Juha Kilponen – Seppo Orjasniemi –
Antti Ripatti – Fabio Verona

The Aino 2.0 model

Bank of Finland Research
Discussion Paper
16 • 2016

The *Aino 2.0* model*

Juha Kilponen† Seppo Orjasniemi‡ Antti Ripatti§ Fabio Verona¶

20 May 2016

Abstract

This paper presents *Aino 2.0* – the dynamic stochastic general equilibrium (DSGE) model currently used at the Bank of Finland for forecasting and policy analysis. The paper provides a detailed theoretical description of the model, its estimation and how it can be used to interpret the evolution of the Finnish economy between 1995 and 2014, including the rise and fall of the electronics industry, the global financial crisis, and the stagnant growth performance since the end of the financial crisis.

* The views expressed are those of the authors and do not necessarily reflect those of the Bank of Finland. We are indebted to the many economists at the Bank of Finland who have worked in the development of the model at different stages. In particular, we would like to thank Mika Kortelainen, Elisa Newby and Jukka Railavo, who contributed to this modelling project in previous years, Hannu Viertola, who has implemented this version of the model into the Bank's forecasting system Foris, and Reijo Siiskonen, who was responsible for managing the Aino database. We would also like to thank Essi Eerola, Esa Jokivuolle, Markus Haavio, Karlo Kauko, Jarmo Kontulainen, Meri Obstbaum, Juha Tarkka, Juuso Vanhala, Jouko Vilmunen, Matti Viren and Tuomas Välimäki for valuable insights, Paolo Gelain, Stefano Neri, Ctirad Slavík and conference and seminar participants for comments and suggestions, and Glenn Harma for editorial assistance. Finally, we would like to thank our managers and the Board of the Bank of Finland for their patience and wisdom to support this modelling project until the end. Any remaining errors are the sole responsibility of the authors. The codes to simulate the model will be available on the Bank of Finland's website.

† Bank of Finland – Monetary Policy and Research Department (juha.kilponen@bof.fi)

‡ National Audit Office of Finland (seppo.orjasniemi@vtv.fi)

§ University of Helsinki, HECER, and Bank of Finland – Monetary Policy and Research Department (antti@ripatti.net)

¶ Bank of Finland – Monetary Policy and Research Department, and University of Porto – *CEF.UP* (fabio.verona@bof.fi)

1 A brief history of the Bank of Finland macroeconomic models

The history of the Bank of Finland macroeconomic models dates back to the 1970s when the series of BOF model was developed. The last one – the BOF5 model (see Willman et al., 2000) – was developed at the end of the 90s as a tool for forecasting and policy analysis in the inflation targeting monetary policy regime. A few years after the release of the BOF5 model, the monetary policy and research department of the Bank of Finland decided in 2000 to start developing a new macroeconomic model. After joining the monetary union, the focus of domestic policy shifted to structural and fiscal issues and the new model was expected to reflect the shift. The project reached its first goal in the fall 2004 when it was first used to produce a quarterly forecast. The model was named *Aino*, after a character in the Finnish national epic, Kalevala. This first version of *Aino* has a life-cycle structure à la Gertler (1999) to study demographic and pension issues (Kilponen and Ripatti, 2006). In addition to the life-cycle structure, the model contains relatively detailed fiscal and pension accounts, and it is still used in many policy simulations related to fiscal and demographic issues.[1] The *Aino* model was also the main integrating forecast tool for the macroeconomic forecast. The model was solved using the perfect foresight solutions of the nonlinear stationarized form[2] and the model parameters were mainly calibrated. This approach was not optimal for the forecasting: the laborious task of the forecast was to find the proper initial values for unobserved shock processes.

In response to the problems in the use of the original *Aino* model in forecasting, and due to the development of model estimation techniques, the demand for a new model increased. The development of the next version (called *eAino*) started just before the global financial crisis. This version shared features with industry-standard models, as *e.g.* the Ramses model developed by the Riksbank (Adolfson et al., 2005, 2007, 2008) and the New Area-Wide Model at the European Central Bank (Christoffel et al., 2008). It was log-linearized and estimated using Bayesian methods. The life-cycle features were abandoned, but some features such as two foreign assets (euro and dollar) and oil prices in the consumption basket were added. It was used for forecasting and policy evaluation since fall 2010. Experiences were good: the linear rational expectations model cast in state-space form is a very effective tool for forecasting and policy analysis.

The crisis eventually added financial frictions to the agenda of macroeconomic research. At the same time, new tasks such as macroprudential supervision, required central banks to employ structural models that facilitate the evaluation of macroprudential policies. These requirements in 2014 set in motion the development of the current version of *Aino* model. *Aino 2.0* is the final product of this effort. Since the fall of 2015, *Aino 2.0* has been used

[1] See *e.g.* Kilponen et al. (2014) and Dieppe and Guarda (2015).

[2] Any model that is implemented to a forecast process needs an information system. The *Aino* model relies on the Foris forecast information system (containing the user interface and version control, among many other features) that is built in-house. The model solution was carried out via Troll software in the first *Aino* model, and by Iris-toolbox (on Matlab) in the later versions.

as the main forecasting model of the Bank of Finland.[3]

In a nutshell, the model features a monopolistically competitive banking sector in the spirit of Gerali et al. (2010), within a small open economy setting similar to that in *eAino*. The model has been estimated using Bayesian methods over the period 1995-2014. According to the estimates, the Finnish economy entails very rigid wage setting and high external habit persistence in consumption, combined with relatively flexible prices. The Finnish business cycle is mainly driven by technology and external shocks, whereas shocks originating from the financial sector only play a minor role. The model attributes a large part of the rise and fall of the electronics industry and stagnant growth performance since the global financial crises to technology (*i.e.* productivity) shocks, shocks to export shares and to export demand.

2 The baseline small open economy model

The small open economy setting is similar to that in Adolfson et al. (2005, 2007, 2008) and Christoffel et al. (2008). Figure 1 shows the structure of the model. Households buy consumption and investment goods, supply labour services monopolistically and rent capital to intermediate-good input producers. They allocate their savings between three types of bonds – euro bonds, rest-of-the-world bonds and euro-denominated government bonds. The model economy is effectively a single good economy, with no distinction between traded and non-traded goods. Instead, varieties of this single intermediate good are produced by the domestic intermediate-good producers. The aggregated good is then combined with imported intermediate goods to produce final goods. The final goods are produced in three sectors describing the final use: consumption goods retailer, investment goods retailer and exporters. The domestic intermediate-good producers and the exporters operate under monopolistic competition, and pricing decisions are subject to Calvo (1983) pricing frictions. Importers also operate under monopolistic competition, but they operate outside Finnish borders. In contrast to many other models, we assume that some importers price their product in the local currency (euro) and the rest in their own currency. This enables more flexible control of the degree of exchange rate pass through to domestic inflation than in models that assume either local or foreign currency pricing (see Freystatter, 2012). Importers' pricing is subject to the Calvo (1983) pricing friction and indexation scheme, as is the domestic intermediate-good producing firm. The public sector produces public output and purchases consumption and investment goods from the private sector. The general government collects labour and capital income taxes, firms' social security contributions and indirect (VAT) taxes. It also makes lump-sum transfers. We assume that the government runs a balanced budget, similarly to Adolfson et al. (2005,

[3] To be clear, *Aino 2.0* is by no means the only input into the forecasting and policy processes at the Bank of Finland; several other models are also used.

2007, 2008) and Christoffel et al. (2008). Monetary policy and the external sector both portray Finland's small size in the euro area. Foreign interest rates, exchange rates, external demand and competitors prices are exogenously given.

We start by describing the structure of goods production. Then we describe the export and the import markets, and finally households and the government sector, as well as the market equilibrium.

2.1 Production of the domestic homogeneous intermediate good

The Cobb-Douglas production function, which is typically used in empirical DSGE models, is not capable of explaining trends in average productivity of capital Y_t/K_t. It also implies constant nominal factor shares. Finnish data prior to the financial crisis portray substantial fluctuations in the average productivity of capital and labour following the rise and the fall of the ICT sector. There have also been relatively wide fluctuations in the labour share, especially in the early 1990s and again after the global financial crisis. Ripatti and Vilmunen (2001) show that a Harrod-neutral Constant Elasticity of Substitution (CES) production function, combined with time-varying markup, fits the Finnish data well and captures the trending average productivity of capital during the 1990s. In particular, they estimate the elasticity of substitution to be significantly less than one. Jalava et al. (2006), using annual Finnish data for 1900-2004 and assuming constant returns to scale, obtain support for the hypothesis by Jones (2005) that the production function might be Cobb-Douglas in the very long run, but CES with the elasticity of substitution well below unity in the short and medium run. In what follows, we assume that the production of domestic intermediate goods is subject to a CES production function, with time varying markup and a Harrod-neutral technological progress.[4]

The domestic composite intermediate good, Y_t, is produced by combining individual brands $Y_t(j)$, $j \in [0,1]$, according to the following Dixit and Stiglitz (1977) aggregator:

$$Y_t = \left[\int_0^1 Y_t(j)^{-\rho_t^z} dj \right]^{-\frac{1}{\rho_t^z}} . \tag{1}$$

As in Ripatti and Vilmunen (2001), we allow for time-varying markup related to the parameter ρ_t^z, to capture changes in gross-operating surplus and labour share in the 1990s and during the financial crisis.[5]

The cost minimization of intermediate-good inputs in production of the composite intermediate good Y_t yields the

[4] See also Klump et al. (2012).

