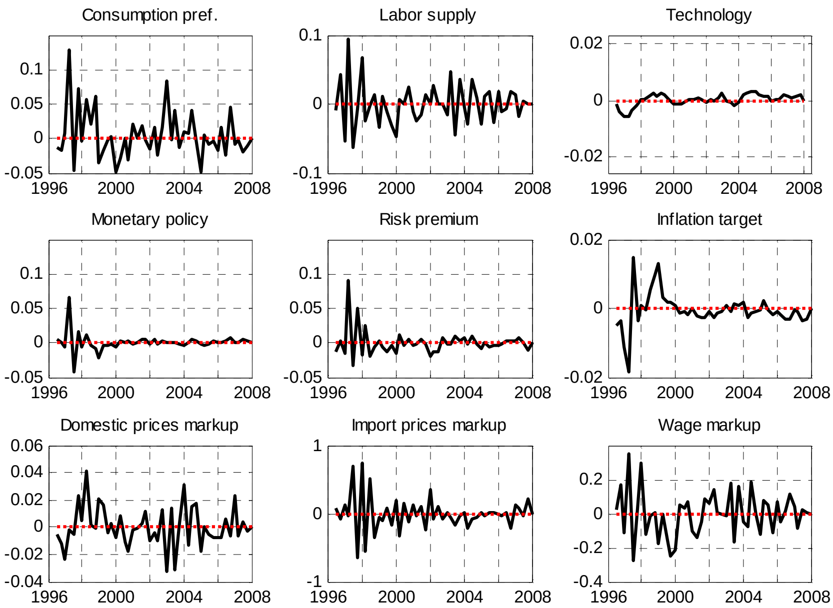


Figure 10: Historical shocks



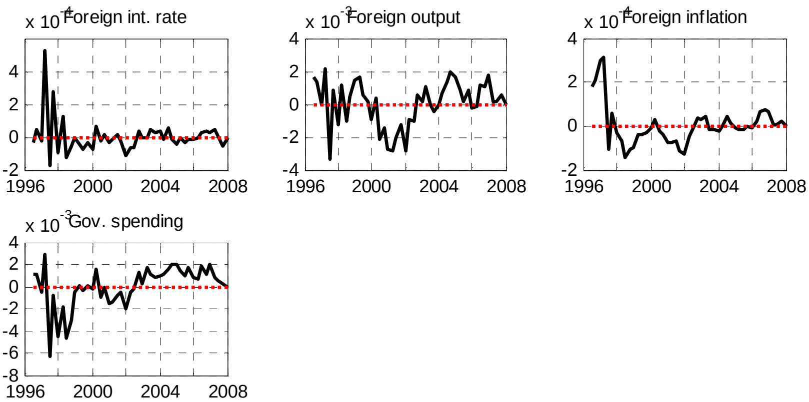


Table 8: Variance decomposition

Variable	real shocks			nominal shocks						other shocks			
	ε_{Z_c}	$\varepsilon_{Z_{ls}}$	ε_{Z_y}	$\varepsilon_{Z_{mp}}$	ε_{π^T}	$\varepsilon_{Z_{rp}}$	ε_{θ_h}	ε_{θ_w}	ε_{θ_f}	ε_{Z_g}	ε_{R^*}	ε_{π^*}	ε_{y^*}
real variables													
h_t	1.8	8.9	1.7	3.8	2.3	11.0	2.9	26.1	35.6	0.4	0.1	0.1	5.3
π_{ct}	65.3	0.1	5.4	6.1	3.4	2.6	0.6	0.4	15.6	0.1	0.0	0.0	0.3
π_{yht}	2.6	1.3	39.8	3.7	2.1	10.6	7.1	3.8	7.1	0.8	0.1	0.1	20.8
rer_t	1.6	0.3	0.0	11.0	6.2	53.0	1.1	1.0	24.1	0.2	0.4	0.1	1.1
nominal variables													
π_{ht}	2.1	3.0	1.7	7.7	4.8	5.7	29.7	7.5	36.4	0.1	0.1	0.0	1.1
π_{wt}	3.2	10.7	4.2	9.5	5.9	5.9	0.3	22.4	36.1	0.1	0.1	0.0	1.6
π_{ft}	1.6	0.1	0.1	6.6	4.1	8.9	0.3	0.3	77.2	0.1	0.1	0.1	0.6
π_t	1.8	0.1	0.1	7.4	4.6	9.0	1.1	0.3	74.7	0.1	0.1	0.1	0.7
R_t	10.8	0.8	0.3	7.1	2.2	11.1	3.8	2.4	57.7	0.8	0.1	0.1	2.7

