

An Estimated Dynamic Stochastic General Equilibrium Model for Estonia

This paper reports an estimated open economy dynamic stochastic general equilibrium model for Estonia. The model is designed to highlight the main driving forces behind the Estonian business cycle and to understand how the euro area economic shocks and its monetary policy affect the small open economy of Estonia. It is a two-area DSGE model incorporating New Keynesian features such as nominal price and wage rigidity, variable capital utilization, investment adjustment costs, as well as other “typical” features — both for the domestic and euro area part of the model. It is rich in structural shocks such as technology, consumption preference, mark-up, etc. The model is estimated by Bayesian techniques using a quarterly data sample that covers main macroeconomic aggregates of Estonia and the euro area. (*JEL* C11, C13, E32, E37, E58)

I. Introduction

This paper describes theoretical foundations and reports main empirical results related to an open economy dynamic stochastic general equilibrium (DSGE) model for Estonia. One of the main goals of building a DSGE model of the Estonian economy is to use it to understand the monetary policy and foreign trade links between a small open economy of Estonia and the much larger adjacent euro area economy. The anticipated integration of Estonia into the common currency area makes a thorough understanding of the interdependence between the two economies particularly important.

A DSGE approach to modeling the Estonian economy has previously been attempted in Colantoni (2007) and Lendvai and Roeger (2008). Colantoni (2007) estimates a two-area DSGE model using Estonian macroeconomic data with the goal of studying the interest rate channel of monetary policy transmission between Estonia and the euro area. While the model presented in this paper has many similarities, its structure better reflects the existing monetary policy regime, adds a foreign trade channel to interactions between the economy of Estonia and the euro area, and has a careful empirical implementation. Lendvai and Roeger (2008) calibrate an open economy DSGE model with several types of households, the housing sector and separate tradable and non-tradable production sectors in order to assess the relative importance of productivity growth and credit expansion in driving the long-run trends of the main Estonian macroeconomic aggregates over the last decade. In contrast to Lendvai and Roeger (2008), where a specific simulation exercise is carried out to understand the long-run trends, this paper presents a DSGE model that looks at the effects of domestic and euro area shocks on the economy of Estonia at the business cycle frequency.

The Bank of Estonia's DSGE model, henceforth abbreviated as EP DSGE, is a medium size New Keynesian DSGE model which incorporates many features that are found to be essential for describing a complex dynamics of the real-world macroeconomic time series (refer to Smets and Wouters, 2003, Christiano, Eichenbaum and Evans, 2005, and Adolfson et al., 2007a). Specifically, the EP DSGE model incorporates external consumption habits, investment adjustment costs, price and wage rigidities and indexation to past inflation, and variable capital utilization. The model contains sixteen structural shocks that determine dynamics of the Estonian and euro area economies.

The open economy aspect of the EP DSGE model is based on the paper by Adolfson et al. (2007a). In particular, exporting and importing firms in the model operate by selling differentiated consumption good to foreign and domestic markets subject to the local currency price stickiness and indexation to past inflation. In contrast to Adolfson et al. (2007a), where both consumption and investment goods are traded, the economies of Estonia and euro area in the EP DSGE model trade in the final consumption good only. Other differences from Adolfson et al. (2007a) include switch of the unit root technology shock to a stationary one, missing working capital channel of the monetary policy, a less articulated modeling of the government sector, as well as the inclusion of a fully specified, partly estimated DSGE model of the euro area.

The latter feature is particularly important. The economy of Estonia is considered to be a small open economy on the fringes of the euro area — its main trading partner and de facto implement of its monetary policy due to the currency board arrangement and free capital flows between the two zones. The euro area economy is described by a fully articulated New Keynesian DSGE model of Smets and Wouters (2003). The two-area structure of the EP DSGE model permits meaningful simulations of the euro area monetary policy effects on the Estonian economy.

The empirical results reported in this paper are satisfactory for the first version of the model. Statistical estimates of the main structural parameters are mostly in line with the previous studies for Estonia, whenever a direct comparison is feasible. However, few areas still await improvements in the future. The external sector is of particular concern, where both the foreign trade dynamics as well as the role of net foreign assets in describing the spread between domestic and euro area interest rates need further examination.

The paper is structured as follows: Section 2 gives an overview of the model, including key equations of the model describing the economies of Estonia and the euro area. An outline of the statistical methodology, data series, priors and calibration is found in Section 3, followed by a description of the empirical results in Section 4. Conclusion gives a summary of the main findings.

2. Bank of Estonia's DSGE Model

2.1. General Overview

The EP DSGE model is designed to account for the following key features of the Estonian economy:

- The currency board regime, free capital mobility and resulting lack of an independent monetary policy conducted by the national central bank. The monetary policy of Estonia is effectively imported from the ECB and therefore depends on the euro area's business cycle.¹ The spread between domestic and euro area interest rates is the key for understanding macroeconomic developments in Estonia over the past decade;
- The Estonian economy is a textbook example of a small open economy in terms of its openness to foreign trade.² The euro area's business cycle impact on the domestic economy of Estonia via the foreign trade is very pronounced;
- Real and nominal convergence still features prominently in the main macroeconomic aggregates of Estonia. However, the EP DSGE model presented in this paper is specified for the business cycle frequency, leaving aside the long-run trends observed in the empirical data.

Chart 1 previews the main building blocks and resource flows inside the EP DSGE model. The model in this paper is a two-area DSGE model, consisting of a small open economy DSGE model for Estonia and a large closed economy DSGE model for the euro area. The two parts are linked through the monetary policy channel — one way from the euro area to Estonia — and by the export-import flows, where the euro area economy serves as a source of imports for the home economy of Estonia as well as generates demand for Estonian exports. Foreign trade with the euro area is assumed to be in terms of the composite final consumption good only.

¹ Prior to re-pegging of the Estonian Kroon to the euro in 1999, it was fixed to the Deutsche Mark at the rate of 1 DM = 8 EEK. During the second half of the 1990s, the Estonian banking system was still not completely integrated with the European and Scandinavian ones. The Asian financial crisis of 1997 and the subsequent Russian financial crisis of 1998 have changed the landscape of the Estonian banking sector, effectively putting all major Estonian banks into the hands of Scandinavian owners. Since then, the spreads between domestic and euro area interest rates have narrowed dramatically.

² The breakdown of Estonian trade statistics in 2008 reveals that 70% of foreign trade takes place with EU countries. However, the share of euro area countries in foreign trade is around 25% because many of Estonia's major trading partners in the Baltic Sea region, such as Latvia, Lithuania, Sweden, Denmark and Poland, are not euro area members. Since these countries are themselves highly open to euro area trade, the assumption of the EP DSGE model about import-export trading links with the euro area is a reasonable approximation.

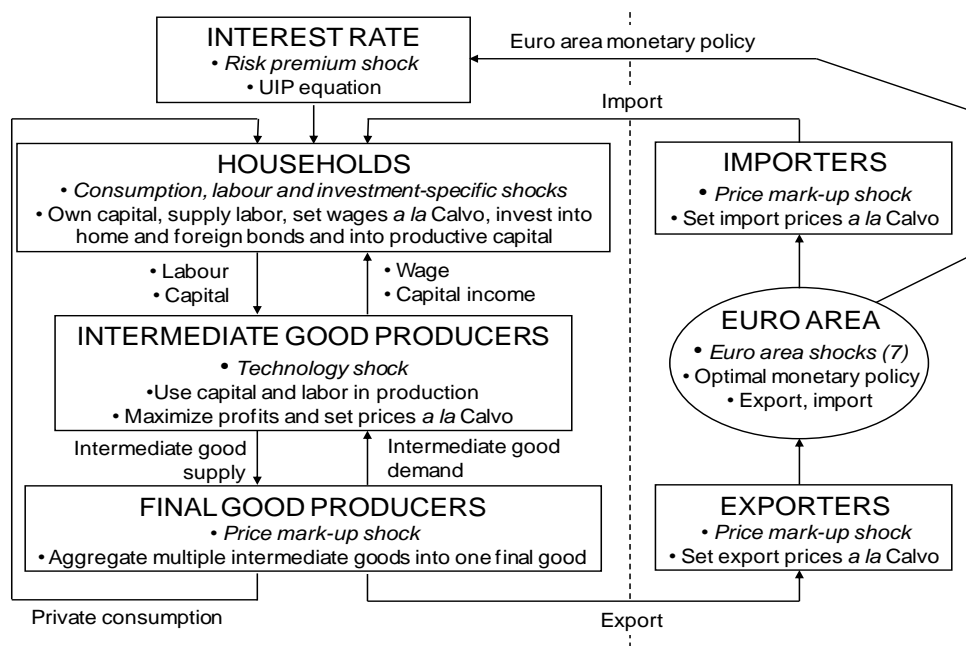


Chart 1: A diagram of the EP DSGE model

The Estonian part of the EP DSGE is a fairly typical small open economy DSGE model that is similar to Adolfson et al. (2007a). There are 25 state variables and 9 structural shocks, and it consists of the following sections:

- Households that own labour and capital, optimize their consumption and supply of working hours, set wages subject to the Calvo (1983) frictions, invest in domestic and foreign bonds, and into productive capital;
- Firms of four types: final good producers operating in a perfectly competitive market, monopolistically competitive domestic intermediate good producers that set prices subject to the Calvo (1983) frictions, and import and export firms that set prices of differentiated consumption goods subject to the Calvo (1983) frictions;
- Government sector that follows a balanced budget fiscal policy driven by an exogenous government spending shock;
- Domestic nominal interest rate is linked to the euro area interest rate via the modified uncovered interest rate parity (UIP) equation. The currency board regime is manifested in the

absence of the exchange rate risk in this equation.³ The interest rate spread depends on the foreign asset position of the Estonian economy as well as an additional idiosyncratic shock.

The euro area part of the EP DSGE is a version of the Smets and Wouters (2003) closed economy DSGE model with 13 state variables and 7 structural shocks. Contrary to Adolfson et al. (2007a), where the rest of the world is described by a low-dimensional VAR system, this paper uses a full-fledged DSGE model as a counterpart to the Estonian economy. Since one of the main objectives of the EP DSGE model is to examine the propagation mechanism through which various euro area structural disturbances impact on the Estonian economy, it is necessary to have a rich euro area model that incorporates a wide range of “deep” shocks with clear economic interpretations.

2.2. Households

Households in the economy, indexed by superscript $0 \leq i \leq 1$, maximize their inter-temporal utility by choosing future consumption, $\{C_t^i : t \geq 0\}$; future investment, $\{I_t^i : t \geq 0\}$; the hours of work, $\{L_t^i : t \geq 0\}$; the rate of capital utilization, $\{z_t^i : t \geq 0\}$; future stream of capital lent to the firms, $\{K_t^i : t \geq 0\}$; and number of domestic, $\{B_t^i : t \geq 0\}$, and euro area, $\{B_t^{i,*} : t \geq 0\}$, bonds in their portfolio:

$$\max_{\{C_t^i, I_t^i, L_t^i, z_t^i, K_t^i, B_t^i, B_t^{i,*} : t \geq 0\}} \mathbf{E}_0 \sum_{t=0}^{\infty} \beta^t \varepsilon_t^\beta U_t$$

$$U_t = \left[\frac{1}{1-\sigma_c} (C_t^i - hC_{t-1}^i)^{1-\sigma_c} \frac{1}{1+\sigma_l} (L_t^i)^{1+\sigma_l} \right]$$

where $\log \varepsilon_t^\beta = \rho_\beta \log \varepsilon_{t-1}^\beta + u_t^\beta$, $u_t^\beta \sim \text{WN}(0, \sigma_\beta^2)$ is the preference shock, and β is the inter-temporal discount factor. Households' consumption is characterized by the external habit: each household in the economy derives a positive utility from consumption in the current period only if it can consume more than a fraction h of the economy-wide per capita consumption in the previous period. Two parameters governing the inter-temporal elasticity of substitution in consumption and the elasticity of work effort with respect to the real wage are denoted by σ_c and σ_l , respectively.