[5] Non-constant markup plays an increasingly important role in estimated DSGE models, as *e.g.* in Smets and Wouters (2003, 2007), Adolfson et al. (2005) and Christoffel et al. (2008).

following conditional demand function for the individual intermediate good:

$$Y_t(j) = \left(\frac{P_t(j)}{P_t}\right)^{-\frac{1}{1+\rho_t^z}} Y_t \ . \tag{2}$$

The corresponding price index for the composite domestic intermediate good can be obtained by substituting (2) into (1) and integrating over firms:

$$P_t = \left[\int_0^1 P_t(j)^{\frac{\rho_t^z}{1+\rho_t^z}} dj\right]^{\frac{1+\rho_t^z}{\rho_t^z}} \ . \tag{3}$$

Following the above motivation, the domestic intermediate goods, $Y_t(j)$, are then produced by combining homogeneous capital services K_t and labour services L_t^F using the following Harrod-neutral CES production function:

$$Y_t(j) = \left[\delta_Y \left(\Lambda_{k,t} K_t\right)^{-\rho_Y} + (1-\delta_Y)\left(\Lambda_{l,t} L_t^F\right)^{-\rho_Y}\right]^{-1/\rho_Y} \ . \tag{4}$$

The elasticity of factor substitution is given by $\sigma_Y \equiv (\rho_Y + 1)^{-1}$, where ρ_Y is the substitution parameter; δ_Y is the quasi factor input share parameter and $\Lambda_{k,t}$ and $\Lambda_{l,t}$ denote capital-augmenting and labour-augmenting technical progress, respectively. With the elasticity of substitution below unity and the factor-specific productivity shifters, the CES production function entails the possibility that technical progress is biased towards either of the production factors in the short and medium run.[6] Yet, we assume that, along the balanced growth path, the technical change is labour-augmenting. Following Adolfson et al. (2005), the labour-augmenting technical change $\Lambda_{l,t}$ is decomposed into a permanent $\Lambda_{l,t}^P$ and a temporary $\Lambda_{l,t}^T$ technology component such that $\Lambda_{l,t} = \Lambda_{l,t}^P \Lambda_{l,t}^T$. The gross growth rate of the permanent component of labour-augmenting technical change, $\mu_t = \Lambda_{l,t}^P / \Lambda_{l,t-1}^P$, follows a stationary first-order autoregressive process.

The intermediate good producing firms minimize the total nominal costs $R_t^K K_t + \left(1+\tau_t^F\right) W_t L_t^F$ subject to technology constraint (4) by adjusting capital and labour inputs so that the marginal products of each factor equal the real factor prices. Capital rental rate prices R_t^K and nominal labour costs $\left(1+\tau_t^F\right) W_t$ – augmented by the firm's social security contribution τ_t^F – are taken as given in this optimisation. The cost minimization results in the following nominal marginal costs:

$$\mathcal{MC}_{\mathrm{t}}(j) = \left[\delta^{\dagger}\left(\frac{R_t^K}{\Lambda_{k,t}}\right)^{\frac{\rho_Y}{\rho_Y+1}} + (1-\delta)^{\dagger}\left(\frac{\left(1+\tau_t^F\right) W_t}{\Lambda_{l,t}}\right)^{\frac{\rho_Y}{\rho_Y+1}}\right]^{\frac{\rho_Y+1}{\rho_Y}} \ , \tag{5}$$

[6] Atkinson and Stiglitz (1969) suggested that technological change should be modelled as directed towards specific capital–labour ratios or towards the specific techniques, and a given technical advance should give rise to some spillovers to other techniques. The CES production function with factor-specific shifters and elasticity of substitution greater than zero essentially captures this idea.

where $\delta^{\dagger} \equiv \delta_Y^{\frac{1}{\rho_Y+1}}$ and $(1-\delta)^{\dagger} = (1-\delta_Y)^{\frac{1}{\rho_Y+1}}$. The nominal marginal cost can be interpreted as a shadow cost of varying the use of factor inputs (capital and labour) in the production of intermediate goods. Since all j firms face the same input prices and production technology, their marginal costs are also equalized such that $\mathcal{MC}_{\mathrm{t}}(j) = \mathcal{MC}_{\mathrm{t}}$.

Pricing

An intermediate good firm sells its differentiated good at price $P_t(j)$. To allow for sluggish price adjustment, price contracts are staggered as in Calvo (1983). The intermediate good firm j re-optimizes its price in each period with probability $1-\zeta$, $\zeta \in [0,1]$. Since there is a continuum of intermediate producers, $1-\zeta$ also represents the share of producers changing their price in each period. Following Christoffel et al. (2008), we allow partial indexing, *i.e.* the firms that cannot optimize their prices index them to the geometric average of past inflation and steady-state inflation according to

$$P_t = \Pi_{t-1}^{\theta} \bar{\Pi}^{1-\theta} P_{t-1} \ , \tag{6}$$

where $\Pi_{t-1} \equiv P_{t-1}/P_{t-2}$, $\bar{\Pi}$ is the gross steady-state inflation and θ the indexation parameter. The steady state inflation is set equal to the sample average.

Let $P_t^{\circ}(j)$ denote the price level set by those intermediate goods producers who received the price-change signal in period t. Because the firms re-optimize their price only occasionally, they have to be forward looking in their decisions. The firm optimising in period t will choose its price $P_t^{\circ}(j)$ so as to maximise the current market value of the profits generated while that price remains effective. Given that with probability ζ^s the price $P_t^{\circ}(j)$ is still in effect at date $t+s$ ($s \geq 0$), the intermediate-goods producer solves the following problem:

$$\max_{\{P_t^{\circ}(j)\}} E_t \sum_{s=0}^{\infty} \zeta^s M_{t,t+s} \left[P_{t+s|t}^{\circ}(j) - \mathcal{MC}_{t+s}(j) \right] Y_{t+s|t}(j) \tag{7}$$

subject to (6) and subject to the sequence of conditional demand functions of its products

$$Y_{t+s|t}(j) = \left(\frac{P_{t+s|t}^{\circ}(j)}{P_{t+s}} \right)^{-\frac{1}{1+\rho_{t+s}^{z}}} Y_{t+s|t} \ .$$

In (7), E_t denotes the expectations conditional on the information at time t, the nominal stochastic discount factor (pricing kernel) $M_{t,t+s} = \beta^s U'(C_{t+s}) P_t^C / \left[U'(C_t) P_{t+s}^C \right]$ is obtained from the household's consumption Euler equation where P_t^C is the price index of composite consumer goods. $Y_{t+s|t}(j)$ denotes demand of intermediate good firm j in period $t+s$ for a firm which last reset its price at time t. Since the firms that cannot re-optimize their

prices are able to index them, the optimized price level $P^{\circ}_{t+s|t}(j)$ in the above formulas is given by

$$P^{\circ}_{t+s|t}(j) \equiv \prod_{i=1}^{s} \Pi^{\theta}_{t+s-i} \bar{\Pi}^{s(1-\theta)} P^{\circ}_{t}(i) \quad .$$

Following (3), the aggregate price level of intermediate goods evolves according to

$$P_t = \left[\zeta \left(\Pi^{\theta}_{t-1} \bar{\Pi}^{1-\theta} P_{t-1} \right)^{\frac{\rho^z_t}{1+\rho^z_t}} + (1-\zeta) P^{\circ}_{t}(j)^{\frac{\rho^z_t}{1+\rho^z_t}} \right]^{\frac{1+\rho^z_t}{\rho^z_t}} \quad . \tag{8}$$

The first term on the right hand side reflects the prices set by those firms that have not received the price-change signal, *i.e.* the price is updated using (6). The second term is the price level set by those firms that have received the price-change signal and re-optimize. In effect, the re-optimizing firms set their prices to include a markup over the weighted average of expected future nominal marginal costs (5), the weights being proportional to the probability that the optimized price remains effective s periods ahead. As a result, the intermediate-goods price is a function of current and expected production costs (capital and labour), past prices and the pricing power (markup) of the intermediate-goods producing firms.

2.2 Production of final consumption and investment goods

Final goods are produced by domestic retailers operating under perfect competition. One retailer specializes in the production of consumption goods and one in investment goods.[7] The consumption goods retailer combines the domestic intermediate goods Y^C_t and imported consumption goods M^C_t to produce the composite consumption good C_t, which is consumed by the households (C^H_t). Similarly, the investment goods retailer combines the domestic and the foreign intermediate goods Y^I_t and M^I_t, respectively, to produce the composite investment good I_t, which is purchased either by households (I^H_t) or the government (I^G_t).