Figure 11: Impulse responses: shock to consumption preferences

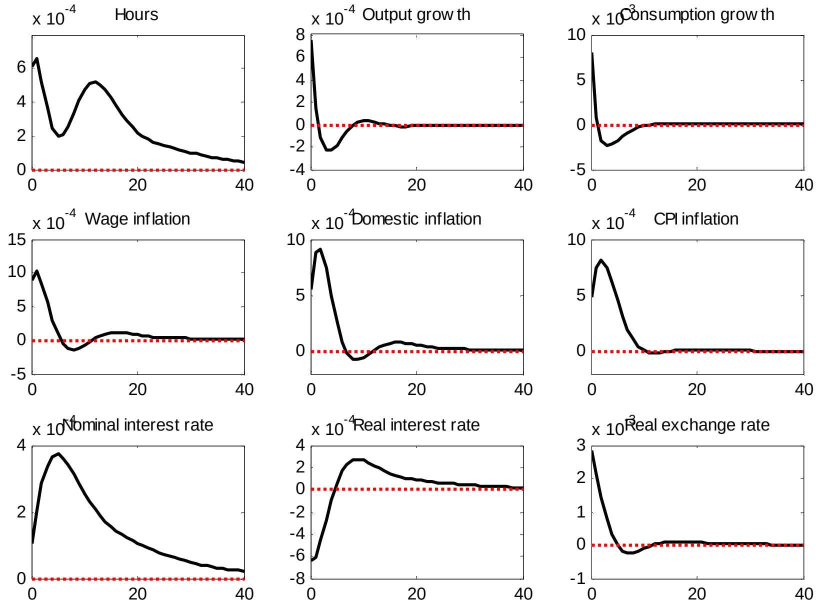


Figure 12: Impulse responses: shock to technology

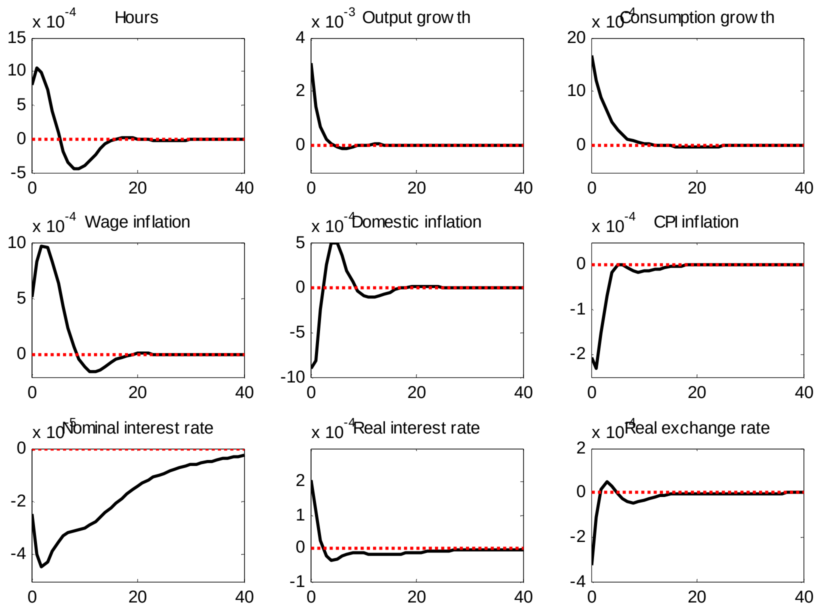


Figure 13: Impulse responses: shock to wage markup

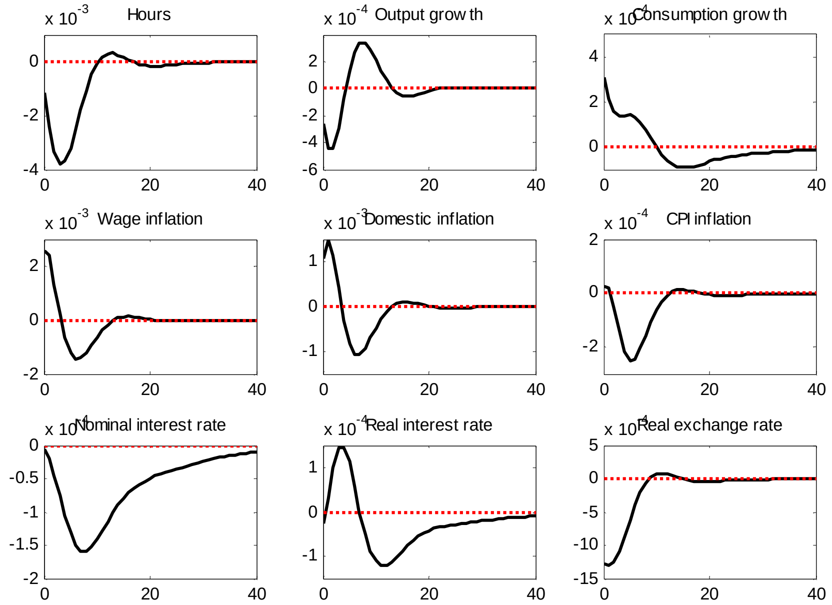


Figure 14: Impulse responses: shock to labor supply

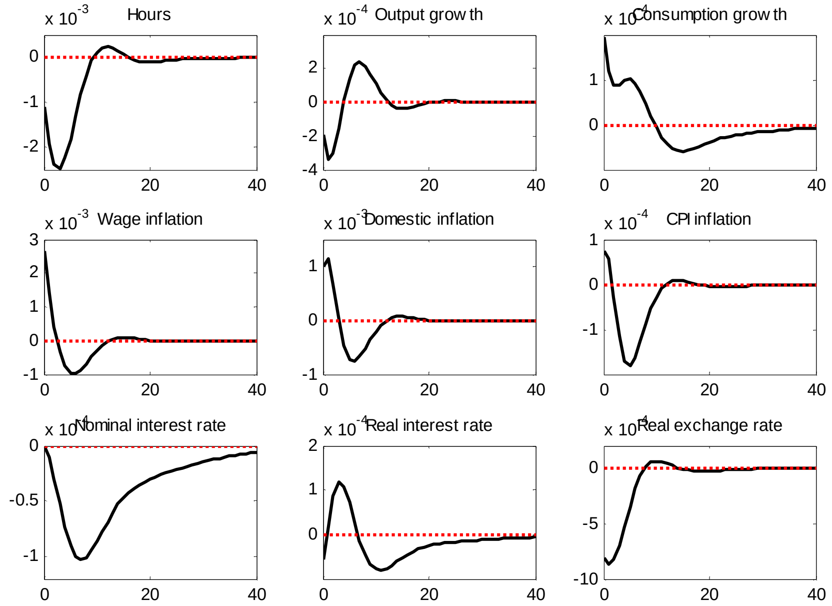


Figure 15: Impulse responses: shock to monetary policy

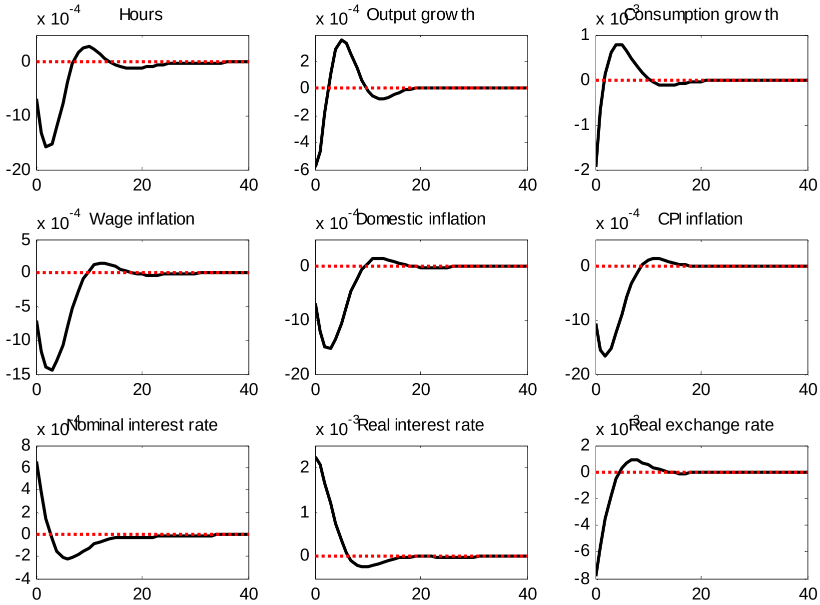


Figure 16: Impulse responses: shock to inflation target

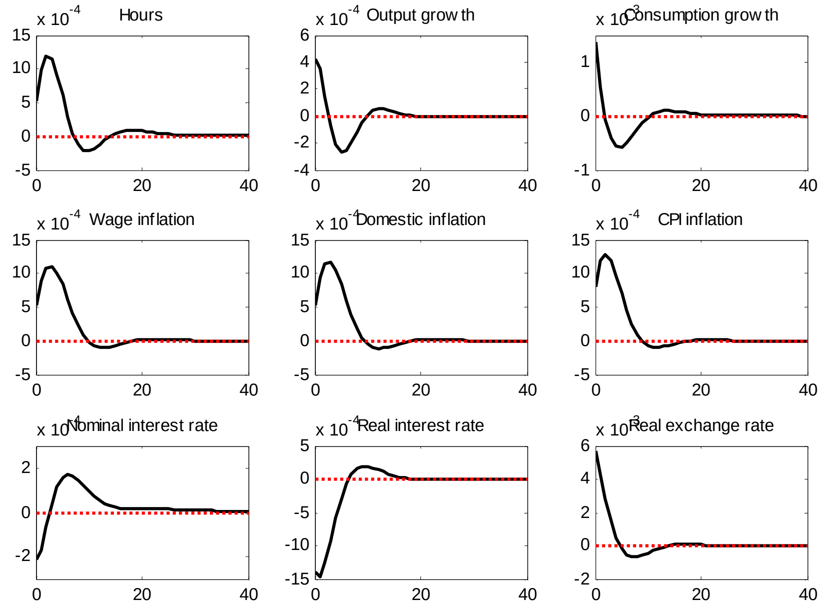


Figure 17: Impulse responses: shock to risk premium

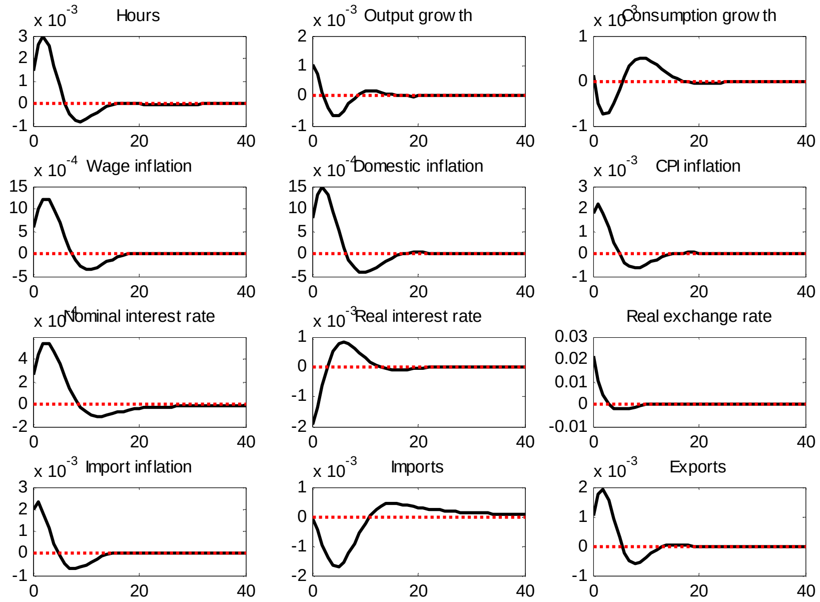