Maximization of the inter-temporal utility function is constrained. Each household faces the following budget restriction, expressed in real terms:

³ In fact, the institutional arrangement of the 17-year-old currency board system in Estonia rules out the possibility of a unilateral Euro peg rate change by the central bank of Estonia. All such changes must be enacted by the national parliament and therefore are likely to take time before coming into effect. The institutional structure of the currency board in Estonia therefore prevents unexpected and unannounced changes of the nominal exchange rate.

$$C_t^i + I_t^i + B_t^i + \bar{e} B_t^{i,*} = R_{t-1}^n \frac{B_{t-1}^i}{\pi_t^c} + \Omega(FA_{t-1}, \varepsilon_{t-1}^{\text{risk}}) \bar{e} R_{t-1}^{n,*} \frac{B_{t-1}^{i,*}}{\pi_t^c} + \frac{W_t^i}{P_t^c} L_t^i + R_t^k z_t^i K_{t-1}^i - \Psi(z_t^i) K_{t-1}^i + T_t^i + D_t^i,$$

where R_t^n denotes the gross nominal domestic interest rate, T_t^i are the net transfers, D_t^i denotes dividends from the firms, $\pi_t^c := P_t^c / P_{t-1}^c$ is the gross rate of consumer inflation, where P_t^c denotes the consumer price index, \bar{e} is the fixed nominal exchange rate, W_t^i is the nominal wage earned by the household, R_t^k is the gross capital rent rate, $\Psi(z_t^i)$ captures the cost of capital utilization, and $\Omega(FA_t, \varepsilon_t^{\text{risk}})$ is the country specific risk premium function:

$$\log \Omega(FA_t, \varepsilon_t^{\text{risk}}) = -\phi_{\text{fa}} FA_t + \log \varepsilon_t^{\text{risk}}, \quad (1)$$

where $FA_t := \frac{\bar{e} B_t^{*,n}}{P_t^d}$ is the net foreign asset position of the Estonian economy, P_t^d denotes the domestic price index, and $\log \varepsilon_t^{\text{risk}} = \rho_{\text{risk}} \log \varepsilon_{t-1}^{\text{risk}} + u_t^{\text{risk}}$, $u_t^{\text{risk}} \sim \text{WN}(0, \sigma_{\text{risk}}^2)$ is an idiosyncratic component of the country specific risk. Equation (1) captures imperfect integration of the Estonian economy into the euro area financial markets: the higher the indebtedness *vis-à-vis* the euro area, the higher the risk of a default and consequently the higher the risk premium over the foreign interest rate (see Schmitt-Grohè and Uribe, 2003).

The capital stock in the economy is owned by the households, whereby each individual household in the economy faces the following capital accumulation dynamics:

$$K_t^i = (1-\delta)K_{t-1}^i + \left[1 - S\left(\frac{I_t^i}{I_{t-1}^i}\right) \right] I_t^i \varepsilon_t^x,$$

where δ is the depreciation rate of capital, $\log \varepsilon_t^x = \rho_x \log \varepsilon_{t-1}^x + u_t^x$, $u_t^x \sim \text{WN}(0, \sigma_x^2)$ is a stationary investment-specific technology shock common across all households in the economy, and $S\left(\frac{I_t^i}{I_{t-1}^i}\right)$ denotes the investment adjustment cost function.

The optimal paths of consumption and investment that maximize the households' inter-temporal utility are given by the following log-linear expressions (see Gelain and Kulikov, 2009):

$$\hat{c}_t = \frac{h}{1+h} \hat{c}_{t-1} + \frac{1}{1+h} \mathbf{E}_t \hat{c}_{t+1} - \frac{1-h}{\sigma_c(1+h)} (\hat{r}_t^n - \mathbf{E}_t \hat{\pi}_{t+1}^c) + \hat{\varepsilon}_t^\beta,$$

$$\hat{i}_t = \frac{1}{1+\beta} \hat{i}_{t-1} + \frac{\beta}{1+\beta} \mathbf{E}_t \hat{i}_{t+1} + \frac{1}{1+\beta} \frac{1}{\varphi} \hat{q}_t + \hat{\varepsilon}_t^x,$$

where \hat{q}_t denotes the price of capital (the Tobin's Q), and φ is the investment adjustment cost function parameter.

The households in the economy act as monopolistic suppliers of differentiated labour services to the domestic intermediate good producers (see Kollmann, 2001, Erceg et al., 2000, and Christiano, Eichenbaum and Evans, 2005). Each household can set its own wage subject to the substitutability between different labour services, facing the following labour demand function:

$$L_t^i = \left(\frac{W_t^i}{W_t} \right)^{-\frac{1+\lambda_t^w}{\lambda_t^w}} L_t,$$

where W_t denotes the aggregate wage, L_t is the aggregate labour demand, and λ_t^w is a stationary wage mark-up shock $\log \frac{\lambda_t^w}{\lambda^w} = \rho_w \log \frac{\lambda_{t-1}^w}{\lambda^w} + u_t^w$, $u_t^w \sim \text{WN}(0, \sigma_w^2)$, where λ_w is the steady-state wage mark-up parameter.

It is also assumed that not all households can optimally re-adjust W_t^i in every time period. Instead, a wage staggering mechanism of Calvo (1983) is used, whereby a randomly chosen fraction $1-\theta_w$ of all households is allowed to set their wages optimally, while the remaining fraction of households indexes wages to the past inflation according to:

$$W_{t+1}^i = \tau_w^c \hat{\pi}_t^w W_t^i,$$

where τ_w is the wage indexation parameter. Given this friction, households set their wages optimally, taking into account the probability of being unable to re-adjust them for a number of time periods into the future. The resulting real wage dynamics in the log-linear form is given by (for derivations details refer to Gelain and Kulikov, 2009):

$$\begin{aligned} \hat{w}_t = & \frac{\beta}{1+\beta} \mathbf{E}_t \hat{w}_{t+1} + \frac{1}{1+\beta} \hat{w}_{t-1} + \frac{\beta}{1+\beta} \mathbf{E}_t \hat{\pi}_{t+1}^c - \frac{1+\beta\tau_w}{1+\beta} \hat{\pi}_t^c + \frac{\tau_w}{1+\beta} \hat{\pi}_{t-1}^c \\ & - \frac{1}{1+\beta} \frac{(1-\beta\theta_w)(1-\theta_w)}{(1+\frac{1+\lambda_w}{\lambda_w}\sigma_l)\theta_w} [\hat{w}_t - \sigma_l \hat{l}_t - \frac{\sigma_c}{1-h} (\hat{c}_t - h\hat{c}_{t-1})] + \hat{\lambda}_t^w. \end{aligned} \quad (2)$$

2.3. Firms

The final output Y_t in the economy is produced using a CES aggregation technology from a multitude of intermediate goods. The cost minimization by the final good producers implies that demand for an intermediate good Y_t^j is given by:

$$Y_t^j = \left(\frac{P_t^j}{P_t^d} \right)^{-\frac{1+\lambda_t^p}{\lambda_t^p}} Y_t, \quad (3)$$

where P_t^j is the price of an intermediate good $0 \leq j \leq 1$, $\log \frac{\lambda_t^p}{\lambda^p} = \rho_p \log \frac{\lambda_{t-1}^p}{\lambda^p} + u_t^p$, $u_t^p \sim \text{WN}(0, \sigma_p^2)$ is a stationary price mark-up shock, and λ^p is the steady-state price mark-up parameter.

Intermediate good producers operate in a monopolistically competitive market. They hire labour and capital from households, paying the salary W_t and capital rent R_t^k . Each firm produces Y_t^j units of differentiated output using the Cobb-Douglas production technology:

$$Y_t^j = A_t (\tilde{K}_{t-1}^j)^\alpha (L_t^j)^{1-\alpha} - \Phi^j, \quad (4)$$

where \tilde{K}_{t-1}^j is the effective capital stock given by $\tilde{K}_{t-1}^j = z_t K_{t-1}^j$, Φ^j is the fixed cost term, and $\log A_t = \rho_a \log A_{t-1} + u_t^a$, $u_t^a \sim \text{WN}(0, \sigma_a^2)$ is a stationary technology shock common to all firms.

The intermediate good producers also face another type of friction. In every period, a random fraction $1 - \theta_p$ of firm can optimally set their prices (see Calvo, 1983). Those who cannot re-adjust prices in the current period are assumed to mechanically index them to the past inflation:

$$P_{t+1}^j = (\pi_t^d)^{\tau_p} P_t^j,$$

where $\pi_t^d = \frac{P_t^d}{P_{t-1}^d}$ denotes the domestic inflation rate, and τ_p governs a degree of price indexation.

The intermediate good producers maximize the expected stream of future discounted profits subject to the demand function (3), technology constraint (4) and the Calvo (1983) price-staggering mechanism. Solution of this maximization problem leads to an equation describing dynamics of the domestic inflation rate; refer to Gelain and Kulikov (2009) for derivations details. The inflation dynamics is characterised by the hybrid New Keynesian Phillips Curve:

$$\hat{\pi}_t^d = \frac{\beta}{1 + \beta \tau_p} \mathbf{E}_t \hat{\pi}_{t+1}^d + \frac{\tau_p}{1 + \beta \tau_p} \hat{\pi}_{t-1}^d + \frac{1}{1 + \beta \tau_p} \frac{(1 - \beta \theta_p)(1 - \theta_p)}{\theta_p} m \hat{c}_t + \lambda_t^p. \quad (5)$$

Note that when prices are fully flexible, i.e. $\theta_p = 0$, and the price mark-up shock is zero, Equation (5) reduces to the usual flexible price condition where the real marginal cost is equal to one.

2.4. Export and Import

The export and import sectors in the EP DSGE model are based on the paper by Adolfson et al. (2007a), with some modifications.⁴

The import sector consists of a continuum of firms, indexed by $0 \leq j \leq 1$, that buy euro area final good and turn it into a multitude of differentiated consumption goods by branding technology, i.e.

⁴ Adolfson et al. (2007a) make a distinction between imported consumption and investment goods. The EP DSGE model omits this distinction because the statistical data related to the prices of imported investment goods for Estonia is not readily available. This may lead to difficulties with estimation of the corresponding model parameters. It is therefore assumed that only consumption goods and services are imported. The same applies to the export sector.

without costs. These goods are sold on the home market, each supplied by a different importing firm and priced at $P_t^{j,m}$, subject to the following demand function:

$$C_t^{j,m} = \left(\frac{P_t^{j,m}}{P_t^m} \right)^{-\frac{1+\lambda_t^m}{\lambda_t^m}} C_t^m,$$

where C_t^m denotes the aggregate import demand, P_t^m is the aggregate import price index, $\log \lambda_t^m = \rho_m \log \lambda_{t-1}^m + u_t^m$, $u_t^m \sim \text{WN}(0, \sigma_m^2)$ is a stationary import price mark-up shock.