The production of consumption and investment goods is based on the following CES production functions, respectively:

$$C^H_t = \left\{ \delta_c \left(\Lambda_{cy,t} Y^C_t \right)^{-\rho_c} + (1-\delta_c) \left[\left(1 - \Gamma_{cm}(\cdot)\right) \Lambda_{cm,t} M^C_t \right]^{-\rho_c} \right\}^{-1/\rho_c} \tag{9}$$

$$I_t = \left\{ \delta_i \left(\Lambda_{iy,t} Y^I_t \right)^{-\rho_i} + (1-\delta_i) \left[\left(1 - \Gamma_{im}(\cdot)\right) \Lambda_{im,t} M^I_t \right]^{-\rho_i} \right\}^{-1/\rho_i} \quad , \tag{10}$$

[7] Final good producers can be regarded as representing the manner in which consumers or a capital rental firm (and public sector) substitute between domestic and foreign intermediate goods and services.

where $\Lambda_{cy,t}$, $\Lambda_{cm,t}$, $\Lambda_{iy,t}$ and $\Lambda_{im,t}$ represent factor-specific preference shifters and

$$\Gamma_{cm}(\cdot) = \frac{\gamma_{cm}}{2}\left(\frac{M_t^C/C_t^H}{M_{t-1}^C/C_{t-1}^H} - 1\right)^2 \quad \text{and} \quad \Gamma_{im}(\cdot) = \frac{\gamma_{im}}{2}\left(\frac{M_t^I/I_t}{M_{t-1}^I/I_{t-1}} - 1\right)^2$$

are the external adjustment cost functions with $\gamma_{cm} > 0$ and $\gamma_{im} > 0$. Interpretation of the parameters ρ_c, δ_c, ρ_i and δ_i is the same as in the case of the intermediate good producing firms. Since the final consumption and investment goods are produced under perfect competition, the consumption and investment good prices (P_t^C and P_t^I, respectively) are each a function of domestic intermediate goods and imported good price (P_t^M defined in section 2.4):

$$P_t^C = \left\{\delta_c^{\sigma_c}\left(P_t/\Lambda_{cy,t}\right)^{\sigma_c\rho_c} + (1-\delta_c)^{\sigma_c}\left[P_t^M/\left(\Lambda_{cm,t}\Gamma_{cm}^{\dagger}\right)\right]^{\sigma_c\rho_c}\right\}^{\frac{1}{\sigma_c\rho_c}}$$

and

$$P_t^I = \left\{\delta_i^{\sigma_i}\left(P_t/\Lambda_{iy,t}\right)^{\sigma_i\rho_i} + (1-\delta_i)^{\sigma_i}\left[P_t^M/\left(\Lambda_{im,t}\Gamma_{im}^{\dagger}\right)\right]^{\sigma_i\rho_i}\right\}^{\frac{1}{\sigma_i\rho_i}} \quad ,$$

where $\sigma_c = \frac{1}{\rho_c+1}$, $\Gamma_{cm}^{\dagger} \equiv 1 - \Gamma_{cm} - \Gamma'_{cm}M_t^C$, $\sigma_i = \frac{1}{\rho_i+1}$ and $\Gamma_{im}^{\dagger} = 1 - \Gamma_{im} - \Gamma'_{im}M_t^I$.

2.3 Export market

Export goods, $X_t(i)$, are produced by export producers with a CES production function:

$$X_t(i) = \left[\delta_x\left(\Lambda_{xy,t}Y_t^X\right)^{-\rho_x} + (1-\delta_x)\left(\Lambda_{xm,t}M_t^X\right)^{-\rho_x}\right]^{-1/\rho_x} \quad , \tag{11}$$

where the factors of production include domestic intermediate goods Y_t^X and imported goods M_t^X. The elasticity of substitution is given by $\sigma_x \equiv (1+\rho_x)^{-1}$, where ρ_x is the substitution parameter in the production function, δ_x is the quasi share parameter, and $\Lambda_{xy,t}$ and $\Lambda_{xm,t}$ denote time-varying technology shifters common to all exporting firms.

Export goods producing firms minimize total factor costs $P_tY_t^X + P_t^MM_t^X$ by adjusting factor inputs such that the marginal product of each factor equals the factor price subject to the technology constraint (11). Factor prices P_t and P_t^M are taken as given in this optimisation. The resulting marginal costs are given by

$$\mathcal{MC}_{x,t}(i) = \left[(\delta_x)^{\frac{1}{1+\rho_x}}\left(\frac{P_t}{\Lambda_{xy,t}}\right)^{\frac{\rho_x}{1+\rho_x}} + (1-\delta_x)^{\frac{1}{1+\rho_x}}\left(\frac{P_t^M}{\Lambda_{xm,t}}\right)^{\frac{\rho_x}{1+\rho_x}}\right]^{\frac{1+\rho_x}{\rho_x}} \quad . \tag{12}$$

Finnish export goods $X_t(i)$ are passed to the foreign retailer firm, which aggregates the continuum of Finnish

exported goods $X_t(i)$. Analogously to the domestic intermediate good producer, the composite Finnish export good is produced using the following CES technology, which bundles the continuum of Finnish export goods:

$$X_t = \left[\int_0^1 X_t(i)^{-\rho_{f,t}} di\right]^{-\frac{1}{\rho_{f,t}}} , \tag{13}$$

where $\rho_{f,t}$ is the time-varying markup in the production of export goods. We assume that the Finnish exporters price their goods in the currency of the aggregator (foreign currency pricing). Hence, the price indices $P_t^X(i)$ are denominated in the foreign currency. The cost minimisation subject to aggregator (13) is consistent with the following conditional demand function:

$$X_t(i) = \left[\frac{P_t^X(i)}{P_t^X}\right]^{-\frac{1}{1+\rho_{f,t}}} X_t , \tag{14}$$

and the price index of composite export good is

$$P_t^X = \left[\int_0^1 P_t^X(i)^{\frac{\rho_{f,t}}{1+\rho_{f,t}}} di\right]^{\frac{1+\rho_{f,t}}{\rho_{f,t}}} . \tag{15}$$

Pricing of export goods

The dynamics of the price level $P_t^X(i)$ of producer i arises from the assumption that the export firm changes its price level when it receives a random price-change signal, which occurs with probability $1-\zeta_x$, $\zeta_x \in [0,1]$. Those firms which cannot optimize their prices index them to the geometric average of past export price inflation and steady-state export price inflation:

$$P_t^X = \Pi_{x,t-1}^{\theta_x} \bar{\Pi}_x^{1-\theta_x} P_{t-1}^X , \tag{16}$$

where $\Pi_{x,t} = P_t^X / P_{t-1}^X$ is the gross export price inflation, $\bar{\Pi}_x$ denotes the steady-state export price inflation and θ_x is the indexation parameter.

Let $P_t^{\circ X}(i)$ denote the price level set by those export goods producers that received the price-change signal in period t. The firm optimising in period t will choose its price $P_t^{\circ X}(i)$ so as to maximise the current market value of the profits generated while that price remains effective.

Let S_t denote the exchange rate defined as €/\$.[8] The export producing firm therefore chooses its price by max-

[8] In practice, this exchange rate is a trade weighted effective exchange rate index, describing the relative strength of the euro with respect to the basket of currencies.

imising the discounted sum of its expected profits (in euro):

$$\max_{\{P_t^{\circ X}(i)\}} \sum_{s=0}^{\infty} \zeta_x^s E_t \left\{ M_{t,t+s} \left[P_{t+s|t}^{\circ X}(i) - S_{t+s}^{-1} \mathcal{MC}_{x,t+s}(i) \right] X_{t+s|t}(i) \right\} \ ,$$

subject to the (16) and to the sequence of conditional demand functions of its products:

$$X_{t+s|t}(i) = \left[\frac{P_{t+s|t}^{\circ X}(i)}{P_{t+s}^{X}} \right]^{-\frac{1}{1+\rho_{f,t+s}}} X_t \ , \tag{17}$$

where $X_{t+s|t}(i)$ denotes demand of export good firm i in period $t+s$ for a firm which reset its price last time at t, and the indexed optimal price level is

$$P_{t+s|t}^{\circ X}(i) \equiv \prod_{i=1}^{s} \Pi_{x,t+s-i}^{\theta_x} \bar{\Pi}_x^{s(1-\theta_x)} P_t^{\circ X}(i) \ .$$

The nominal exchange rate enters into the price optimisation problem due to the assumption of foreign currency pricing.

The price index for export goods evolves according to the following equation of motion:

$$P_t^X = \left\{ \zeta_x \left(\Pi_{x,t-1}^{\theta_x} \bar{\Pi}_x^{1-\theta_x} P_{t-1}^X \right)^{\frac{\rho_{f,t}}{\rho_{f,t+1}}} + (1-\zeta_x) P_t^{\circ X}(i)^{\frac{\rho_{f,t}}{\rho_{f,t+1}}} \right\}^{\frac{\rho_{f,t+1}}{\rho_{f,t}}} \ . \tag{18}$$

The first term on the right hands side reflects the prices set by those firms that have not received the price-change signal, *i.e.* the price is updated using (16), and the second term is the price level set by those firms that have received the price-change signal. In effect, the aggregate export price is a markup over the weighted average of expected future nominal marginal costs (12), reflecting the price of domestic intermediate goods and the price of imported goods used in the production of export goods, as well as the past export prices and exporters' pricing power (markup).