Figure 18: Impulse responses: shock to government spending

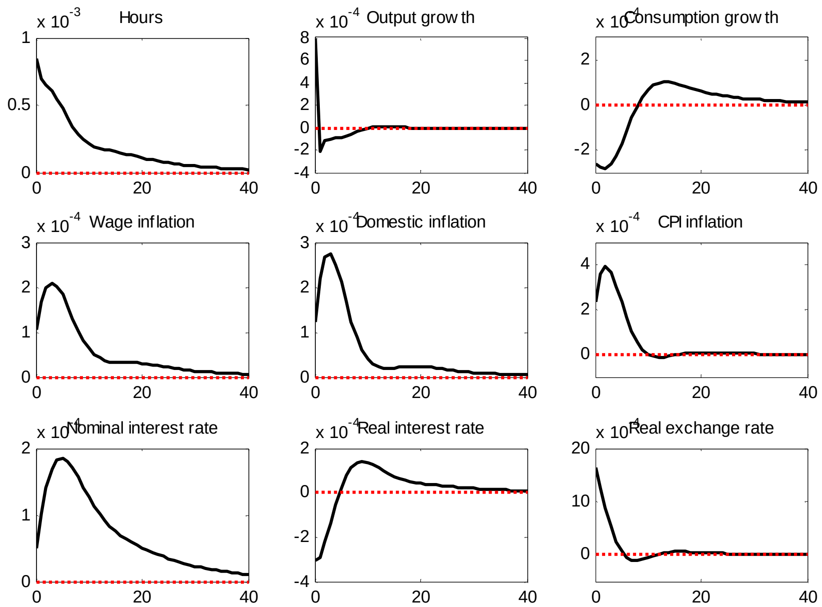


Figure 19: Impulse responses: shock to domestic prices makrup

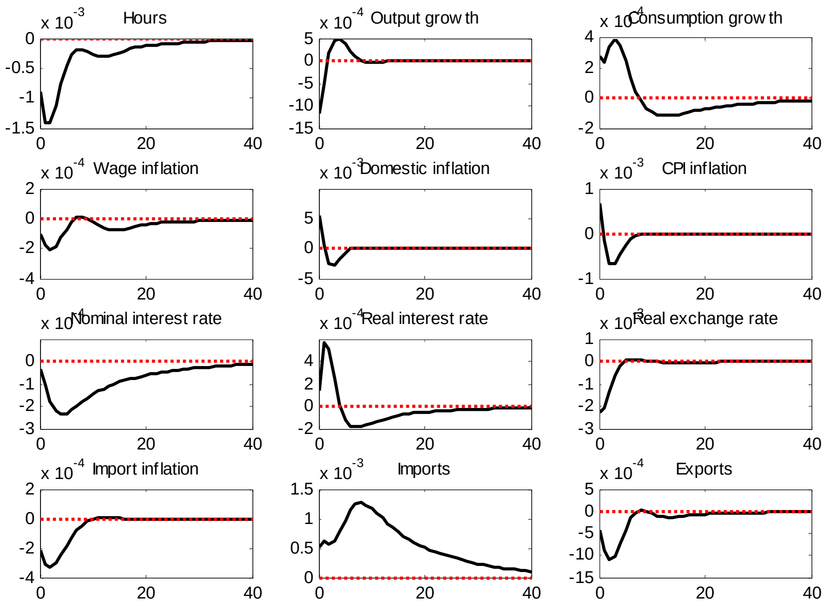


Figure 20: Impulse responses: shock to import prices makrup

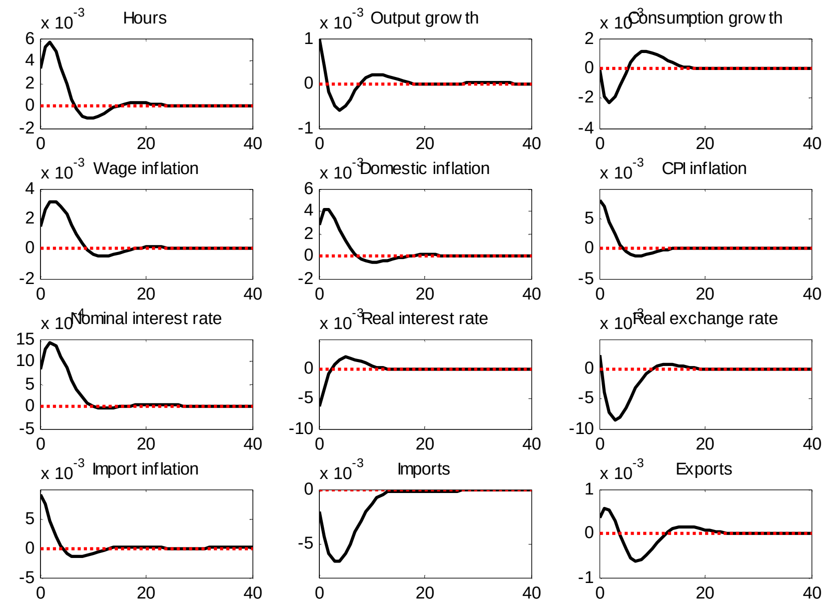


Figure 21: Impulse responses: shock to foreign interest rate

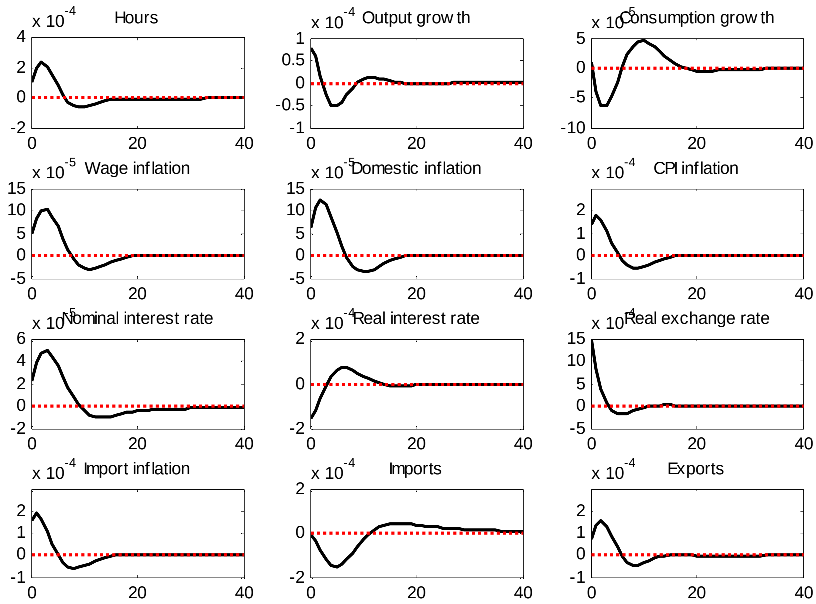


Figure 22: Impulse responses: shock to foreign output

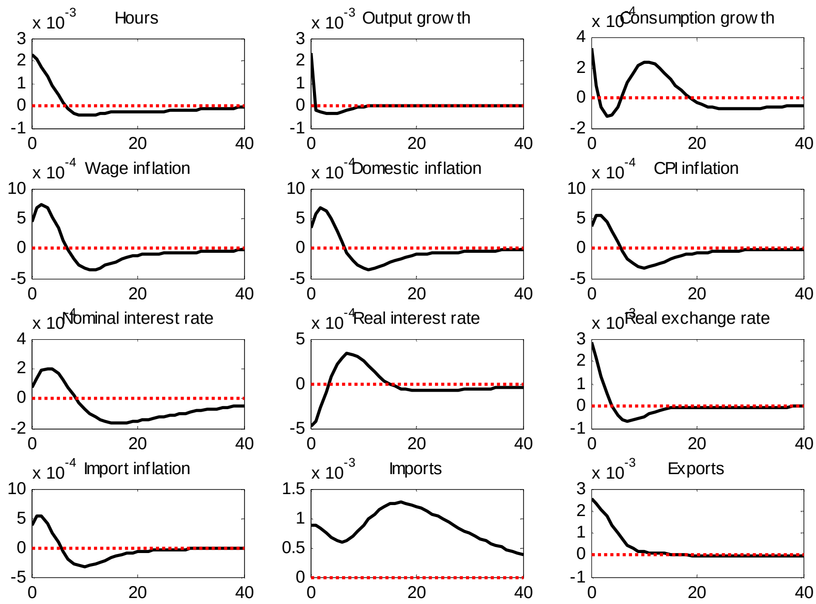


Figure 23: Impulse responses: shock to foreign inflation

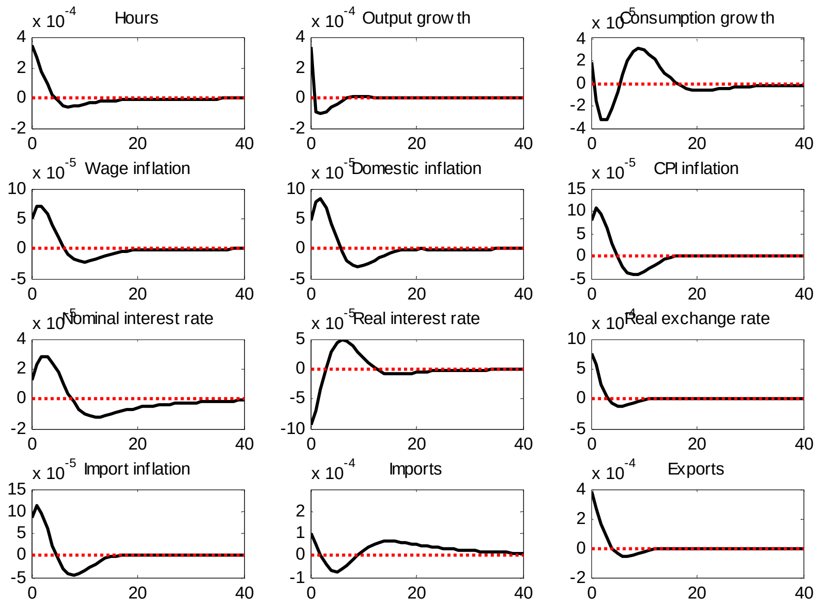


Figure 24: Exchange rate pass-through

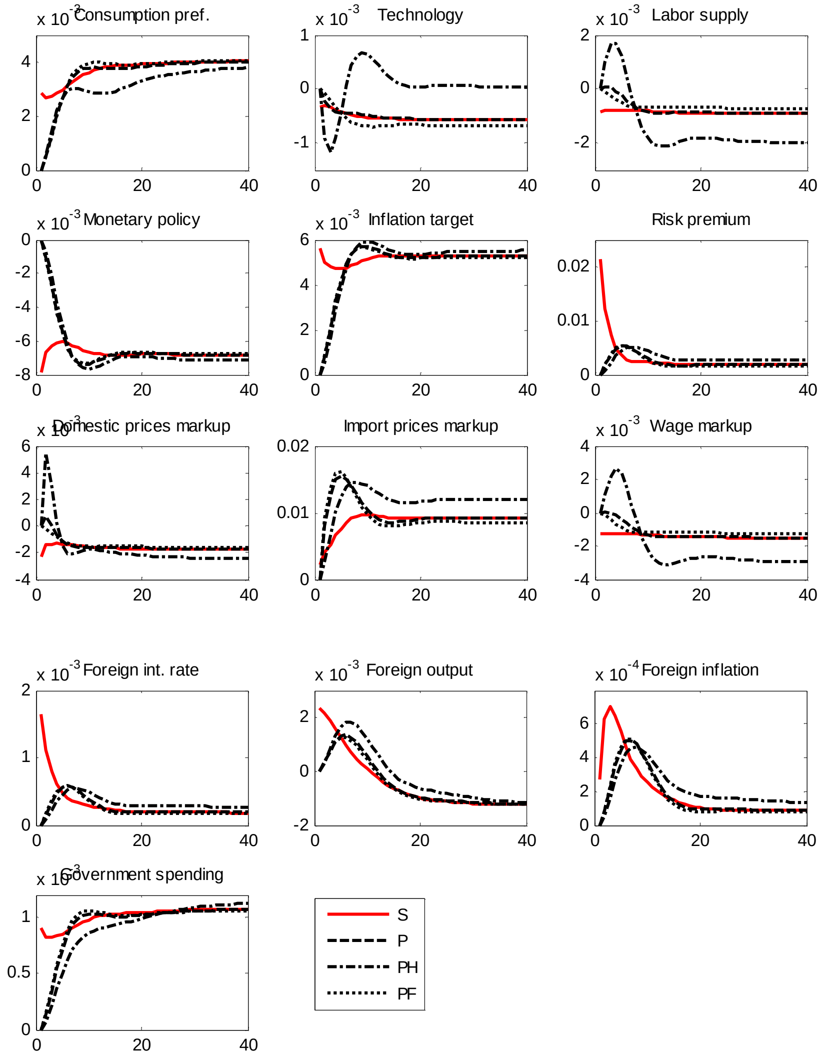