In addition, the prices set by importing firms are subject to the Calvo (1983) price stickiness. In every time period a random fraction $1 - \theta_m$ of importers is allowed to optimally set their prices, while the remaining fraction adjusts prices according to the indexation formula:

$$P_{t+1}^{j,m} = (\pi_t^m)^{\tau_m} P_t^{j,m},$$

where $\pi_t^m := \frac{P_t^m}{P_{t-1}^m}$ denotes the gross rate of import price inflation, and τ_m is the import price indexation coefficient. Importing firms maximize their profits subject to the Calvo (1983) price stickiness restriction. The resulting import price inflation dynamics is given by the following equation in log-linear form (derivations details can be found in Gelain and Kulikov, 2009):

$$\hat{\pi}_t^m = \frac{\beta}{1 + \beta \tau_m} \mathbf{E}_t \hat{\pi}_{t+1}^m + \frac{\tau_m}{1 + \beta \tau_m} \hat{\pi}_{t-1}^m + \frac{1}{1 + \beta \tau_m} \frac{(-\theta_m) \hat{m} - \beta \theta_m \hat{m}}{\theta_m} \hat{m} \hat{c}_t^m + \hat{\lambda}_t^m. \quad (6)$$

Exporting firms buy the final consumption good from the domestic market and differentiate it by brand naming. They sell the multitude of differentiated consumption goods to the euro area households, facing the following demand function for their products:

$$C_t^{j,e} = \left(\frac{P_t^{j,e}}{P_t^e} \right)^{-\frac{1+\lambda_t^e}{\lambda_t^e}} X_t,$$

where X_t denotes aggregate export, P_t^e is the export price index expressed in the local currency of the export market, and $\log \lambda_t^e = \rho_e \log \lambda_{t-1}^e + u_t^e$, $u_t^e \sim \text{WN}(0, \sigma_e^2)$ is the stochastic price mark-up shock. The price stickiness implies that a random fraction $1 - \theta_e$ of exporting firms can re-adjust prices in every period. For the rest, prices evolve according to the following indexation formula, where τ_e denotes the export price indexation parameter:

$$P_{t+1}^{j,e} = (\pi_t^e)^{\tau_e} P_t^{j,e}.$$

Exporting firms maximize their profits subject to the demand function and price stickiness restriction described above. The resulting export price inflation dynamics is given by the following expression (derivations details can be found in Gelain and Kulikov, 2009):

$$\hat{\pi}_t^e = \frac{\beta}{1+\beta\tau_e} \mathbb{E}_t \hat{\pi}_{t+1}^e + \frac{\tau_e}{1+\beta\tau_e} \hat{\pi}_{t-1}^e + \frac{1}{1+\beta\tau_e} \frac{(1-\theta_e)(1-\beta\theta_e)}{\theta_e} m\hat{c}_t^e + \hat{\lambda}_t^e. \quad (7)$$

The Estonian economy in the EP DSGE model is assumed to be small relative to the euro zone, playing a negligible part in the aggregate euro area consumption Y_t^* . The euro area demand for Estonian exports is given by:

$$X_t = \left(\frac{P_t^e}{P_t^*} \right)^{-\eta_*} Y_t^*,$$

where P_t^* denotes the consumer price index in the euro area, and η_* is the elasticity of substitution between imported and own consumption goods in the euro area.

2.5. Fiscal and Monetary Policy

The fiscal policy is exogenous and assumed have the following dynamics:

$$\log \frac{G_t}{G} = \rho_g \log \frac{G_{t-1}}{G} + u_t^g,$$

where G is the steady-state level of government spending, and $u_t^g \sim \text{WN}(0, \sigma_g^2)$ is the government spending shock. In addition, the balanced budget assumption implies that $G_t = -T_t$, where $-T_t$ are lump sum taxes paid by the households in the economy.

The monetary policy of Estonia is subject to the currency board arrangement and free capital mobility between the home economy and the euro area market. The UIP condition stipulates that domestic nominal interest rates are linked to the euro area nominal interest rates via the country-specific risk premium (see Schmitt-Grohè and Uribe, 2003):

$$R_t^n = \Omega(FA_t, \varepsilon_t^{\text{risk}}) R_t^{n,*}.$$

Therefore R_t^n is determined by the euro area monetary policy, fluctuations in the net foreign assets FA_t , and an idiosyncratic shock $\varepsilon_t^{\text{risk}}$.

2.6. The Aggregate Resource Constraint

The aggregate resource constraint is given by:

$$Y_t = C_t^d + C_t^m + I_t + G_t + \Psi(z_t)K_{t-1} + X_t - M_t. \quad (8)$$

By assumption, import is restricted to the final consumption good only, whereby $M_t \equiv C_t^m$. After substituting components of the domestic output into (8), the following expression is obtained:

$$Y_t = (1-\alpha_c) \left(\frac{P_t^d}{P_t^c} \right)^{-\eta_c} C_t + I_t + G_t + \Psi(z_t)K_{t-1} + \left(\frac{P_t^e}{P_t^*} \right)^{-\eta_*} Y_t^*,$$

In this expression, the aggregate consumption C_t is given by the following CES aggregate:

$$C_t = [(1 - \alpha_c) \frac{1}{\eta_c} (C_t^d)^{\frac{\eta_c - 1}{\eta_c}} + \alpha_c \frac{1}{\eta_c} (C_t^m)^{\frac{\eta_c - 1}{\eta_c}}]^{\eta_c},$$

where C_t^d denotes real consumption of domestically produced goods, α_c is the share of imports in consumption and η_c is the elasticity of substitution between domestic and imported consumption goods in Estonia.

The consumer price inflation $\hat{\pi}_t^c$ is defined as:

$$\hat{\pi}_t^c = (1 - \alpha_c)(\gamma^c)^{1 - \eta_c} \hat{\pi}_t^d + \alpha_c (\gamma^m)^{1 - \eta_c} \hat{\pi}_t^m,$$

where γ^c and γ^m denote steady state relative price parameters; refer to Gelain and Kulikov (2009) for derivations details.

2.7. The Euro Area Economy

The euro area part of the EP DSGE model is based on the seminal paper by Smets and Wouters (2003). Its structure is similar to the Estonian economy part of the model described above, but without the foreign trade links to the rest of the world, and with an independent monetary policy. Differently from the original Smets and Wouters (2003) paper, the inflation objective, price of capital and labour supply shocks are excluded in order to balance the number of shocks and observables in the final model. In addition, the relative risk aversion parameter is set to unity.

The euro area monetary policy rule expressed in the log-linear form is given by:

$$\hat{r}_t^{n,*} = \phi_m \hat{r}_{t-1}^{n,*} + (1 - \phi_m)[r_\pi \hat{\pi}_{t-1}^* + r_y (\hat{y}_{t-1}^* - \hat{y}_{t-1}^{p,*})] + r_{\Delta\pi} (\hat{\pi}_t^* - \hat{\pi}_{t-1}^*) + r_{\Delta y} [\hat{y}_t^* - \hat{y}_t^{p,*} - (\hat{y}_{t-1}^* - \hat{y}_{t-1}^{p,*})] + \hat{\varepsilon}_t^{r,*},$$

where $\hat{\varepsilon}_t^{r,*} = \rho_r^* \hat{\varepsilon}_{t-1}^{r,*} + u_t^{r,*}$, $u_t^{r,*} \sim \text{WN}(0, \sigma_{r,*}^2)$ is the euro area monetary policy shock, $\hat{\pi}_t^*$ denotes the inflation rate, \hat{y}_t^* denotes the euro area output, and $\hat{y}_t^{p,*}$ is the potential output level, where the latter is defined as the level of output that would prevail under flexible prices and wages in the absence of so-called “inefficient” wage and price mark-up shocks.

3. Data and Estimation

Prior to estimation, the EP DSGE model described in Section 2 is solved and log-linearized, resulting in 38 equations describing the evolution of state variables, and 16 equations giving the dynamics of structural shocks.⁵ The model is estimated by Bayesian methods⁶ using a dataset consisting of 16 seasonally-adjusted macroeconomic time series, including 6 series that describe the euro area variables. All empirical variables are quarterly, covering the time interval from 1995:2 to

⁵ Full details of the solution and log-linearization procedures can be found in Gelain and Kulikov (2009).

⁶ The estimation is carried out in Dynare, refer to Juillard (2004).

2008:3, thus giving 54 observations per data series. All domestic economy observables are sourced from the EMMA quarterly model of the Estonian economy (refer to Kattai, 2005), whereas the euro area empirical data is taken from the AWM database (refer to Fagan et al., 2005).

A short description of the individual data series used in the estimation is given below:

- Data series for \hat{y}_t is computed using linearly de-trended real per capita output variable, which itself consists of the sum of real per capita private consumption, real per capita investment, real per capita government consumption and real per capita trade balance;⁷
- Data series for \hat{c}_t is based on the national accounts linearly de-trended real per capita private consumption variable;
- Data series for \hat{i}_t is the linearly de-trended real per capita firms capital formation series, based on the national accounts statistics;
- Data series for \hat{x}_t is calculated as the linearly de-trended real per capita export of goods and services, based on the national accounts statistics;
- Data series for \hat{e}_t is computed as the linearly de-trended share of employed in the working age population, where the latter is defined as 15 to 74 year old;
- Data series for \hat{w}_t is based on the linearly de-trended per capita real wage, which is calculated as the nominal quarterly wage bill net of social security contributions deflated by the GDP deflator;
- Data series for $\hat{\pi}_t^d$, $\hat{\pi}_t^x$ and $\hat{\pi}_t^m$ are calculated as linearly de-trended quarter-on-quarter changes in the GDP deflator, export deflator, and import deflator series respectively;
- Data series for \hat{r}_t^n is obtained by linearly de-trending the 3-month average deposit rate in Estonia, since no statistics on short-term interest rates on government obligations is available;
- Data series for the euro area variables \hat{y}_t^* , \hat{c}_t^* , \hat{i}_t^* , \hat{e}_t^* , \hat{w}_t^* and $\hat{r}_t^{n,*}$ are Hodrick-Prescott filtered series of the real per capita output, real per capita private consumption, real per capita investment, share of employed in the working age population, real compensation per employee and the nominal 3-month interest rate respectively.

Similarly to Smets and Wouters (2003), the lack of suitable working hours statistics is mitigated by assuming the following *ad hoc* linkage between the observable economy-wide employment share series \hat{e}_t and the latent labour effort state variable \hat{l}_t :

⁷ Definition of the real output is consistent with the national accounts real GDP aggregate, apart from the final consumption of non-profit entities, which is excluded from \hat{y}_t .

$$\hat{e}_t = \frac{\beta}{1+\beta} \mathbf{E}_t \hat{e}_{t+1} + \frac{1}{1+\beta} \hat{e}_{t-1} + \frac{1}{1+\beta} \frac{(1-\beta\chi)(1-\chi)}{\chi} (\hat{l}_t - \hat{e}_t),$$

where χ can be interpreted as an employment adjustment parameter that determines how fast the firms are able to bring in or shed the number of workers in the face of fluctuations in the required labour effort. A similar function in terms of the parameters β^* and χ^* is assumed to link \hat{e}_t^* and \hat{l}_t^* variables in the euro area part of the model.