Export demand

Given the factor cost minimisation and optimal pricing decision, the producers of the composite export good finally face the competition of other countries producing similar export goods. The following export demand function can

be obtained from the CES aggregator by combining the imperfectly competitive export goods from all countries:

$$X_t = \exp(\epsilon_{x,t}) \left[\frac{P_t^X}{P_t^W} \right]^{-\frac{1}{1+\rho_w}} M_t^W \ , \tag{19}$$

where $\sigma_w = (\rho_w + 1)^{-1}$ is the elasticity of substitution, M_t^W denotes the exogenously given world demand, P_t^W is the respective world price index, reflecting competitors' prices, and $\epsilon_{x,t}$ is an exogenous external export share shock. As above, P_t^X is in terms of the foreign currency.[9]

2.4 Import market

There are also three sets of import firms: an import retailer (or aggregator), foreign importers pricing their products in euro (FCP firms, share ω_m), and foreign importers pricing their products in foreign currency (PCP firms, share $1-\omega_m$). Pricing is subject to Calvo friction and to the partial indexation scheme, as is the domestic intermediate good producing firm. As a consequence, import price inflation varies because of both fluctuations in the exchange rate and in importers' real marginal costs. Exchange rate pass-through is stronger, the larger the share of importers pricing their products in foreign currency, *i.e.* the larger the fraction $1-\omega_m$ of PCP firms.

Aggregated import prices depend on expected future import price inflation, current and expected future changes in foreign exchange rates and on the real marginal costs of the importers. The nominal marginal cost of importers is determined by the foreign price P_t^W.

We denote by M_t the aggregate imported good with the corresponding aggregate price level P_t^M, and the prices related to FCP and PCP firms are denoted by $P_t^{M,FCP}$ and $P_t^{M,PCP}$ respectively (prices are denoted in foreign currency since these firms operate outside of Finnish borders[10]). The quantities are M^{FCP} and M^{PCP} respectively, and the foreign discount factor between periods t and $t+k$ is denoted by $R^\star_{t,t+k}$.[11]

2.4.1 Import retailer

An importing retailer aggregates the products of the foreign importing firms (FCP and PCP firms). The goods are produced in a number of varieties or *brands* defined over a continuum of unit mass. Brands of goods by FCP firms are indexed by $k \in [0, \omega_m)$ and those of PCP firms by $k \in (\omega_m, 1]$. The composite import good M_t is produced

[9] When stationarizing the model, we assume that in the balanced growth world demand grows at the same rate as the Finnish economy. This can be interpreted as if the Finnish economy shared the growth rate of permanent labour productivity with the rest of the world.

[10] Due to this assumption, the profits resulting from the imperfect competition are earned by foreign households.

[11] Under the assumption of full consumption risk-sharing, the domestic and foreign discount factors are the same, *i.e.* $R^\star_{t,t+k} = M_{t,t+k}$.

according to the following CES production function:

$$M_t = \left[\int_o^{\omega_m} M_t^{FCP}(k)^{-\rho_{m,t}} \, dk + \int_{\omega_m}^{1} M_t^{PCP}(k)^{-\rho_{m,t}} \, dk \right]^{-1/\rho_{m,t}} , \tag{20}$$

where $\rho_{m,t}$ denotes the common price markup of FCP and PCP firms.

The cost minimisation with respect to varieties is consistent with the following demand functions for each variety:

$$M_t^{FCP}(k) = \left[\frac{P_t^{M,FCP}(k)}{P_t^M} \right]^{-\frac{1}{1+\rho_{m,t}}} M_t \tag{21}$$

$$M_t^{PCP}(k) = \left[\frac{S_t P_t^{M,PCP}(k)}{P_t^M} \right]^{-\frac{1}{1+\rho_{m,t}}} M_t \tag{22}$$

for FCP and PCP firms, respectively. The corresponding price index for the composite imported good can be obtained by substituting conditional factor demand functions into (20) and integrating over the varieties:

$$P_t^M = \left\{ \int_0^{\omega_m} P_t^{M,FCP}(k)^{\frac{\rho_{m,t}}{1+\rho_{m,t}}} \, dk + \int_{\omega_m}^{1} \left[S_t P_t^{M,PCP}(k) \right]^{\frac{\rho_{m,t}}{1+\rho_{m,t}}} \, dk \right\}^{\frac{1+\rho_{m,t}}{\rho_{m,t}}} . \tag{23}$$

2.4.2 Foreign importers

Foreign importers face imperfect competition in their output markets, taking into account account the demand functions (21) and (22) in their pricing decisions. We assume that all FCP and PCP firms share the same nominal marginal cost function $\mathcal{MC}_m(k)$, equal to the foreign price P_t^W. They also mutually share the same stochastic discount factor $R^{\star}_{t,t+k}$.

The dynamics of the price level $P_t^{M,j}(k)$ of importer k ($j = FCP, PCP$) are analogous to those of the exporting and domestic intermediate good firms. We denote the probability of receiving a price-change signal as $1 - \zeta_m$, $\zeta_m \in [0,1]$, common to FCP and PCP firms. The price indexation scheme is also similar to that of the domestic intermediate goods producing firms. In other words, the firms that cannot optimize their price level may index their prices to the geometric average of past import price inflation and steady-state import price inflation:

$$P_t^{M,j} = \Pi_{m,t-1}^{\theta_m} \bar{\Pi}_m^{1-\theta_m} P_{t-1}^{M,j} , \tag{24}$$

where $\Pi_{m,t} = P_t^M / P_{t-1}^M$ and $\bar{\Pi}_m$ denotes the steady-state import price inflation for FCP and PCP firms. θ_m is price indexation parameter for both the FCP and PCP firm.

Let $P_t^{\circ M,j}(k)$ denote the price level set by those firms that received the price-change signal in period t. The FCP and PCP firms both maximise their expected discounted profits in home currency. The import producing firms therefore choose their price by maximizing the expected discounted stream of future profits:

$$\max_{\{P_t^{\circ M,j}(k)\}} \sum_{s=0}^{\infty} \zeta_m^s E_t \left[R_{t,t+s}^* \mathcal{D}_{t+s|t}^j (k) \right]$$

subject to (24) and subject to the conditional demand functions of its products:

$$M_{t+s|t}^{FCP}(k) = \left[\frac{P_{t+s|t}^{M,FCP}(k)}{P_{t+s}^{M,FCP}} \right]^{-\frac{1}{1+\rho_{m,t}}} M_{t+s|t}$$

$$M_{t+s|t}^{PCP}(k) = \left[\frac{S_{t+s} P_{t+s|t}^{M,PCP}(k)}{P_{t+s}^{M,PCP}} \right]^{-\frac{1}{1+\rho_{m,t}}} M_{t+s|t} \quad .$$

The nominal profits for FCP and PCP firms are given, respectively, by

$$\mathcal{D}_{t+s|t}^{FCP}(k) = \left[P_{t+s|t}^{\circ M,FCP}(k) - S_{t+s} \mathcal{MC}_{m,t+s}(k) \right] M_{t+s|t}^{FCP}(k) \tag{25}$$

$$\mathcal{D}_{t+s|t}^{PCP}(k) = \left[P_{t+s|t}^{\circ M,PCP}(k) - \mathcal{MC}_{m,t+s}(k) \right] S_{t+s} M_{t+s|t}^{PCP}(k) \quad . \tag{26}$$

Note that $P_{t+s|t}^{\circ M,PCP}$ is the optimal price in foreign currency while $P_{t+s|t}^{\circ M,FCP}$ is the price in euro. As before, they are given by

$$P_{t+s|t}^{\circ M,j}(k) \equiv \prod_{i=1}^{s} \Pi_{m,t+s-i}^{\theta} \bar{\Pi_m}^{s(1-\theta)} P_t^{\circ M,j}(k) \quad j \in \{PCP, FCP\}.$$

The marginal cost $\mathcal{MC}_{m,t+s}(k)$ is denominated in foreign currency, *i.e.* it is given by P_{t+s}^W, and it is assumed to be the same for all firms.

The aggregate price levels $P_t^{M,FCP}$ and $P_t^{M,PCP}$ evolve according to the following law of motion:

$$P_t^{M,FCP} = \left\{ \zeta_m \left(\Pi_{m,t-1}^{\theta_m} \bar{\Pi}_m^{1-\theta_m} P_{t-1}^{M,FCP} \right)^{\frac{\rho_{m,t}}{1+\rho_{m,t}}} + (1-\zeta_m) \left[P_{t+s|t}^{\circ M,FCP}(k) \right]^{\frac{\rho_{m,t}}{1+\rho_{m,t}}} \right\}^{\frac{1+\rho_{m,t}}{\rho_{m,t}}} \tag{27}$$

$$S_t P_t^{M,PCP} = \left\{ \zeta_m \left(S_t \Pi_{m,t-1}^{\theta_m} \bar{\Pi}_m^{1-\theta_m} P_{t-1}^{M,PCP} \right)^{\frac{\rho_{m,t}}{1+\rho_{m,t}}} + (1-\zeta_m) \left[S_t P_{t+s|t}^{\circ M,PCP}(k) \right]^{\frac{\rho_{m,t}}{1+\rho_{m,t}}} \right\}^{\frac{1+\rho_{m,t}}{\rho_{m,t}}} \quad , \tag{28}$$

where $S_t P_t^{M,PCP}$ denotes the aggregate price level of PCP firms in domestic currency.

2.5 Households

The economy is populated by a continuum of households, indexed by $h \in (0,1)$, that maximize their lifetime utility over the sequences of consumption $(C_{h,\tau})$, investment $(I_{h,t})$, capital $(K_{h,t+1})$, euro area $\left(B^{€}_{h,t+1}\right)$, the rest of the world $\left(B^{\$}_{h,t+1}\right)$ and domestic $(B_{h,t+1})$ asset holdings.[12] We divide the net foreign assets into intra and extra euro area assets in order to acknowledge the large export share of extra euro area countries. Households supply differentiated labour services to firms and government and act as wage setters in the monopolistically competitive labour markets. Labour services are demand determined in the equilibrium since the households commit to supply any given demand of labour at the equilibrium wage.