Figure 25: Wage-price dynamics

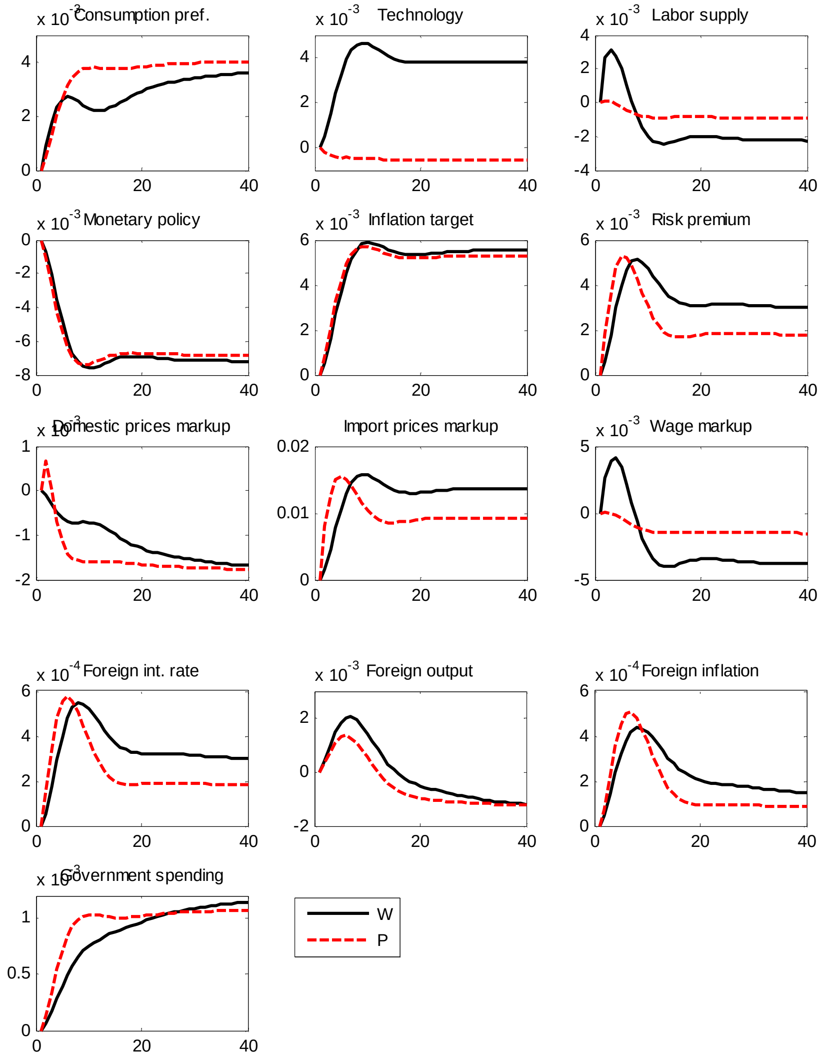


Table 9: Comparison of the models

Param.	Prior	FDP	FDEP	BM	FEP	FDIPH	FIP	FW	FWDIEP
Nominal rigidities									
δ_f	0.75	0.7596	0.7657	0.7530	0.7564	[0.2]	[0.2]	0.7571	[0.2]
δ_h	0.75	[0.2]	[0.2]	0.4181	0.4242	[0.2]	0.4902	0.3988	[0.2]
δ_w	0.75	0.8351	0.8579	0.8569	0.8299	0.8498	0.8382	[0.2]	[0.2]
δ_x	0.75	0.6323	[0.2]	0.6329	[0.2]	0.7007	0.7016	0.6745	[0.2]
Miscellaneous (CPI index, risk premium)									
γ	0.27	0.1374	0.1351	0.1629	0.1508	0.5133	0.5128	0.0940	0.2172
φ	0.05	0.0203	0.0197	0.0192	0.0190	0.0238	0.0203	0.0230	0.0243
Preferences									
hab	0.75	0.6892	0.7010	0.6937	0.6884	[0.2]	0.6537	0.5461	0.4972