Regarding the choice of prior distributions and calibrated parameters, this paper follows the usual conventions in the DSGE modelling literature. The prior distributions and associated hyper-parameters for the Estonian part of the EP DSGE model are selected according to Adolfson et al. (2007a); refer to Table 2 for details. In addition, some steady-state shares and few “deep” parameters of the model, for which good theoretical reference values are available, are calibrated; see Table 1. Among the calibrated parameters in the table, the steady-state shares are set to match the corresponding sample averages, capital-output ratio α is taken from Ratto et al. (2008), the inter-temporal discount factor β is taken from Lendvai and Roeger (2008), corresponding to the steady-state annual interest rate of 5%, the steady-state wage mark-up parameter λ^w is taken from Smets and Wouters (2003), and the remaining parameters are selected to have empirically plausible steady-state import-to-output ratio.

Table 1: Steady-state shares and calibration

Consumption-income share (C/Y)	0.5500
Capital-output ratio (α)	0.4600
Capital depreciation rate (δ)	0.0250
Inter-temporal discount factor (β)	0.9875
Steady-state wage mark up (λ^w)	3.0000
Steady-state relative export price (γ^e)	1.0000
Share of imports in consumption (α_c)	0.5000

The euro area part of the EP DSGE model is estimated partly because of the computational feasibility considerations: priors for the standard errors and autoregressive parameters of seven structural shocks are taken from Smets and Wouters (2003). All other parameters of the euro area part are calibrated using the corresponding posterior mode values from Smets and Wouters (2003).

4. Empirical Results

Table 2 reports posterior summary statistics for all 52 estimated parameters of the EP DSGE model, split into several structural groups. In this section, the parameters in Table 2 are discussed in an order corresponding to their perceived economic importance.

The estimated posterior mean of ϕ_{ea} , that enters the country specific risk premium function $\Omega(FA_t, \varepsilon_t^{\text{risk}})$ in (1), is equal to 0.0294. This value appears to be relatively low in comparison to some previously reported estimates in the literature. For example, in Adolfson et al. (2007a) the posterior mean of this parameter is 0.2520 in their benchmark euro area model.⁸ The relatively low

⁸ However, their results are subject to a substantial variation. In another paper, which estimates a similar model on a long sample of Swedish data covering the period from 1980 to 2004, Adolfson et al. (2007b) report a posterior median of ϕ_{ea} in the range between 0.0310 to 0.0460 depending a particular model specification. It must be noted, that the risk premium function in that paper includes dependence on the expected exchange rate fluctuations, so that direct comparison to the EP DSGE model results is not possible.

Table 2: Prior and posterior distributions of the EP DSGE model parameters

Parameter	Prior distribution			Posterior distribution			
	type	mean	std. dev.	mean	std. dev.	10%	90%
<i>Standard deviations (Estonia):</i>							
Fiscal policy (σ_g)	<i>IG</i>	0.30	∞	0.2619	0.0859	0.1577	0.3885
Preference (σ_β)	<i>IG</i>	0.20	∞	0.0278	0.0029	0.0245	0.0316
Technology (σ_a)	<i>IG</i>	0.40	∞	0.0889	0.0145	0.0710	0.1094
Investment-specific (σ_x)	<i>IG</i>	0.10	∞	0.0736	0.0099	0.0610	0.0872
Risk premium (σ_{risk})	<i>IG</i>	0.08	∞	0.0113	0.0012	0.0099	0.0129
Wage mark-up (σ_w)	<i>IG</i>	0.25	∞	0.0344	0.0034	0.0306	0.0389
Domestic price mark-up (σ_p)	<i>IG</i>	0.15	∞	0.0238	0.0027	0.0203	0.0277
Import price mark-up (σ_m)	<i>IG</i>	0.40	∞	0.0881	0.0148	0.0690	0.1093
Export price mark-up (σ_e)	<i>IG</i>	0.40	∞	0.0990	0.0177	0.0757	0.1263
<i>Standard deviations (euro area):</i>							
Fiscal policy ($\sigma_{g,*}$)	<i>IG</i>	0.30	∞	0.2381	0.0219	0.2098	0.2683
Preference ($\sigma_{\beta,*}$)	<i>IG</i>	0.20	∞	0.0950	0.0142	0.0762	0.1158
Technology ($\sigma_{a,*}$)	<i>IG</i>	0.40	∞	0.3203	0.0299	0.2809	0.3615
Investment-specific ($\sigma_{x,*}$)	<i>IG</i>	0.10	∞	0.9168	0.1003	0.7860	1.0608
Wage mark-up ($\sigma_{w,*}$)	<i>IG</i>	0.25	∞	0.1073	0.0107	0.0935	0.1218
Price mark-up ($\sigma_{p,*}$)	<i>IG</i>	0.15	∞	0.0384	0.0047	0.0324	0.0449
Monetary policy ($\sigma_{r,*}$)	<i>IG</i>	0.10	∞	0.0693	0.0065	0.0610	0.0784
<i>Auto-regressive coeff. (Estonia):</i>							
Fiscal policy (ρ_g)	<i>B</i>	0.85	0.10	0.8539	0.0679	0.7688	0.9322
Preference (ρ_β)	<i>B</i>	0.85	0.10	0.2793	0.0715	0.1933	0.3692
Technology (ρ_a)	<i>B</i>	0.85	0.10	0.6451	0.0872	0.5338	0.7550
Investment-specific (ρ_x)	<i>B</i>	0.85	0.10	0.5968	0.0900	0.4795	0.7094
Risk premium (ρ_{risk})	<i>B</i>	0.65	0.10	0.8968	0.0344	0.8484	0.9395
Wage mark-up (ρ_w)	<i>B</i>	0.85	0.10	0.3717	0.0982	0.2507	0.5022
Domestic price mark-up (ρ_p)	<i>B</i>	0.85	0.10	0.5895	0.1198	0.4466	0.7332
Import price mark-up (ρ_m)	<i>B</i>	0.85	0.10	0.8583	0.0699	0.7613	0.9439
Export price mark-up (ρ_e)	<i>B</i>	0.85	0.10	0.8298	0.0822	0.7318	0.9236
<i>Auto-regressive coeff. (euro area):</i>							
Fiscal policy (ρ_g^*)	<i>B</i>	0.85	0.10	0.8469	0.0655	0.7648	0.9228
Preference (ρ_β^*)	<i>B</i>	0.85	0.10	0.6285	0.0574	0.5512	0.7022
Technology (ρ_a^*)	<i>B</i>	0.85	0.10	0.7757	0.0698	0.6874	0.8615
Investment-specific (ρ_x^*)	<i>B</i>	0.85	0.10	0.4302	0.0722	0.3387	0.5222
Wage mark-up (ρ_w^*)	<i>B</i>	0.85	0.10	0.1785	0.0442	0.1243	0.2353
Price mark-up (ρ_p^*)	<i>B</i>	0.50	0.15	0.7134	0.0550	0.6411	0.7815
Monetary policy (ρ_m^*)	<i>B</i>	0.85	0.10	0.6998	0.0597	0.6183	0.7728

Table 2: Prior and posterior distributions of the EP DSGE model parameters (cont.)

Parameter	Prior distribution			Posterior distribution			
	type	mean	std. dev.	mean	std dev.	10%	90%
<i>Calvo parameters (Estonia):</i>							
Wage (θ_w)	<i>B</i>	0.70	0.05	0.4965	0.0491	0.4341	0.5576
Domestic prices (θ_p)	<i>B</i>	0.75	0.05	0.6376	0.0441	0.5854	0.6894
Import prices (θ_m)	<i>B</i>	0.50	0.10	0.2532	0.0462	0.1970	0.3120
Export prices (θ_e)	<i>B</i>	0.50	0.10	0.1145	0.0242	0.0850	0.1457
<i>Indexation parameters (Estonia):</i>							
Wage (τ_w)	<i>B</i>	0.75	0.15	0.8617	0.0763	0.7329	0.9636
Domestic prices (τ_p)	<i>B</i>	0.75	0.15	0.7387	0.1750	0.5476	0.9098
Import prices (τ_m)	<i>B</i>	0.50	0.15	0.5012	0.1689	0.3059	0.6990
Export prices (τ_e)	<i>B</i>	0.50	0.15	0.3655	0.1562	0.1936	0.5553
<i>Elasticity parameters (Estonia):</i>							
Consumption subst. (σ_c)	<i>N</i>	1.00	0.375	1.3302	0.2997	0.9639	1.7140
Labour supply (σ_l)	<i>N</i>	2.00	0.25	1.7988	0.2686	1.4514	2.1418
Domest.-import subst. (η_c)	<i>IG</i>	2.00	0.10	1.8678	0.1684	1.6698	2.0781
Import-domest. Subst. (η_m)	<i>IG</i>	2.00	0.10	1.7616	0.1421	1.5857	1.9479
Capital utilization (ψ)	<i>N</i>	0.20	0.05	0.1694	0.0512	0.1035	0.2357
Investment adjustment (φ)	<i>N</i>	4.00	1.50	7.5716	1.1154	6.1969	8.9783
<i>Other parameters (Estonia):</i>							
Share of fixed cost (ϕ)	<i>N</i>	0.45	0.08	0.1386	0.0796	0.0407	0.2374
Consumption habit (h)	<i>B</i>	0.70	0.05	0.8115	0.0341	0.7669	0.8535
Risk premium (ϕ_{fa})	<i>IG</i>	0.50	∞	0.0294	0.0059	0.0219	0.0377
Consumer-domest. price (γ^c)	<i>IG</i>	1.20	∞	1.1038	0.1021	1.0350	1.1777
Import-domest. price (γ^m)	<i>U</i>	1.00	1.30	1.1097	0.1449	1.0180	1.2242
Employment adjustment (χ)	<i>B</i>	0.50	0.15	0.8011	0.0205	0.7739	0.8275

Notes: The EP DSGE model parameter name and symbol are shown in the first column. The following three columns describe the corresponding prior distribution: its type and the first two moments. In the case of an uniform prior, distribution's support is shown. The last four columns summarize the posterior distribution: its mean, standard deviation, and the 10th and 90th deciles. All posterior statistics are computed using the Metropolis-Hastings sampler. IG=inverse gamma, B=beta, N=Normal, U=uniform

estimate of ϕ_{fa} in Table 2 may indicate that the net foreign asset position of Estonia cannot fully explain the observed interest rate spread between domestic and foreign interest rates. This is corroborated by the fact that the idiosyncratic component of the risk premium function, given by $\varepsilon_t^{\text{risk}}$, is very persistent, with the estimated posterior mean of ρ_{risk} equal to 0.8968, suggesting that it captures a high share of the risk premium variation in the data. This can partly be explained by data issues: there are two pronounced interest rate spikes in Estonian interest rates in the second half of the 1990s induced by the Asian and Russian financial crises. These events coincided with substantial structural shifts in the Estonian banking sector and a dramatic reduction in the interest rate spread in the following years. The specification of $\Omega(FA_t, \varepsilon_t^{\text{risk}})$ function in (1) might be too

parsimonious to describe these changes, and therefore may warrant a revision in future versions of the EP DSGE model.

The group of Calvo parameters reported in Table 2 carries information about the timing of price and wage setting decisions by firms and households (see Equations (2), (5), (6), and (7)). The summary statistics for prior and posterior distributions of θ_w , θ_p , θ_m and θ_e reveal that the data has a lot to say about these parameters.