Household preferences are given by

$$E_t \sum_{s=t}^{\infty} \beta^{s-t} \left[\zeta_s^C \log\left(C_{h,s} - b_c C_{s-1}\right) - \frac{\left(H_{h,s}\right)^{1+\sigma_l}}{1+\sigma_l} \right] \ , \tag{29}$$

where $\beta \in (0,1)$ is the discount factor, ζ_τ^C a consumption preference shock, $b_c > 0$ the degree of external habit formation, $\sigma_l > 0$ the inverse of the Frisch labor supply elasticity, and $H_{h,s} = H^F_{h,s} + H^G_{h,s}$, so that total hours supplied by workers is the sum of hours worked in the private sector $(H^F_{h,s})$ and in the public sector $(H^G_{h,s})$.

Household h faces the following nominal period-by-period budget constraint:

$$\begin{aligned}
&\left(1+\tau_s^C\right) P_s^C C_{h,s} + P_s^I I_{h,s} + B_{h,s+1} + B^{€}_{h,s+1} + S_s B^{\$}_{h,s+1} \\
&= \left(1-\tau_s^W\right) W_s H_{h,s} + \left(1-\tau_s^K\right) R_s^K K_{h,s} + \delta \tau_s^K P_s^I K_{h,s} \\
&+ \mathcal{D}_{h,s} + R_{s-1} B_{h,s} + \Gamma_{A^*}\left(A_s^*, \zeta^{€}_{s-1}\right) \left(R^{€}_{s-1} B^{€}_{h,s} + R^{\$}_{s-1} S_s B^{\$}_{h,s} \right) \\
&- \mathcal{TR}_{h,s} + \mathcal{S}_{h,s} \ .
\end{aligned} \tag{30}$$

On the left-hand side, we have nominal spending on consumption (τ_t^C is the tax rate on consumption), investment, and on domestic assets $(B_{h,t+1})$, euro assets $(B^{€}_{h,t+1})$, and the trade weighted rest of the world denominated foreign assets $(B^{\$}_{h,t+1})$. On the right-hand side of the budget constraint, we have after-tax wage income $\left(1-\tau_t^W\right) W_t H_{h,t}$, lump-sum transfers from the government $\mathcal{TR}_{h,t}$, profits from the firms $\mathcal{D}_{h,t}$, as well as after-tax returns on capital (τ_t^W and τ_t^K are the tax rates on labor and on capital income, respectively). The tax revenues are used by the

[12] In the model with the banking sector introduced in the next section, households do not make the decisions regarding K_{t+1} and I_t. These decisions are made by, respectively, entrepreneurs and the capital goods producer.

government for public purchases of intermediate consumption and final investment goods as well as employment of households in the production of public goods and services. $\mathcal{S}_{h,t}$ denotes state-contingent securities. These are introduced into the budget constraint to allow each household to insure against wage-income risk, guaranteeing that each household chooses the same allocations. The euro area interest rate ($R^{€}$) and foreign interest rate ($R^{\$}$) are modeled as exogenous first order processes.

The premium on foreign bond holdings $\Gamma_{A^*}(\cdot)$ is assumed to be debt-elastic to provide a well defined steady state for the net foreign assets (see *e.g.* Schmitt-Grohe and Uribe, 2003). We assume following functional form for the foreign bond holdings:

$$\Gamma_{A^*}\left(A^*_{t+1}, \zeta^{€}_t\right) = \exp\left\{-\phi_a\left(A^*_{t+1} - A^*\right) + \zeta^{€}_t\right\}$$

$$A^*_{t+1} \equiv \frac{B^*_{t+1}}{P_t Y_t} = \frac{B^{€}_{t+1}}{P_t Y_t} + \frac{S_t B^{\$}_{t+1}}{P_t Y_t}$$

where A^*_{t+1} denotes total net foreign assets (in euro) per nominal income held by households and ϕ_a is the elasticity of return with respect to the net foreign asset position. This creates an endogenous wedge between the domestic (Finnish) and foreign bond rates. The shock $\zeta^{€}_t$ represents the exogenous domestic risk premium shock, which also drives a wedge between domestic and foreign interest rates.

The law of motion for the physical capital stock is given by

$$K_{h,t+1} = (1-\delta) K_{h,t} + \zeta^I_t F\left(I_{h,t}, I_{h,t-1}\right) \quad , \tag{31}$$

where δ is the depreciation rate, ζ^I_t is the investment-specific technology shock and $F\left(I_{h,t}, I_{h,t-1}\right) = \left[1 - \Gamma_I\left(I_{h,t}/I_{h,t-1}\right)\right] I_{h,t}$ denotes investment net of investment adjustment costs.[13]

Wage setting

Each household h supplies differentiated labour services to firms and to government in monopolistically competitive markets. There is sluggish wage adjustment due to staggered wage contracts. In particular, we assume that household h optimally resets its nominal wage $W_{h,t}$ in a given period t with probability $1-\xi_w$, $\xi_w \in [0,1]$. Those households that cannot reset their wage contract, are subject to the following wage indexation scheme:

$$W_{h,t} = \mu_t \Pi_{t-1} W_{h,t-1} \quad , \tag{32}$$

[13] See section 3.1 for details on the investment adjustment cost function.

where $\Pi_{t-1} = P_{t-1}/P_{t-2}$ is the past inflation rate of intermediate goods. Household labour is transformed into a homogeneous input good H_t via the following production function:

$$H_t = \left[\int_0^1 (H_{h,t})^{\frac{1}{\lambda_{w,t}}} dh\right]^{\lambda_{w,t}} , \tag{33}$$

where $\lambda_{w,t} \geq 1$ is the gross time-varying wage markup. The demand for labour in period $t+s$ for the household that resets its wage in period t is determined by

$$H_{h,t+s|t} = \left(\frac{W_{h,t+s|t}}{W_{t+s}}\right)^{\frac{\lambda_{w,t+s}}{1-\lambda_{w,t+s}}} H_{t+s} , \tag{34}$$

where W_{t+s} is the aggregate wage in period t and $W_{h,t+s|t}$ is the wage for the household that last reset its wage in period t. Notice that for the household that last optimised its wage in time t, the wage in $t+s$ can be expresssed also as $W_{h,t+s|t} = \prod_{k=1}^{s} (\mu_{t+k}\Pi_{t+k-1}) W^{\star}_{h,t}$, where $W^{\star}_{h,t}$ is the optimal wage rate chosen in period t by all households able to reset their wage contracts.[14] Now we can write

$$H_{h,t+s|t} = \left(\frac{\prod_{k=1}^{s} (\mu_{t+k}\Pi_{t+k-1}) W^{\star}_{h,t}}{W_{t+s}}\right)^{\frac{\lambda_{w,t+s}}{1-\lambda_{w,t+s}}} H_{t+s} .$$

Each household h, that can reoptimise its wage contract in period t maximises its lifetime utility stream (29) subject to its periodic budget constraint (30), demand for labour (34), and the wage indexation scheme (32). The maximisation problem is

$$\max_{\{W^{\star}_{h,t}\}} E_t \sum_{s=0}^{\infty} (\xi_w \beta)^s \left[\phi_{h,t+s} \left(1 - \tau^W_{t+s}\right) \mu^s_t \Pi^s_t W^{\star}_{h,t} H_{h,t+s} - \frac{\zeta^L_{t+s}}{1+\sigma_l} (H_{h,t+s})^{1+\sigma_l}\right] , \tag{35}$$

where $\mu^s_t = \prod_{k=1}^{s} \mu_{t+k}$ and $\Pi^s_t = \prod_{k=1}^{s} \Pi_{t+k-1}$. The marginal utility of consumption as well as labour demand are equal across households, *i.e.* $\phi_{h,t+s} = \phi_{t+s}$, $H_{h,t+s} = H_{t+s}$ so that

[14] This follows from $W_{h,t+1} = \mu_t \Pi_{t-1} W^{\star}_{h,t}$, $W_{h,t+2} = \mu_{t+1}\Pi_{t-1}\mu_t\Pi_{t-1} W^{\star}_{h,t}$, ..., $W_{h,t+s|t} = \prod_{k=1}^{s} (\mu_{t+k}\Pi_{t+k-1}) W^{\star}_{h,t}$.