υ	3.00	2.7051	2.7843	2.7062	2.8382	2.5112	2.5180	3.9320	3.7854
Monetary policy reaction function									
α	0.80	0.8991	0.8969	0.8972	0.8957	0.8281	0.8503	0.8964	0.8408
ω_π	1.70	1.7014	1.7002	1.7026	1.7036	1.7109	1.7174	1.6877	1.7384
ω_{yh}	0.10	0.1025	0.1024	0.1070	0.1028	0.1105	0.1103	0.0988	0.0984
Production and export function									
ψ	0.60	0.6522	0.6406	0.6498	0.6370	0.6961	0.6724	0.6019	0.6094
ρ_{xp}	0.10	0.2521	0.1175	0.2500	0.1178	0.2283	0.2400	0.1453	0.0702
Shock persistence									
ρ_{π^T}	0.40	0.4167	0.4092	0.4184	0.4138	0.4446	0.4637	0.4159	0.4449
ρ_{θ_h}	0.40	0.4448	0.4523	0.3151	0.3151	0.4903	0.2876	0.3182	0.4574
ρ_{θ_w}	0.40	0.3824	0.398	0.3918	0.3817	0.3918	0.3751	0.6070	0.5972
ρ_{θ_f}	0.40	0.1711	0.1722	0.1705	0.1707	0.5234	0.5223	0.1714	0.5464
ρ_{zc}	0.40	0.4491	0.455	0.4440	0.4487	0.5134	0.3803	0.5025	0.5160
ρ_{zy}	0.40	0.4207	0.4049	0.4193	0.4063	0.3524	0.3680	0.4198	0.3929
ρ_{zrp}	0.40	0.5785	0.5815	0.5719	0.5705	0.5919	0.5767	0.5807	0.6136
Standard deviation of shocks									
σ_{Z_c}	0.01	0.0275	0.0297	0.0281	0.0285	0.0096	0.0236	0.0197	0.0167
$\sigma_{Z_{ls}}$	0.01	0.0401	0.2022	0.1415	0.0228	0.1405	0.0146	0.0064	0.0066
$\sigma_{Z_{mp}}$	0.01	0.0036	0.0037	0.0036	0.0037	0.0032	0.0030	0.0036	0.0033
σ_{π^T}	0.01	0.0065	0.0064	0.0064	0.0064	0.0058	0.0065	0.0064	0.0073
σ_{Z_y}	0.01	0.0031	0.0032	0.0031	0.0032	0.0029	0.0031	0.0032	0.0030

$\sigma_{Z_{rp}}$	0.01	0.0090	0.0088	0.0091	0.0090	0.0077	0.0078	0.0087	0.0069
σ_{θ_h}	0.01	0.0078	0.0079	0.0163	0.0170	0.0082	0.0227	0.0156	0.0082
σ_{θ_w}	0.01	0.1331	0.0168	0.0878	0.1417	0.0430	0.1452	0.0307	0.0303
σ_{θ_f}	0.01	0.1358	0.1526	0.1321	0.1352	0.0317	0.0318	0.1279	0.0264
Standard deviation of measurement errors									
π_{yt}	0.01	0.0031	0.0034	0.0031	0.0033	0.0043	0.0041	0.0033	0.0034
π_t	0.01	0.0101	0.0101	0.0102	0.0101	0.0123	0.0123	0.0104	0.0117
log data density		978.57	976.53	972.79	969.39	949.23	947.52	935.20	900.71

Figure 10: Vector autocorrelations for the benchmark, the flexible wage and the flexible domestic prices models