The posterior mean of θ_p , the parameter that governs degree of price stickiness faced by the domestic intermediate good producers, is estimated at 0.6376. This implies that domestic prices persist on average for about 2.75 quarters. This is somewhat lower than a recent survey evidence documented in Druant et al. (2009) who report an average price duration of 3.33 quarters for Estonia, even though their methodology does not make a distinction between domestic and consumer prices. Dabušinskas and Kulikov (2007) also find Calvo parameters being somewhat higher, in the range between 0.6830 and 0.8632, using three alternative specifications of the New Keynesian Phillips Curve estimated on a sample of Estonian domestic inflation data from 1994:4 to 2005:3. However, the conclusion of Dabušinskas and Kulikov (2007) that price setting in Estonia is more flexible than in the euro area still holds: most empirical euro area DSGE models have substantially higher Calvo parameters associated with domestic price setting (see Smets and Wouters, 2003; Adolfson et al., 2007a).

Turning to the export-import sector, it is worth noting that the corresponding price stickiness parameters are considerably lower than θ_p . The implied price durations range from 1.34 quarters in the import sector (the posterior mean of θ_m is estimated at 0.2532) to just 1.13 quarters in the export sector (the posterior mean of θ_e is estimated at 0.1145). Adolfson et al. (2007a) also report lower price stickiness parameters in the export-import sector relative to the domestic one in their euro area model, though the implied durations according to their results range from 1.86 quarters for import prices to 2.77 quarters for export prices.

The posterior mean of the wage stickiness coefficient θ_w is estimated at 0.4965. According to this result, an average duration of a nominal wage contract in Estonia is about 2 quarters. This is twice lower than the survey evidence in Druant et al. (2009) for Estonia, where nominal wages are found to stay unchanged for a year on average. The corresponding result for the euro area also indicates a higher degree of wage stickiness, with an implied nominal wage durations of around 4 quarters (see Smets and Wouters 2003; and Adolfson et al., 2007a).

The next set of parameters in Table 2 is related to price and wage indexation. Coefficients τ_w , τ_p , τ_m and τ_e are linked to the weights of forward- and backward-looking inflation components in the real wage Equation (2) and corresponding New Keynesian Phillips Curves (5), (6), and (7). The

prior-posterior summary statistics suggests that the data is informative only about τ_w and τ_e indexation coefficients.

The posterior mean of the nominal wage indexation coefficient τ_w is estimated at 0.8617, being noticeably higher than the corresponding results for the euro area documented by Smets and Wouters (2003) and Adolfson et al. (2007a). The estimated value of τ_w is difficult to put into perspective, because empirical evidence about wage indexation in Estonia is patchy. Druant et al. (2009) report that 34% of Estonian firms index wages to past inflation, but they do not quantify the degree of indexation adopted by the firms in their survey sample, making a direct comparison with the estimated τ_w coefficient problematical.

Another parameter of interest that can be calculated using empirical results in Table 2 links the real marginal cost term to the domestic inflation rate in the New Keynesian Phillips Curve Equation (5). This parameter, estimated at the posterior means of θ_p and τ_p , is equal to 0.1217. This is considerably higher than previously reported by Dabušinskas and Kulikov (2007), where a related coefficient was found to lie in the range from 0.0026 to 0.0113 depending on the model specification, but a formal statistical comparison of these results is infeasible due to differences in the estimation methodologies.

Other parameters of interest in Table 2 are following. The posterior mean of σ_c , the parameter governing inter-temporal elasticity of substitution of a representative household's consumption, is equal to 1.3302. It is in line with the value 1.3910 found by Smets and Wouters (2003) for the euro area, and implies that Estonian households respond to variations in the real interest rate in the same way as their European counterparts. The external consumption habit parameter h for Estonia is estimated at 0.8115, which exceeds both benchmark results reported for the euro area: 0.5920 in Smets and Wouters (2003) and 0.7080 in Adolfson et al. (2007a). It can be attributed to the “catching up with Joneses” effect that characterizes a country with high GDP growth rate such as Estonia.

The inverse elasticity of work effort with respect to the real wage is controlled by the parameter σ_l , with the posterior mean of 1.7988 reported in Table 2. The corresponding elasticity of labour supply with respect to the real wage is given by 0.5559, which is close to the result obtained in Staehr (2008), where he finds that a “1 per cent increase in after-tax hourly income would lead to a 0.6 percentage point increase in individuals being employed”. On the other hand, Smets and Wouters (2003) find that the posterior mean of σ_l for the euro area is equal to 2.5030.

Two other elasticity parameters reported in Table 2 are η_c and η_s , which are respectively the elasticity of substitution between domestic and imported consumption goods in Estonia and

between imported and domestic consumption goods in the euro area. Their estimated posterior means are very similar: 1.8678 for η_c and 1.7616 for η_* .⁹ The pair of similar parameters for the euro area in Ratto et al. (2008) is reported to be 1.1724 and 2.5358 respectively, while Adolfson et al. (2007a) estimate the value of η_* at 1.4860.

Parameter φ that governs the elasticity of the investment adjustment cost function is estimated at 7.5716. The corresponding elasticity estimate is 0.1297, and according to the interpretation in Christiano et al. (2005), this implies that a 1% permanent change in the price of capital induces about a 13% change in investment. Similar parameter estimate obtained by Adolfson et al. (2007a) for the euro area is equal to 8.6700.

Finally, a pairwise comparison of estimated autoregressive parameters for Estonia and euro area in Table 2 reveals that the dynamics of structural shocks in both parts of the EP DSGE model is similar, except for the inter-temporal preference shocks $\hat{\varepsilon}_t^\beta$ and $\hat{\varepsilon}_t^{\beta,*}$. The summary statistics of the posterior distributions of ρ_β for Estonia and ρ_β^* for the euro area differ considerably, with the respective posterior means given by 0.2793 and 0.6285, the latter still being lower than the typical estimates obtained by Smets and Wouters (2003) and Adolfson et al. (2007a). An explanation of this finding might be related to the structure of shock transmission within the EP DSGE model: euro area structural shocks propagate to the Estonian economy, and therefore persistence of Estonian macroeconomic variables in part depends on the persistence of the euro area structural shocks. Hence, the inter-temporal preference shock ε_t^β can be less persistent without compromising the ability of the model to explain fluctuations of the main Estonian macroeconomic aggregates.

4.1. Model Response to Structural Shocks

Reaction of the endogenous model variables to structural shocks, such as changes in the risk premium, preferences or technology, can be examined using orthogonalized impulse response functions. For the estimated EP DSGE model, a collection of impulse response functions to some of the model's structural shocks are shown in Figures 1 to 9.¹⁰

Figure 4 depicts a number of impulse responses to one standard deviation orthogonalized innovation to the risk premium shock. The set of endogenous variables on this figure, and all other figures showing the impulse response functions, contains central macroeconomic quantities related to both the domestic and euro area economy parts of the model. In order to understand the propagation of this shock through the model, one would ideally need to appeal to its effect on the

⁹ The typical estimates from micro-datasets for the elasticity of substitution between domestic and foreign goods range from 5 to 20 (refer to Obstfeld and Rogoff, 2000). However, macro-datasets usually yield much lower elasticity estimates, typically from 1.5 to 2 (e.g., see Collard and Dellas, 2002).

¹⁰ Due to the space limitations only a subset of all impulse responses is reported in Figures 1 to 9. The full set of results is available from the authors on request.

real exchange rate, which in turns would have an impact on the export-import sector of the model. However, while the real exchange rate is not an explicit part of the EP DSGE model, the model contains two relative prices which are implicitly linked to the real exchange rate.

A positive and unexpected risk premium shock generates an increase in both the nominal and real domestic interest rates, which in turn has a pronounced effects on the inter-temporal allocation decisions by the households. In particular, consumption and capital accumulation activity of the households decreases in favor of investing into bonds. This generates a demand-driven downturn in the domestic economy, with an associated decrease in the labour effort, real wage and the price of capital. On the production side, marginal cost drops and producer prices start to go down gradually through the standard mechanism of sticky prices. This leads to a depreciation of the real exchange rate and an associated rise in exports because of increased competitiveness vis-à-vis the euro area. At the same time, imports drop because of the lower entire sample period, as the country borrowed funds needed to restructure its economy. The cyclical net foreign asset position refers to this data after removing the downward-sloping linear trend. However, de-trended net foreign asset position data series is not used for estimating the parameters of the EP DSGE model. domestic demand. The foreign asset position improves and the interest rate spread decreases to compensate for the initial risk premium shock. Note that domestic output rebounds sooner than both the consumption and investment because of the export-driven upturn. None of the euro area endogenous variables are affected by an idiosyncratic shock to the country specific risk premium, making it essentially one of the domestic shocks in the EP DSGE model.

Figure 2 depicts the model response to a one standard deviation unexpected orthogonalized innovation to the technology shock. This shock hits the production side of the domestic economy: productivity of labour and capital rises uniformly for all intermediate good producers, leading to a decrease in marginal cost. A gradual process of producer price reduction ensues, and domestic inflation falls. The real exchange rate depreciates, leading to an increase in the exports to euro area. At the same time, imports fall initially, because of the substitution effect in favor of the domestic goods. The foreign asset position of Estonia improves, leading to a reduction of the risk premium and domestic nominal and real interest rates. As the result, households move from saving to consumption and capital accumulation, leading to an overall upturn in the economy. Note that the labour effort initially falls as a result of a positive technological innovation, a finding that is emphasized by Galì (1999) (and later corroborated by Smets and Wouters, 2005; Adolfson et al., 2007a; and others). A combination of sticky wages and prices drives the substitution from labour to capital at the point of initial impact of the technology shock, generating this result. The subsequent upturn in the economic activity drives up both the labour effort and the capital accumulation.

Impact of the investment-specific technology shock on the EP DSGE model is shown in Figure 3. The propagation mechanism of this shock is standard in DSGE literature; details can be found in Smets and Wouters (2003).

The model response to one standard deviation orthogonalized innovation to the domestic price mark-up shock is shown in Figure 6. A positive shock reduces substitutability between the variety of differentiated domestically produced intermediate goods, and drives up the mark-ups charged by the intermediate good producers. As a result, domestic price inflation jumps up, leading to an appreciation of the real exchange rate and the initial drop in exports. At the same time, consumers shift from relatively more expensive domestic goods to the cheaper euro area imports. The net foreign asset position deteriorates, and the spread between domestic and euro area nominal interest rates increases. From this point on the response of main macroeconomic aggregates is similar to the previously described effect of a risk premium shock: reduced economic activity drives the marginal cost down, compensating for the initial jump in mark-ups, domestic prices start falling, the real exchange rate depreciates, and the exports rebound.

A positive unexpected wage mark-up shock has a very similar effect on the domestic economy. The corresponding collection of impulse response functions is shown in Figure 5. The only difference with previously described effect of a price mark-up shock is that the marginal cost is driven up by an initial jump in real wages.¹¹

The collection of impulse response functions describing an effect of one standard deviation orthogonalized innovation to the preference shock is depicted in Figure 1. A positive preference shock generates a boom-bust response of the domestic output in the EP DSGE model. The initial jump in output is due to an increased optimism of the households that shift from the capital accumulation to consumption. However, the drop in investment is so severe, that it quickly generates a bust in the overall level of economic activity. Employment, wages and domestic prices start to fall, and the real exchange rate depreciates. The latter leads to a subsequent pick-up in the euro area exports, generating a comeback in economic activity. At the same time, the initial jump in imports leads to a deterioration of the net foreign asset position and a gradual widening of the interest rate spread, which moderates the export-driven rebound.