$$\max_{\{W^{\star}_{h,t}\}} E_t \sum_{s=0}^{\infty} (\xi_w \beta)^s \left[\begin{array}{c} \phi_{t+s} \left(1-\tau^W_{t+s}\right) \mu^s_t \Pi^s_t W^{\star}_{h,t} \left(\frac{\mu^s_t \Pi^s_t W^{\star}_{h,t}}{W_{t+s}} \right)^{\frac{\lambda_{w,t+s}}{1-\lambda_{w,t+s}}} H_{t+s} \\ -\frac{\zeta^L_{t+s}}{1+\sigma_l} \left(\left(\frac{\mu^s_t \Pi^s_t W^{\star}_{h,t+s}}{W_{t+s}} \right)^{\frac{\lambda_{w,t+s}}{1-\lambda_{w,t+s}}} H_{t+s} \right)^{1+\sigma_l} \end{array} \right]$$

$$= \max_{\{W^{\star}_{h,t}\}} E_t \sum_{s=0}^{\infty} (\xi_w \beta)^s \left[\begin{array}{c} \phi_{t+s} \left(1-\tau^W_{t+s}\right) W_{t+s} \left(\frac{\mu^s_t \Pi^s_t W^{\star}_{h,t}}{W_{t+s}} \right)^{\frac{1}{1-\lambda_{w,t+s}}} H_{t+s} \\ -\frac{\zeta^L_{t+s}}{1+\sigma_l} \left(\left(\frac{\mu^s_t \Pi^s_t W^{\star}_{h,t}}{W_{t+s}} \right)^{\frac{\lambda_{w,t+s}}{1-\lambda_{w,t+s}}} H_{t+s} \right)^{1+\sigma_l} \end{array} \right]$$

This expression implies that the newly optimised wage contracts equate the households' discounted sum of expected after-tax marginal revenues to the discounted sum of expected marginal cost of working (due to the disutility of labour). Households' wage setting is thus forward looking. We note that in the absence of wage rigidity, the optimal labour supply decision can be written as

$$\psi_{\Lambda,t} \left(1-\tau^W_t\right) \frac{W_{h,t}}{P^C_t \Lambda^P_{l,t}} = \lambda_{w,t} H^{\sigma_l}_{h,t} \ . \tag{36}$$

Equation (36) is the standard intratemporal labour supply condition, but recognizing the market power of households. The factor $\lambda_{w,t}$ is markup of the real after-tax wage over the households' marginal rate of substitution between utility of consumption and disutility of labour, reflecting the degree of monopoly power of households in the wage setting. Hence, in the absence of nominal wage rigidity, the households would set the nominal wage such that the after tax real wage would equal the markup over the marginal rate of substitution between utility of consumption and disutility of labour.

When nominal wages are rigid, as assumed here, the aggregate wage index evolves according to

$$W_t = \left[\xi_w \left(\mu_t \Pi_{t-1} W_{h,t-1} \right)^{\frac{1}{1-\lambda_{w,t}}} + (1-\xi_w) \left(W^{\star}_{h,t} \right)^{\frac{1}{1-\lambda_{w,t}}} \right]^{1-\lambda_{w,t}} \ . \tag{37}$$

The aggregated nominal wage is weighted average of past aggregated wage and re-optimized wages. In effect, the optimized nominal wage depends on aggregate nominal wage, the current and future gap between the marginal rate of substitution and the real wage, the future expected wage inflation, and the wage markup.

2.6 Fiscal authority

The fiscal authority collects taxes and issues euro denominated bonds to finance government spending on goods and services (public purchases). Government spending is the sum of government demand for domestic intermediate goods, investment goods and public production. The nominal price of public purchases is equal to the price of consumption goods. We assume full home bias in public sector consumption demand, while in the case of investment goods, the public sector purchases final investment goods. Consequently, the relevant price index for the public sector investment goods is P_t^I. For public sector consumption, the relevant price index is the price index of domestic intermediate goods P_t.

Public purchases of domestic intermediate goods and investments goods are determined exogenously. Furthermore, we assume that public production technology is linear in public labour. Consequently, we have the following nominal relationship linking public consumption, investments and production:

$$P_t^G G_t = P_t C_t^G + P_t^I I_t^G + \left(1+\tau_t^F\right) W_t L_t^G \ ,$$

where C_t^G denotes exogenous public purchases, I_t^G denotes exogenous public investments, τ_t^F is the social security payment rate of the public sector, and L_t^G is the exogenous public sector labour demand. Given public spending, the fiscal authority's nominal budget constraint takes the form

$$\begin{aligned} P_t^G G_t + B_t &= \tau_t^C P_t^C C_t^H + \left(\tau_t^W + \tau_t^F\right) W_t \left(L_t^F + L_t^G\right) \\ &+\tau_t^K R_t^K K_t - \tau_t^K P_t^I \delta K_t + \mathcal{TR}_t + \frac{B_{t+1}}{R_t} \ . \end{aligned}$$

Government lump sum taxes $\mathcal{TR}_t$ close the fiscal authority's budget constraint in each period, and the distortionary tax rates τ_t^s, $s = C$, W, F, K are time-invariant and are set to their steady-state values.

2.7 Market equilibrium

2.7.1 Factor markets

In equilibrium, the supply of differentiated labour services is equal to the intermediate goods producing firms' labour demand and public sector labour demand such that

$$H_t = L_t^F + L_t^G \ ,$$

with $\int_0^1 H_{h,t}^F dh = H_t^F = L_t^F$, and $\int_0^1 H_{h,t}^G dh = H_t^G = L_t^G$. Aggregating over the continuum of households h yields

$$\int_0^1 H_{h,t}^F dh = \int_0^1 \left(\frac{W_{h,t}}{W_t}\right)^{\frac{\lambda_w}{1-\lambda_w}} H_t^F \ . \tag{38}$$

The demand for labour in period $t+s$ for the household that reset its wage in period t is determined by

$$H_{h,t}^F = \int_0^1 \left(\frac{W_{h,t}}{W_t}\right)^{\frac{\lambda_w}{1-\lambda_w}} H_t^F dh = \Delta_{w^F,t} H_t^F = L_t^F \ ,$$

where $\Delta_{w,t} = \int_0^1 \left(\frac{W_{h,t}}{W_t}\right)^{\frac{\lambda_w}{1-\lambda_w}}$ gives the wage dispersion across differentiated household labour services. The total wage paid by the intermediate good producing firms is

$$\begin{aligned}\int_0^1 W_{h,t} H_{h,t} dh &= \int_0^1 W_{h,t} \left(\frac{W_{h,t}}{W_t}\right)^{\frac{\lambda_w}{1-\lambda_w}} H_t^F dh = H_t^F \left(W_t\right)^{-\frac{\lambda_w}{1-\lambda_w}} \int_0^1 \left(W_{h,t}\right)^{\frac{1-\lambda_w}{1-\lambda_w}+\frac{\lambda_w}{1-\lambda_w}} dh \\ &= H_t^F \left(W_t\right)^{-\frac{\lambda_w}{1-\lambda_w}} \int_0^1 \left(W_{h,t}\right)^{\frac{1}{1-\lambda_w}} dh = H_t^F W_t\end{aligned}$$

where we have used the fact that

$$W_t = \left[\int_0^1 \left(W_{h,t}\right)^{\frac{1}{1-\lambda_w}} dh\right]^{1-\lambda_w} \ .$$

Market clearing in capital markets implies that the capital services provided by households is equal to the total demand:

$$\int_0^1 K_{h,t} dh = \int_0^1 K_{j,t} dj = K_t \ .$$

2.7.2 Intermediate goods market

Each intermediate-good producing firm acts as price setter in the monopolistically competitive intermediate goods market. Since the domestic intermediate goods are used as inputs to produce consumption, investment and export goods in competitive markets, the supply of differentiated goods must be equal to the total demand. Hence, the corresponding equilibrium condition states that

$$\int_0^1 Y_t\left(j\right) dj = Y_t^C + Y_t^I + Y_t^X \ , \tag{39}$$

where the right hand side corresponds to the conditional factor demands of consumption, investment and export goods producing firms. The left hand side is the total supply of the intermediate goods producing firms. Aggregating

over the continuum of intermediate goods producing firms, we obtain

$$\int_0^1 Y_t(j)\,dj = \Delta_{p,t} Y_t \ , \tag{40}$$

where $\Delta_{p,t} = \int_0^1 \left(\frac{P_t(j)}{P_t}\right)^{-\frac{1}{1+\rho_t^x}} dj$ is the price dispersion term. In nominal terms, it follows that

$$P_t Y_t = \int_0^1 P_t(j)\, Y_t(j)\, dj = P_t(Y_t^C + Y_t^I + Y_t^X) \ . \tag{41}$$

2.7.3 Export market

Finnish export goods $X_t(i)$ are aggregated by the foreign retailer firm, such that total supply of Finnish export goods is given by $\int_0^1 X_t(i)\,di$. In market equilibrium, the total supply of Finnish exports will be equal to demand's, hence

$$\int_0^1 X_t(i)\,di = \int_0^1 \left(\frac{P_t^X(i)}{P_t^X}\right)^{-\frac{1}{1+\rho_{f,t}}} X_t di = \Delta_{px} X_t = X_t \ , \tag{42}$$

where $\Delta_{px} = \int_0^1 \left(\frac{P_t^X(i)}{P_t^X}\right)^{-\frac{1}{1+\rho_{f,t}}}$ is the export price dispersion term and X_t is the total export demand, given by equation (19). This holds trivially also in nominal terms, such that $P_t^X X_t = \int_0^1 P_t^X(i)\, X_t(i)\, di$, given the properties of the price index P_t^X and conditional export demand $X_t(i)$.

2.7.4 Import market

We assume that the supply of foreign goods used as inputs in the production of domestic and exported final goods is fully elastic and matches the total demand. Total demand for imported composite goods is equal to the sum of imported consumption, investment, and foreign goods used in the production of domestic export goods such that

$$M_t = M_t^C + M_t^I + M_t^X \ .$$

The right hand side of the equation is total demand, resulting from aggregating the products of the foreign importing firms (FCP and PCP firms, see equation 20). In nominal terms it holds that

$$P_t^M M_t = P_t^M \left(M_t^C + M_t^I + M_t^X\right) \ ,$$

where the corresponding price indices for the imported composite good is obtained by integrating over the prices set by FCP and PCP firms (see equation 23).