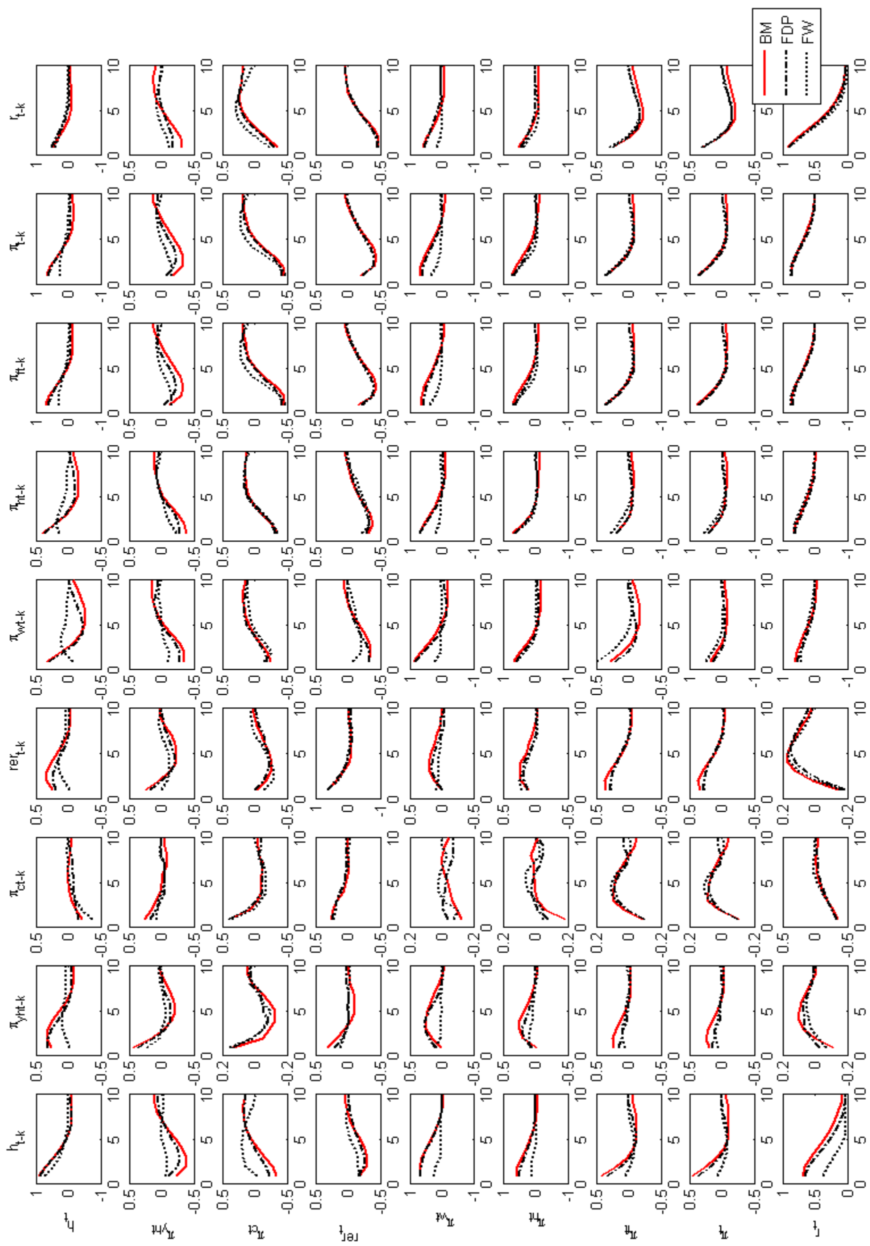


Figure 11: Impulse responses of selected variables for various shocks under different assumptions about nominal rigidity (Part1)

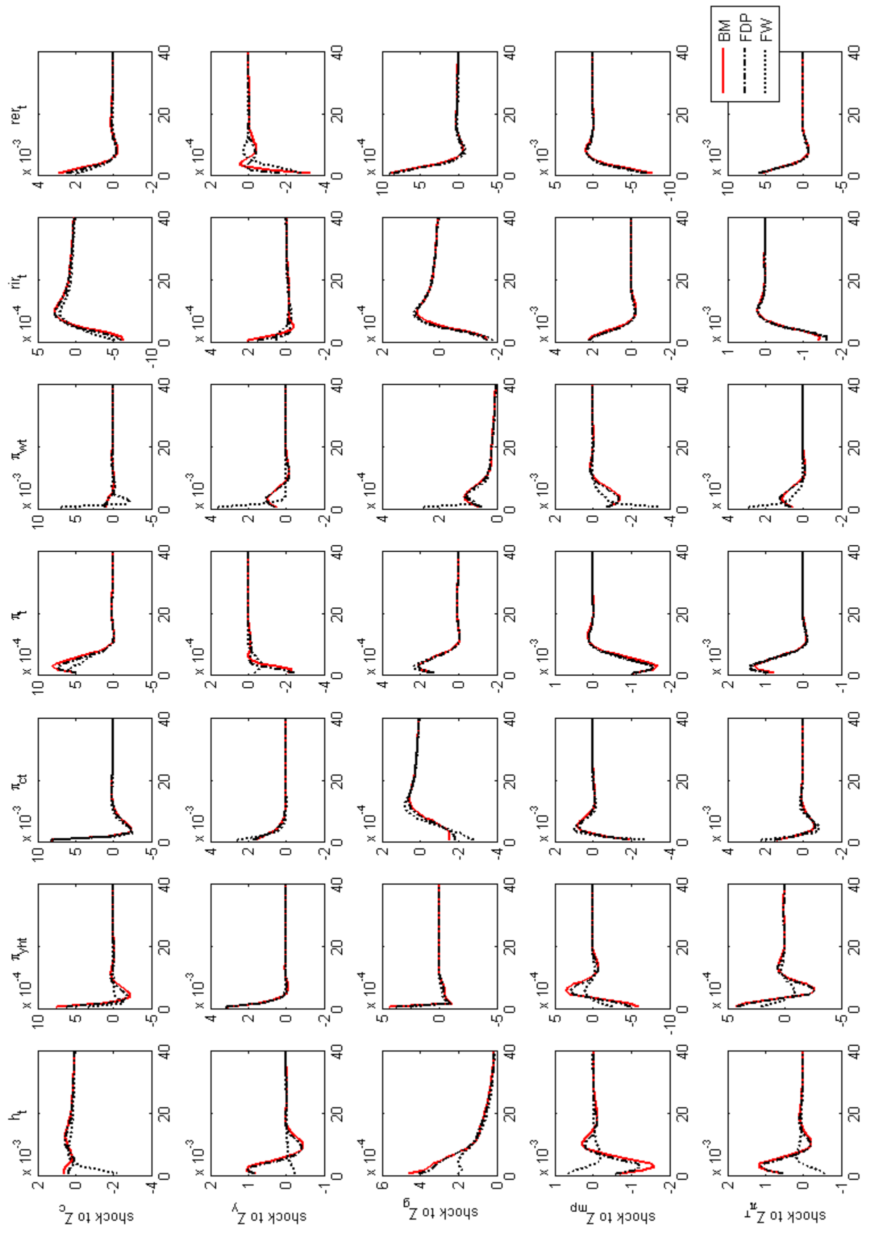


Figure 12: Impulse responses of selected variables for various shocks under different assumptions about nominal rigidity (Part 2)