The remaining part of this subsection covers the effect of three different euro area shocks on the Estonian economy. Recall that the EP DSGE model stipulates two types of links between domestic

¹¹ The effect of a wage mark-up shock can be interpreted in different ways. If the shock is seen as a measure of how strong the trade unions are in the economy, wages rise in response to a positive wage mark-up shock because the unions have more bargaining power and can contract higher wages. According to the wage bargaining theory, this results in a lower overall employment in the economy. A different view on the wage mark-up shock is that it measures specific skills of different employees, and thereby substitutability of different types of labour in the economy. When a positive wage mark-up shock occurs, the labour demand described by (19) becomes less elastic, and the households that supply labour can earn a higher premium on their specific skills.

and euro area economy: the monetary policy channel via the UIP Equation (14) and the trading channel via the export-import sector. In addition, the structural shocks hitting domestic and euro area economy are assumed to be independent. One of the key assumptions of the EP DSGE model is that Estonian economy acts like a small open economy on the fringes of the big euro area economy: none of the domestic shocks in Figures 1 to 6 affect euro area macroeconomic variables.

Consider a monetary policy shock that hits the euro area economy; see Figure 9 for the corresponding collection of impulse response functions. A positive euro area monetary policy shock has well-known effects on its output and inflation; a detailed description of these effects can be found in Smets and Wouters (2003). The model also generates an endogenous response of the euro area monetary policy authority to this shock; see Equation (38).

What are the effects of this shock on the Estonian economy? There are two effects which have a negative impact on the domestic output. Firstly, exports fall because of a decrease in the euro area output, at the same time imports from the euro area increase as they become relatively cheaper. Secondly, domestic nominal interest rate gradually increases because of the higher euro area interest rate and a deterioration in the net foreign asset position. Downturn in Estonian economy depresses consumption, wages and employment, as well as domestic prices. The latter helps to improve competitiveness vis-à-vis the euro area and has a moderating effect on the downturn.

Next, consider an euro area wage mark-up shock; the model responses are depicted in Figure 8. A positive wage mark-up shock effectively makes euro area less competitive vis-à-vis the Estonian economy. As a result, domestic economy experiences a boom driven by increased exports and the shift from relatively more expensive euro area imports to the domestically produced substitutes. Domestic investment, employment and wages increase, giving the households an extra income to spend on the consumption goods. Eventually, the net foreign asset position starts deteriorating due to the increased imports, and the interest rate spread widens, moderating the initial domestic economy boom.

The final euro area shock considered in this subsection is a one standard deviation orthogonalized positive innovation to the technology shown in Figure 7. Its effect is essentially opposite to the previously described euro area wage mark-up shock: this time the euro area competitiveness improves vis-à-vis the Estonian economy. A foreign trade induced downturn in the domestic economic activity ensues, exaggerated by a rapid deterioration in the net foreign asset position and a resulting increase of the domestic nominal interest rate.

4.2. Variance Decomposition Analysis

The relative importance of various structural shocks included into the EP DSGE model can be measured by the share of total variation that a particular shock helps to explain for each endogenous

variable of the model. The variance decomposition methodology is borrowed from the time series analysis (refer to Hamilton, 1994).

Table 3 presents the variance decomposition results for the main endogenous variables of the EP DSGE model.¹² Full complement of 16 structural innovations and the set of endogenous variables are divided into two groups: those related to the domestic economy and those linked to the euro area economy. The table can therefore be subdivided into four quadrants. The upper left quadrant shows a contribution of the domestic innovations to the Estonian economy. The results are mostly in line with the structural assumptions underlying most of the innovations, but some comments are still warranted. Two domestic innovations, the fiscal policy innovation and the export price mark-up innovation, appear to have a very limited contribution to the dynamics of model variables. Somewhat unexpectedly, the domestic price markup innovation adds very little to the dynamics of domestic inflation, but at the same time contributes significantly to other parts of the Estonian economy. The lower left quadrant of Table 3 is filled with zeros because Estonian innovation have no effect on euro area state variables.

Moving on to the contribution of euro area structural innovations, the lower right quadrant of Table 3 gives variance decomposition of the EP DSGE model's euro area part. This decomposition is similar to the results reported in Smets and Wouters (2003). The upper right quadrant of the table shows contribution of the euro area innovations to the Estonian economy. It can be observed that the euro area price and wage mark-up innovations explain a significant share of the variation of most domestic endogenous variables. Given the small open economy nature of Estonia in the EP DSGE model, this result is not unexpected. However, these two innovations easily overwhelm the effect of most domestic innovations, which is especially noticeable in the case of domestic inflation, real interest rate, and price of capital.

¹² This results are produced by Dynare and are based on 20 lags approximation to the unconditional variance-covariance matrix of the vector of state variables. Full variance decomposition results are available from the authors on demand.

Table 3. Variance decomposition of endogenous variables in estimated EP DSGE model (in

	u_t^a	u_t^g	u_t^β	u_t^w	u_t^p	u_t^{risk}	u_t^m	u_t^e	$u_t^{p,*}$	$u_t^{w,*}$	$u_t^{r,*}$	$u_t^{\beta,*}$	$u_t^{a,*}$	$u_t^{x,*}$	$u_t^{g,*}$	
\hat{y}_t	15.22	1.24	0.49	4.52	3.59	12.10	0.03	1.03	0.11	23.55	19.27	3.00	0.36	15.15	0.08	0.25
\hat{c}_t	7.73	0.48	25.30	4.14	1.80	5.46	0.46	0.70	0.01	13.52	27.96	3.29	0.03	6.58	2.44	0.10
\hat{l}_t	8.70	0.67	9.49	49.01	2.21	4.96	0.19	0.33	0.00	4.64	12.40	3.05	0.06	2.21	2.06	0.03
$\hat{\pi}_t$	3.45	0.08	2.44	0.96	0.77	3.57	0.84	0.83	0.02	26.47	39.03	4.93	0.15	14.64	1.60	0.23
$\hat{\pi}_t^n$	9.81	0.26	14.65	3.24	2.13	9.32	7.01	2.68	0.06	9.05	15.79	6.73	0.80	6.06	12.31	0.11
$\hat{\pi}_t^d$	6.10	0.14	0.78	1.06	1.22	7.20	0.07	0.78	0.04	24.18	35.51	6.39	0.25	14.04	2.02	0.23
$\hat{\pi}_t^c$	1.76	0.04	0.22	0.30	0.35	2.07	0.02	2.32	0.01	27.94	36.21	8.19	0.45	17.50	2.35	0.28
\hat{k}_t	2.73	0.30	3.51	85.82	0.71	1.31	0.05	0.11	0.00	0.75	2.56	1.17	0.02	0.33	0.62	0.01
\hat{l}_t	17.84	1.17	0.49	3.83	4.31	10.70	0.03	1.12	0.11	23.31	18.87	2.65	0.35	14.95	0.04	0.25
\hat{q}_t	5.89	0.16	5.88	5.05	1.30	5.60	0.60	0.72	0.02	20.28	36.98	4.39	0.07	10.40	2.50	0.16
\hat{w}_t	11.87	0.10	4.05	1.65	21.55	36.85	0.15	1.51	0.02	7.13	9.53	0.98	0.04	3.98	0.53	0.07
\hat{r}_t^*	13.88	0.76	1.04	4.21	2.01	22.30	0.07	0.78	0.09	20.07	19.59	2.36	0.23	12.26	0.14	0.20
$\hat{f}a_t$	10.22	0.27	15.27	3.38	2.22	9.71	1.69	2.79	0.06	9.79	16.42	7.20	0.94	7.09	12.80	0.15
$\hat{\pi}_t^m$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.14	0.00	30.93	30.65	8.15	0.66	20.88	2.28	0.32
$\hat{\pi}_t^x$	5.83	0.13	0.75	1.04	1.17	6.74	0.07	0.77	0.93	24.09	35.56	6.41	0.25	13.97	2.05	0.22
\hat{x}_t	11.58	0.35	3.23	4.03	2.54	11.46	0.27	3.42	0.68	26.31	11.40	2.82	0.81	18.62	2.14	0.35
\hat{m}_t	10.30	0.23	23.33	2.11	2.15	11.16	1.15	5.57	0.22	10.81	16.17	2.01	0.53	6.94	7.20	0.12
\hat{c}_t^*	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.47	0.82	13.28	57.04	14.98	10.29	3.12
\hat{l}_t^*	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.55	0.64	6.31	11.55	7.97	71.70	1.28
$\hat{r}_t^{k,*}$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	7.07	8.43	17.20	5.19	21.78	33.85	6.48
$\hat{r}_t^{n,*}$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.00	7.00	12.77	35.36	29.11	10.05	2.71
$\hat{\pi}_t^*$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	34.19	30.98	8.14	0.72	23.27	2.34	0.36
\hat{w}_t^*	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	21.54	55.75	0.61	0.98	16.26	4.78	0.08
\hat{l}_t^*	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.01	1.46	18.72	8.41	34.16	26.46	9.78
\hat{y}_t^*	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.35	1.60	20.29	11.18	22.65	31.63	11.30

percent)

5. Conclusion

This paper lays out the theoretical foundations and reports Bayesian estimations results for an open economy dynamic stochastic general equilibrium model for Estonia. The model is designed to match the key characteristics of the Estonian economy: the currency board regime, free capital mobility and dependence on the external economic environment via foreign trade. These are typical features of a small open economy in the vicinity of a much larger economic area. The EP DSGE model consists of two inter-dependent parts: the domestic economy part describing Estonia and the euro area part acting as a large closed economy with the monetary policy and trade linkages to the

first part. The evolution of Estonian economy is described by 25 state variables and 9 structural shocks, while the euro area part consists of 13 state variables and 7 structural shocks.

The empirical part of this paper reports Bayesian estimation of the main model parameters.¹³ Out of 59 structural parameters in the EP DSGE model, 52 are estimated using a data sample consisting of 16 macroeconomic series for Estonia and euro area. The main empirical findings are largely in line with previous studies for Estonia, whenever a direct comparison can be made. It is worth mentioning that the net foreign asset position of Estonia is found to be an economically significant factor in explaining the country risk premium in the UIP equation, but the empirical results suggest that other explanatory factors may also be warranted.

The empirical relevance of structural shocks in the model is assessed by the variance decomposition of the main endogenous variables. It is found that three most important domestic shocks in explaining the variability of Estonian macroeconomic series are the consumption preference shock and two technology shocks. Euro area shocks also play a prominent role in driving the dynamics of Estonian macroeconomic aggregates. Among the most significant euro area shocks that affect Estonia are the price and wage mark-up shocks.

The EP DSGE model described in this paper is focused on the business cycle frequency fluctuations of the main Estonian macroeconomic aggregates, leaving their long-run trends aside. Future developments of the model are likely to incorporate the long-run dynamics as well, considering that Estonia is still experiencing the effects of real and nominal convergence as it catches up with the developed euro area economies. Other potential future extensions of the model include incorporation of the financial sector with the associated frictions, integration of the housing sector together with collateral-constrained households, and expansion of the government sector.¹⁴

References

- Adolfson, M., Laséen, S., Lindé, J., Villani, M., (2007a). Bayesian estimation of an open economy DSGE model with incomplete pass-through. *Journal of International Economics*, Vol. 72, pp. 481–511.
- Adolfson, M., Laséen, S., Lindé, J., Villani, M., (2007b). Evaluating an estimated new Keynesian small open economy model. *Working Paper Series*, No. 203, Sveriges Riksbank.
- Calvo, G., (1983). Staggered prices in a utility maximizing framework. *Journal of Monetary Economics*, Vol. 12, pp. 383–398.
- Christiano, L.J., Eichenbaum, M., Evans, C.L., (2005). Nominal rigidities and the dynamic effects of a shock to monetary policy. *Journal of Political Economy*, Vol. 113, pp. 1–45.
- Colantoni, L., (2007). Monetary transmission in Estonia: The interest rate channel. Mimeo.