2.7.5 Domestic final good market

The final good market for the production of consumption goods, investment goods and composite export goods are fully competitive. Hence, market clearing in the final goods markets implies that, in addition to (42), the total supply of consumption and investment goods is equal to total demand:

$$C_t = C_t^H = \int_0^1 C_{h,t} dh$$

$$I_t = I_t^H + I_t^G = \int_0^1 I_{h,t} dh + I_t^G$$

2.7.6 Bond market

The fiscal authority's budget constraint determines the supply of domestic bonds. Under the assumption that the fiscal authority balances its budget at all times, the market clearing condition can be expressed simply as

$$B_t = \int_0^1 B_{h,t} dh = 0 \ .$$

As for the internationally traded bonds, we assume that the supply of foreign bonds is fully elastic, matching the demand of domestic residents holdings of foreign bonds:

$$\int_0^1 B_{h,t}^{€} dh + \int_0^1 B_{h,t}^{\$} dh = B_t^{€} + B_t^{\$} \ .$$

2.7.7 Nominal aggregate resource constraint

Combining the market clearing conditions for the domestic final goods markets and the intermediate goods markets results in the following representation of the economy's nominal resource constraint (in domestic currency):

$$P_t Y_t + \left(1 + \tau_t^F\right) W_t L_t^G = P_t^C C_t^H + P_t^I I_t^H + P_t^G G_t + S_t P_t^X X_t - P_t^M \left(M_t^C + M_t^I + M_t^X\right) \ .$$

Recalling that $P_t^G G_t = P_t C_t^G + P_t^I I_t^G + \left(1+\tau_t^F\right) W_t L_t^G$, the above equation can be written as

$$P_t Y_t = P_t^C C_t^H + P_t^I I_t^H + P_t C_t^G + P_t^I I_t^G + S_t P_t^X X_t - P_t^M \left(M_t^C + M_t^I + M_t^X\right) \ .$$

2.7.8 Net foreign assets, trade balance and terms of trade

The economy's net foreign assets equal the economy-wide net holdings of the foreign bonds such that

$$NFA_{t+1}^* = R_t^{€} B_t^{€} + R_t^{\$} S_t B_t^{\$} + TB_t \ ,$$

where TB_t denotes the trade balance given by

$$TB_t = S_t P_t^X X_t - P_t^M \left(M_t^C + M_t^I + M_t^X\right) \ .$$

Finally, the terms of trade is defined as

$$ToT_t = S_t P_t^X / P_t^M \ .$$

3 Introducing a banking sector into the model

The model presented in section 2 does not include financial intermediaries even though, in principle, some activities could require financing. For instance, the management of capital by households may involve financing because the construction of capital requires a substantial initial outlay of resources, while the return from capital flows in over time. More importantly, the global financial crisis that started in 2007 has clearly shown, among other things, that developments in the financial sector have a far greater impact on economic activity than previously realized. In recent years, economists have indeed started to embed financial frictions and markets into general equilibrium models, acknowledging that distortions in financial intermediation can have large impacts on the macroeconomy. In particular, the literature that incorporates a banking sector into a DSGE framework has bloomed in the aftermath of the global financial crisis.[15] In this section, we follow this recent literature and introduce a banking sector into the

[15] A first attempt to introduce financial frictions in a New Keynesian DSGE framework was made by Bernanke et al. (1999). In that model, shocks are amplified by the financial accelerator effect, but otherwise the financial sector does not play an important role. Subsequently, the structure and role of the financial sector in DSGE models has been developed along several lines. Iacoviello (2005) extended the Bernanke et al. (1999) model by introducing collateral constraints for firms, as in Kiyotaki and Moore (1997). Christiano et al. (2003, 2008) and Goodfriend and McCallum (2007) considered a perfectly competitive banking sector that offers agents a variety of financial assets with different returns, while Kobayashi (2008) and Gerali et al. (2010) considered imperfect competition in the banking

model described in section 2. Doing so allows us to analyze the potential role of financial factors in the generation of shocks and their propagation to the Finnish economy.

The banking sector in this paper is modeled in the spirit of Gerali et al. (2010). We first separate borrowers from lenders by introducing a new set of agents – named entrepreneurs – who have special skills in the operation and management of physical capital (as in *e.g.* Unsal, 2013 and Verona et al., 2013). Since in Finland, firms' financing relies heavily on banks' intermediated funding, we assume that the entrepreneurs have to borrow from banks, as their own financial resources are not sufficient to fully finance the capital expenditures (as in *e.g.* Christiano et al., 2014). Banks provide loans to the entrepreneurs by combining deposits (collected from households) with their own bank capital, which is accumulated through retained earnings. Figure 2 sketches the structure of the model with the banking sector.

3.1 Capital goods producer

There is a single, representative, competitive capital producer (owned by the households). New capital K_{t+1} produced in period t can be used in the productive activities in period $t+1$. At the end of period t, the capital producer purchases existing capital, $(1-\delta)K_t$, from entrepreneurs and investment goods, I_t^{CGP} , and combines them to produce new capital, K_{t+1}, using the following technology:

$$K_{t+1} = (1-\delta)K_t + \zeta_t^I F\left(I_t^{CGP}, I_{t-1}^{CGP}\right) \quad ,$$

where $F\left(I_t^{CGP}, I_{t-1}^{CGP}\right) = \left[1 - \Gamma_I\left(I_t^{CGP}/I_{t-1}^{CGP}\right)\right] I_t^{CGP}$ denotes investment net of investment adjustment costs. $\Gamma_I = \frac{\gamma_I}{2}\left(\frac{I_t^{CGP}}{I_{t-1}^{CGP}} - \mu\right)^2$ is assumed to be increasing, convex and to satisfy $\Gamma_I = \Gamma_I' = 0$ and $\Gamma_I{}'' = \gamma_I > 0$ in the steady state. Old capital can be converted one-to-one into new capital, while the transformation of the investment good is subject to adjustment costs. Investment goods are purchased at price P_t^I. Let P_t^K be the nominal price of new capital. Since the marginal rate of transformation between new and old capital is unity, the price of old capital is also P_t^K.

sector so as to model the setting of interest rates by banks. Curdia and Woodford (2010) allowed for a time-varying spread between deposits and lending rates, while Verona et al. (2013) built a model with both a loan and a bond market. A number of papers (see *e.g.* Van den Heuvel, 2008, de Walque et al., 2010, Meh and Moran, 2010 and Gertler and Karadi, 2011) studied the role of bank capital in the transmission of macroeconomic shocks. Other recent contributions include *e.g.* Covas and Fujita (2010), Christiano et al. (2011), Fujiwara and Teranishi (2011), Paries et al. (2011), Agenor et al. (2012, 2013), Lombardo and McAdam (2012), Kannan et al. (2012), Angeloni and Faia (2013), Brzoza-Brzezina and Kolasa (2013), Brzoza-Brzezina et al. (2013), Kamber and Thoenissen (2013), Kollmann (2013), Unsal (2013), Agenor and Pereira da Silva (2014), Gambacorta and Signoretti (2014), Gelain and Ilbas (2014), Kiley and Sim (2014), Kolasa and Lombardo (2014), Quint and Rabanal (2014), Clerc et al. (2015) and Chang et al. (2016).

The capital producer's period-t profit maximization problem is thus given by

$$\max_{I_t^{CGP}} \quad E_0 \sum_{t=0}^{\infty} \beta^t \phi_t \left\{ P_t^K \left[(1-\delta) K_t + \zeta_t^I F\left(I_t^{CGP}, I_{t-1}^{CGP} \right) \right] \right\} - P_t^K (1-\delta) K_t - P_t^I I_t^{CGP} \ , \tag{43}$$

where ϕ_t is the Lagrange multiplier associated with the households' budget constraint. Taking the first order condition and rearranging yields

$$\frac{P_t^I}{P_t^C} = \frac{P_t^K}{P_t^C} \zeta_t^I F'\left(I_t^{CGP}, I_{t-1}^{CGP} \right) + \beta E_t \frac{\psi_{t+1}}{\psi_t} \frac{P_{t+1}^K}{P_{t+1}^C} \zeta_{t+1}^I F'\left(I_{t+1}^{CGP}, I_t^{CGP} \right) \ , \tag{44}$$

where $\psi_{h,t} = \phi_{h,t} P_t^C$ is the nominal shadow price of a unit of the consumption good. We note that equation (44) is very similar to the household's first order condition with respect to investment that would result in the model without banks.

3.2 Entrepreneurs

The economy is populated by a continuum of identical entrepreneurs of mass 1. To keep the notation simple, in what follows we describe the problem solved by the representative entrepreneur.