¹³ Additional empirical results can be found in Gelain and Kulikov (2009).

¹⁴ For a version of the model incorporating financial frictions in the form of the so-called financial accelerator see Gelain and Kulikov (forthcoming).

- Collard, F., Dellas, H., (2002). Exchange rate systems and macroeconomic stability. *Journal of Monetary Economics*, Vol. 49, pp. 571–599.
- Dabušinskas, A., Kulikov, D., (2007). New Keynesian Phillips Curve for Estonia, Latvia and Lithuania. *Working Papers Series*, No. 7/2007, Eesti Pank.
- Druant, M., Fabiani, S., Kezdi, G., Lamo, A., Martins, F., Sabbatici, R., (2009). How are firms' wage and prices linked: survey evidence in Europe. *ECB Working Paper Series*, No. 1084.
- Erceg, C.J., Henderson, D.W., Levin, A.T., (2000). Optimal monetary policy with staggered wage and price contacts. *Journal of Monetary Economics*, Vol. 46, pp. 281–313.
- Fagan, G., Henry, J., Mestre, R., (2005). An area-wide model (AWM) for the euro area. *Economic Modelling*, Vol. 22, pp. 39–59.
- Gelain, Paolo and Dmitry Kulikov, (2009). An estimated dynamic stochastic general equilibrium model for Estonia. *Working Papers Series*, No. 5/2009, Eesti Pank.
- Gelain, Paolo and Dmitry Kulikov, (forthcoming). An Estimated Dynamic Stochastic General Equilibrium Model with Financial Frictions for Estonia. *Eastern European Economics*.
- Juillard, M., (2004). *Dynare Manual*. CEPREMAP.
- Kattai, R., (2005). EMMA: A quarterly model of the Estonian economy. *Working Papers Series*, No. 12/2005, Eesti Pank.
- Kollmann, R., (2001). The exchange rate in a dynamic-optimizing current account model with nominal rigidities: A quantitative investigation. *Journal of International Economics*, Vol. 55, pp. 243–262.
- Lendvai, J., Roeger, W., (2008). Estonia 1995 to 2007: Catching-up and beyond. Mimeo.
- Obstfeld, M., Rogoff, K., (2000). The six major puzzles in international macroeconomics: Is there a common cause? *NBER Macroeconomics Annual*, MIT Press.
- Ratto, M., Roeger, W., in't Veld, J., (2008). Quest III: An estimated DSGE model of the euro area with fiscal and monetary policy. *DG ECFIN Economic Paper*, No. 335.
- Schmitt-Grohé, S., Uribe, M., (2003). Closing small open economy models. *Journal of International Economics*, Vol. 61, pp. 163–185.
- Smets, F., Wouters, R., (2003). An estimated dynamic stochastic general equilibrium model of the euro area. *Journal of the European Economic Association*, Vol. 1, pp. 1123–1175.
- Staehr, K., (2008). Estimates of employment and welfare effects of personal labour income taxation in a flat-tax country: The case of Estonia. *Working Papers Series*, No. 3/2008, Eesti Pank.

Figures

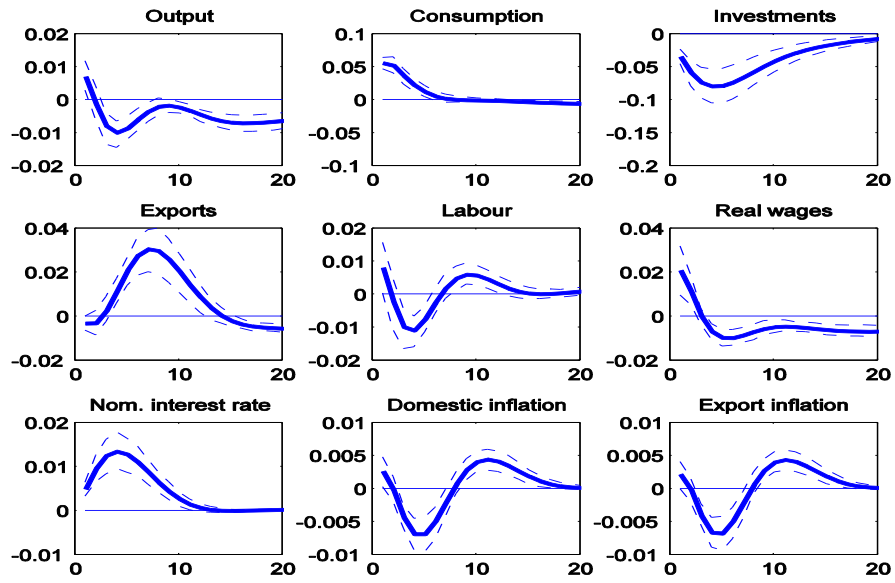


Figure 1: Impulse response functions (expressed in percentage deviations from the steady states) to one standard deviation orthogonalized innovation to preference shock.

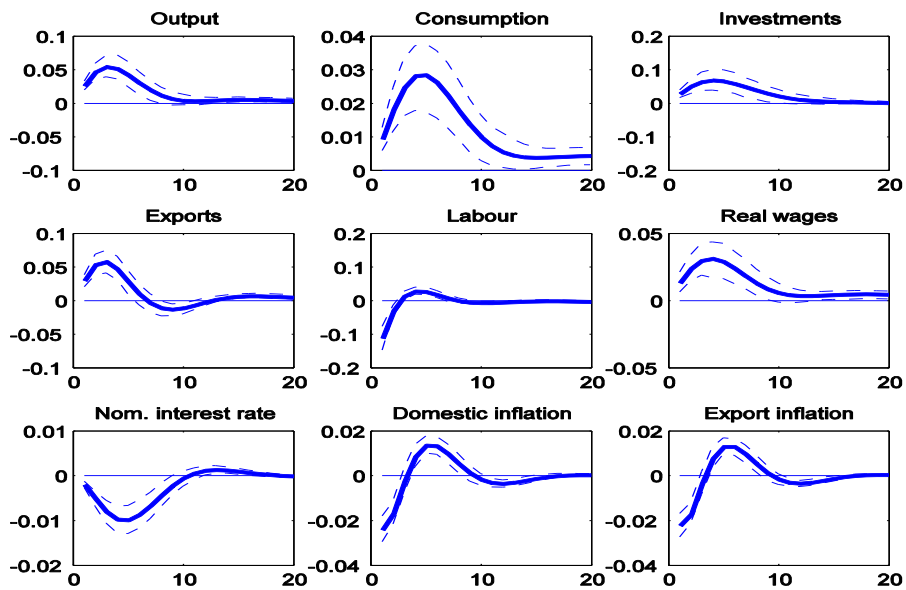


Figure 2: Impulse response functions (expressed in percentage deviations from the steady states) to one standard deviation orthogonalized innovation to technology shock.

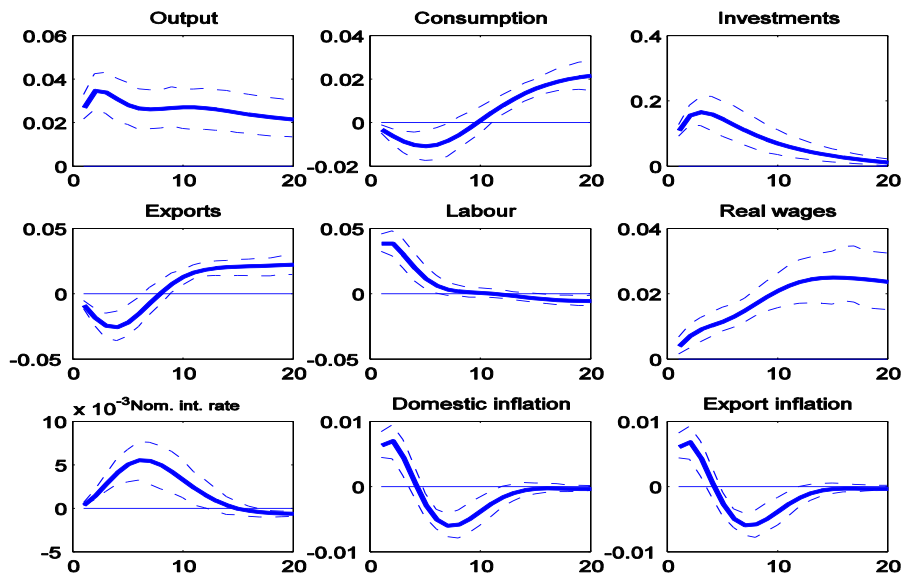


Figure 3: Impulse response functions (expressed in percentage deviations from the steady states) to one standard deviation orthogonalized innovation to investments specific shock.

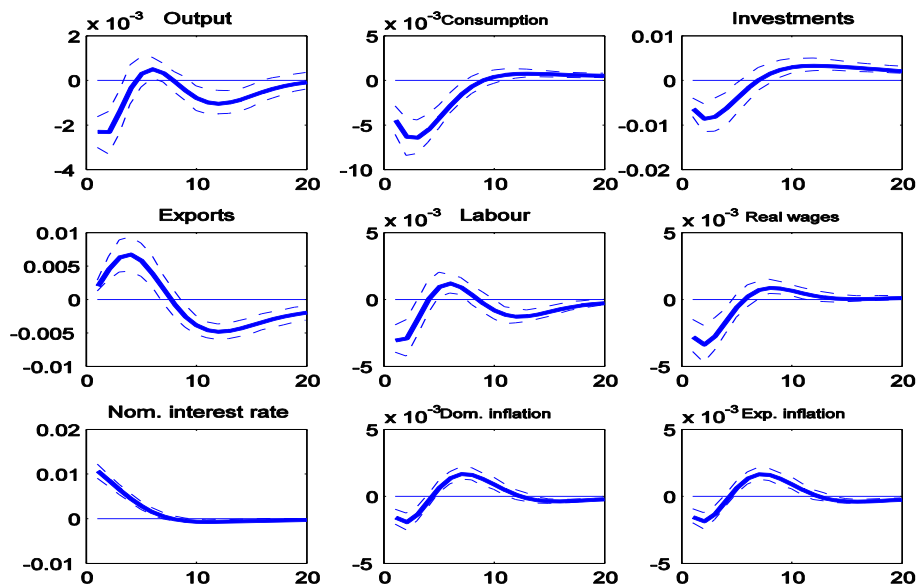


Figure 4: Impulse response functions (expressed in percentage deviations from the steady states) to one standard deviation orthogonalized innovation to country specific shock.

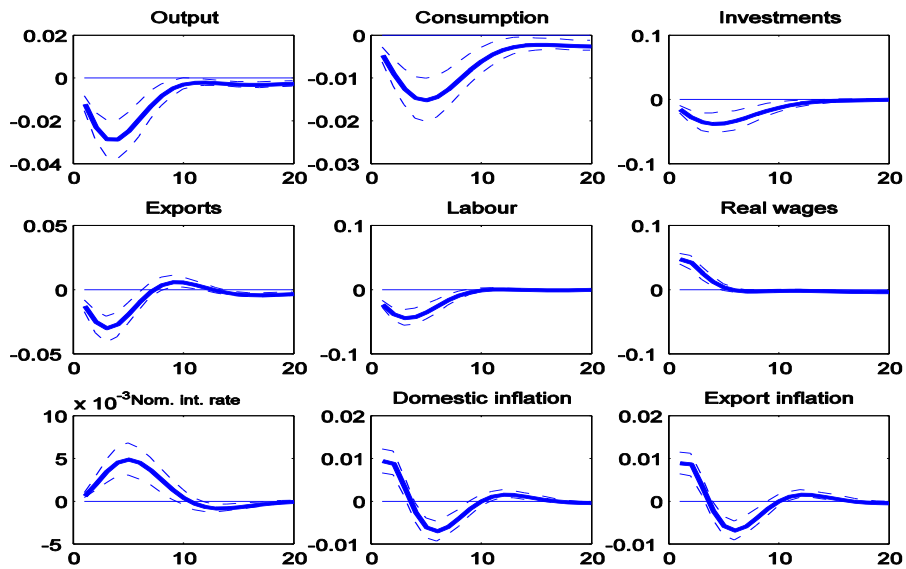


Figure 5: Impulse response functions (expressed in percentage deviations from the steady states) to one standard deviation orthogonalized innovation to wage mark-up shock.

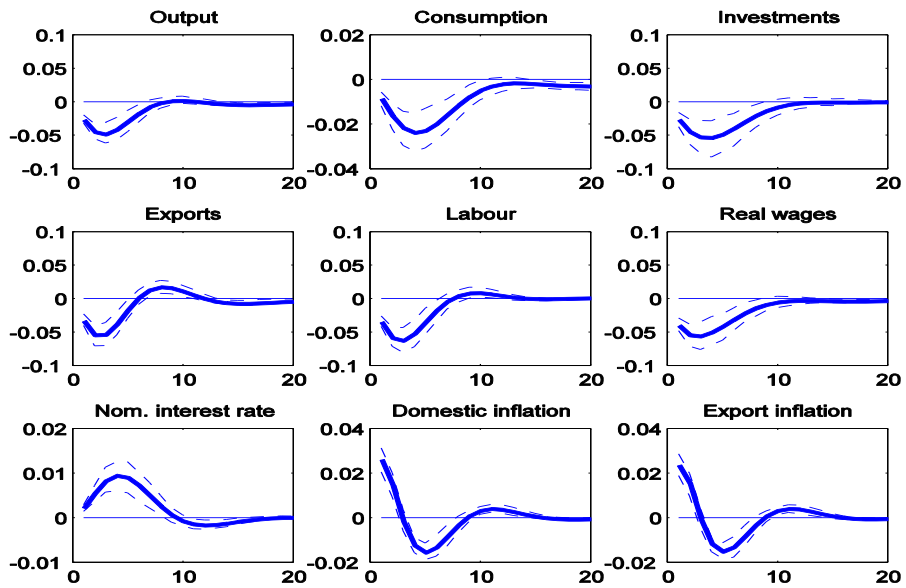


Figure 6: Impulse response functions (expressed in percentage deviations from the steady states) to one standard deviation orthogonalized innovation to price mark-up shock.

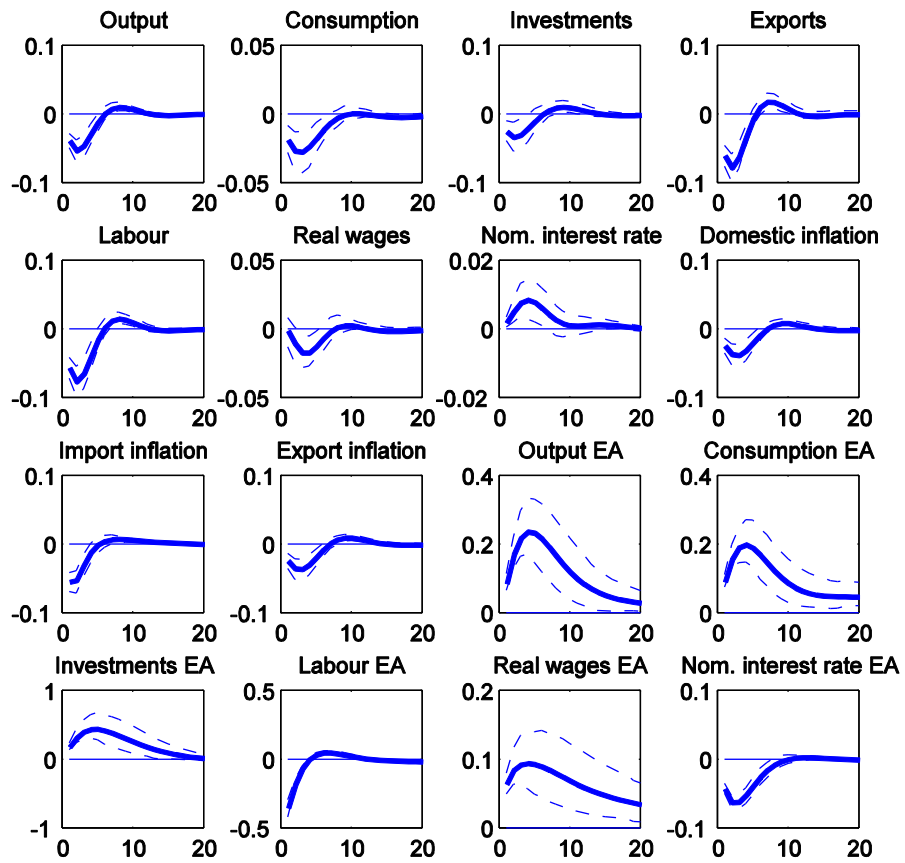


Figure 7: Impulse response functions (expressed in percentage deviations from the steady states) to one standard deviation orthogonalized innovation to EA technology shock.

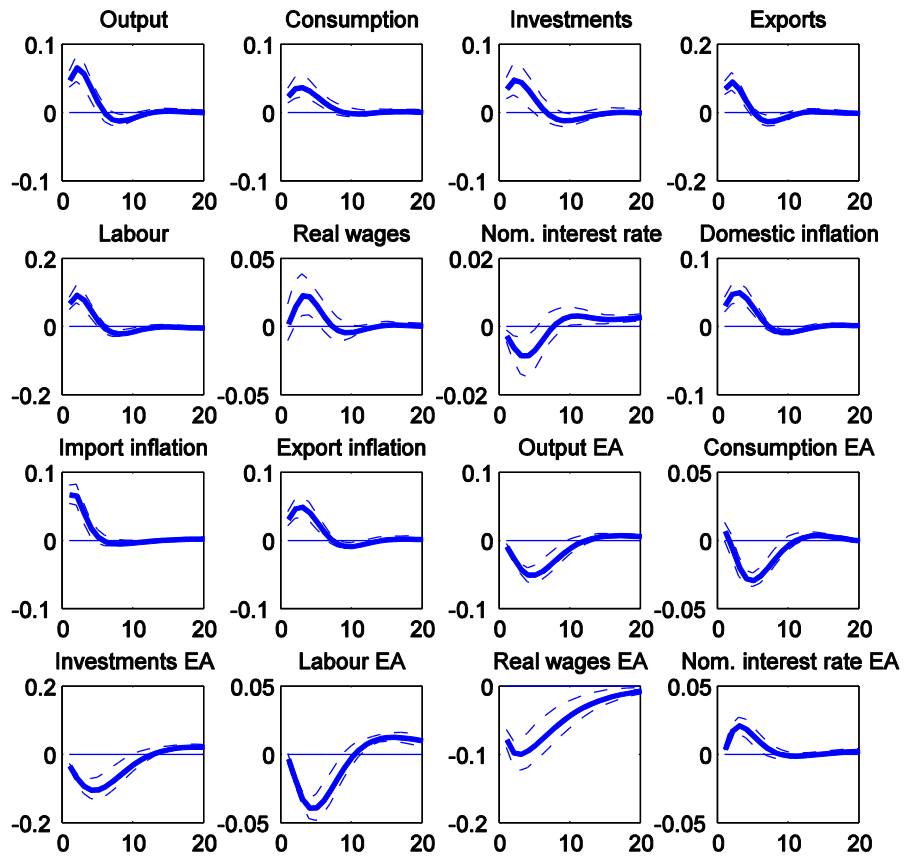


Figure 8: Impulse response functions (expressed in percentage deviations from the steady states) to one standard deviation orthogonalized innovation to EA price mark-up shock.

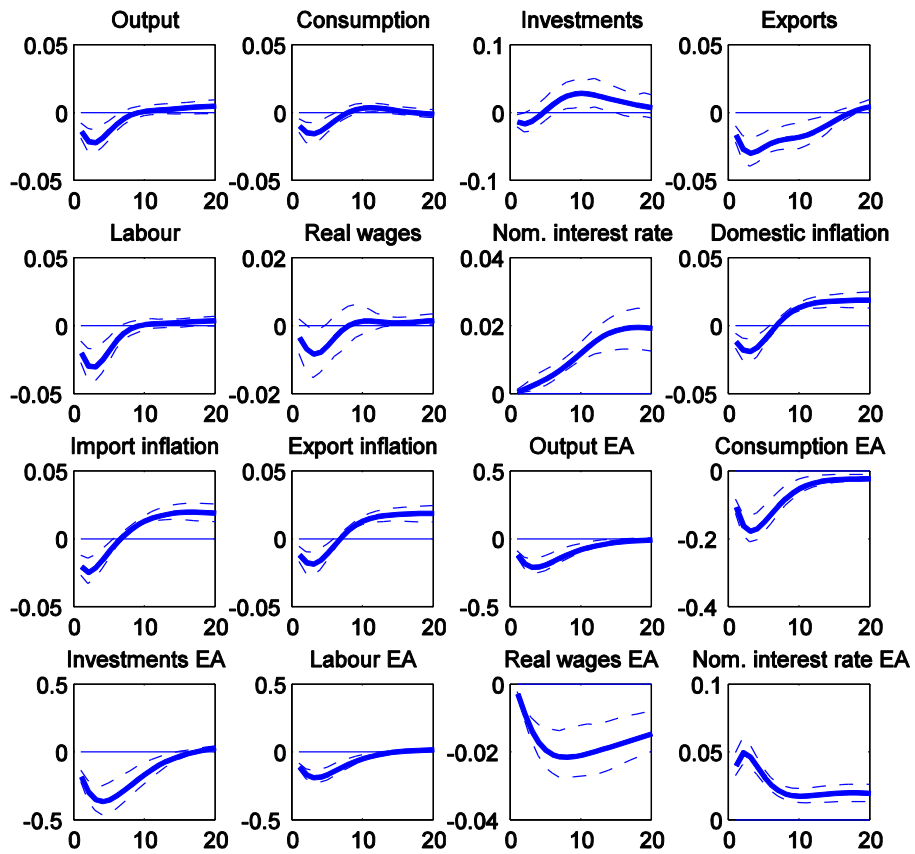


Figure 9: Impulse response functions (expressed in percentage deviations from the steady states) to one standard deviation orthogonalized innovation to EA monetary policy shock.