3.2.1 Profit maximization problem

In period t, the entrepreneur rents capital to the domestic intermediate good firms (see section 2.1). Then, at the end of period t, he sells the undepreciated capital to capital producers at price P_t^K, pays back the loan and purchases the new capital K_{t+1} from the capital producers at price P_t^K. At the end of period t, the entrepreneur has available net worth, N_{t+1}, which he uses to finance his capital expenditures, $P_t^K K_{t+1}$. To finance the difference between expenditures and net worth, he borrows from the bank an amount BL_{t+1} which is given by

$$BL_{t+1} = P_t^K K_{t+1} - N_{t+1} \ . \tag{45}$$

The entrepreneur's time-t nominal profits, Π_t^{entr}, are given by

$$\Pi_t^{entr} = \left(1 - \tau_t^K\right) R_t^K K_t + (1-\delta) P_t^K K_t + \delta \tau_t^K P_t^K K_t + P_t^K K_{t+1} - r_{t-1}^b \left(P_{t-1}^K K_t - N_t \right) \ ,$$

where r_{t-1}^b is the net nominal interest rate on loans. In period t the entrepreneur chooses K_{t+1} so as to maximize Π_t^{entr}, taking as given the loan interest rate. We note that R_t^K is the rental cost of capital, which is equal to the

marginal productivity of capital.

The first order condition is

$$P_t^K = \beta E_t \left\{ \left(1 - \tau_{t+1}^K\right) R_{t+1}^K + \left(1 - \delta + \delta\tau_{t+1}^K\right) P_{t+1}^K - r_t^b P_t^K \right\} \quad . \tag{46}$$

The capital Euler equation (46) equates the value of a unit of installed capital at time t (left hand side) to the expected discounted return of that extra unit of capital in period $t+1$ (right hand side). Let $Q_t = P_t^K / P_t^C$ be the real price of capital; then equation (46) can be rewritten as[16]

$$Q_t = \frac{\beta}{1 + \beta r_t^b} E_t \left[\left(1 - \tau_{t+1}^K\right) \frac{R_{t+1}^K}{P_t^C} + \frac{\left(1 - \delta + \delta\tau_{t+1}^K\right) Q_{t+1} P_{t+1}^C}{P_t^C} \right] \quad . \tag{47}$$

The entrepreneur's equity at the end of period t, V_t, is given by

$$V_t = \left[\left(1 - \tau_t^K\right) R_t^K + \left(1 - \delta + \delta\tau_t^K\right) P_t^K \right] K_t - \left(1 + r_{t-1}^b\right) \left(P_{t-1}^K K_t - N_t \right) \quad . \tag{48}$$

The first term represents the after-tax rental income of capital and the proceeds from selling undepreciated capital to capital producers, plus after-tax return on capital. The second term represents the payment (interest and principal) on the loan for period $t-1$. Using $P_t^K = Q_t P_t^C$, equation (48) can be rewritten as

$$V_t = \left[\left(1 - \tau_t^K\right) \frac{R_t^K}{P_t^C} + \left(1 - \delta + \delta\tau_t^K\right) Q_t \right] P_t^C K_t - \left(1 + r_{t-1}^b\right) \left(Q_{t-1} P_{t-1}^C K_t - N_t \right) \quad . \tag{49}$$

To avoid a situation in which the entrepreneur accumulates enough net worth to become self-financed, we follow *e.g.* Bernanke et al. (1999) and assume that, in each period, the entrepreneur exits the economy with probability $1 - \gamma$. In that case, he rebates his equity to the households as a lump-sum. To keep the entrepreneurs' population constant, a new entrepreneur is born with probability $1 - \gamma$.

The entrepreneurs' net worth N_{t+1} combines equity and a transfer, W^e, received from households, which corresponds to the initial net worth (seed money) necessary for the entrepreneur's activity to start. The law of motion for the entrepreneurs' net worth is then given by

$$N_{t+1} = \gamma V_t + W^e \quad . \tag{50}$$

[16] We assume that the entrepreneur's discount factor is the same as the households'.

3.2.2 Financing cost minimization problem

In the model, there is a continuum of banks, indexed by $z \in [0,1]$, and each bank z has some market power in providing its intermediation services. This reflects the fact that the banking sector is very concentrated in Finland: the five largest banks held over 80% of total assets of the banking sector at the end of 2013. An entrepreneur seeking a nominal amount of borrowing for period $t+1$ equal to BL_{t+1}, defined by (45), would allocate his borrowing among different banks so as to minimize the total repayment due. At the end of period t, the entrepreneur decides on how much to borrow from bank z, $bl_{t+1}(z)$, by solving the following problem:

$$\min_{bl_{t+1}(z)} \int_0^1 r_t^b(z)\, bl_{t+1}(z)\, dz$$

$$s.t.\;\; BL_{t+1} = \left\{ \int_0^1 \left[bl_{t+1}(z) \right]^{\frac{\varepsilon_t^b - 1}{\varepsilon_t^b}} dz \right\}^{\frac{\varepsilon_t^b}{\varepsilon_t^b - 1}} ,$$

where $r_t^b(z)$ is the interest rate charged by the z-th bank and $\varepsilon_t^b > 1$ is the time-varying interest rate elasticity of the demand for loans, which measures the degree of competition in the banks' lending activities. The first order condition yields the following entrepreneur's demand for loans:

$$bl_{t+1}(z) = \left(\frac{r_t^b(z)}{r_t^b} \right)^{-\varepsilon_t^b} BL_{t+1} ,$$

where r_t^b is the nominal average loan rate prevailing in the market at time t, defined as:

$$r_t^b = \left\{ \int_0^1 \left[r_t^b(z) \right]^{1-\varepsilon_t^b} dz \right\}^{\frac{1}{1-\varepsilon_t^b}} .$$

As expected, the loan demand curve has a negative slope: when the interest rate set by the z-th bank rises relative to the average rate, the entrepreneur wants to borrow less funds from that particular bank.

3.3 Banks

The banking sector is modeled along the lines of Gerali et al. (2010). This allows the banks to set rates on loans and to adjust them in response to shocks or to the cyclical conditions of the economy.[17] Banks balance-sheet is $loans = deposits + capital$, where the bank capital is accumulated through retained earnings. Furthermore, banks have an optimal exogenous target for their capital-to-assets ratio (*i.e.* the inverse of leverage), deviations from which

[17] We assume perfect competition in the market for households' deposits, and also rule out the entry and exit of banks.

are costly. The optimal leverage ratio in this context can be thought of as a shortcut for studying the implications and costs of regulatory capital requirements. Given these assumptions, the bank capital affects the total credit supply and, as such, generates a feedback loop between the real and financial sides of the economy. In particular, when macroeconomic conditions deteriorate, the banks' profits and capital might be negatively hit; depending on the nature of the shock hitting the economy, banks might respond to the weakening of their financial position by reducing lending, hence exacerbating the contraction.

To highlight more clearly the distinctive features of the banking sector and to facilitate exposition, we conceive of each bank z in the model as composed of two retail branches and one wholesale unit. The first retail branch is responsible for giving out differentiated loans to entrepreneurs and sets rates monopolistically, subject to adjustment costs. The second retail branch operates under perfect competition and collects deposits from households, taking the interest rates as given. Finally, the wholesale unit manages the capital position of the group.

3.3.1 Wholesale branch

The wholesale branch operates under perfect competition: on the liability side, it combines net worth, or bank capital (K^b), and wholesale deposits (D); on the asset side, it issues wholesale loans (BL) to entrepreneurs. We impose a cost on this wholesale activity, related to the capital position of the bank. In particular, the bank has to pay a quadratic cost (parameterized by a coefficient κ_{K^b} and proportional to outstanding bank capital) whenever the capital-to-assets ratio K^b/BL is different from the target value v_t^b. A possibly time-varying capital ratio may be viewed and used as a macroprudential instrument, related *e.g.* to countercyclical capital buffer requirements.

Bank capital is accumulated out of retained earnings:

$$K_{t+1}^b = \left(1-\delta^b\right)\frac{K_t^b}{\varepsilon_t^{Kb}} + J_t^b \ , \tag{51}$$

where the J_t^b are overall profits in period t for the three branches of each bank and δ^b could capture either the costs associated with managing bank capital and conducting overall banking activity (as in Gerali et al., 2010), or with the dividends policy of the bank (see *e.g.* Brubakk and Gelain, 2014). Also, since in this model neither the borrowers nor the banks default endogenously, an exogenous financial shock – ε_t^{Kb} – is introduced to capture borrower defaults (*e.g.* in the form of net impairment losses) or possible bank defaults.

The wholesale bank chooses loans and deposits so to maximize the discounted sum of cash flows:

$$\max_{\{BL_{t+1},D_{t+1}\}} R_t^b BL_{t+1} - R_t^d D_{t+1} - \frac{\kappa_{K^b}}{2}\left(\frac{K_{t+1}^b}{BL_{t+1}} - v_t^b\right)^2 K_{t+1}^b \ ,$$

subject to $BL_{t+1} = D_{t+1} + K_{t+1}^b$, given the net wholesale loan rate R_t^b and the net wholesale deposit rate R_t^d.

The first order condition yields the following equation that links the spread between wholesale rates on loans and on deposits to the degree of leverage B_{t+1}/K_{t+1}^b:

$$R_t^b = R_t^d - \kappa_{K^b}\left(\frac{K_{t+1}^b}{BL_{t+1}} - v_t^b\right)\left(\frac{K_{t+1}^b}{BL_{t+1}}\right)^2 \ .$$

To close the model, we assume that banks have access to unlimited finance at the rate $r_t^{FI} = R_t - 1$, which is the net rate of return on government bonds.[18] Hence, by arbitrage $R_t^d = r_t^{FI}$ and the above equation becomes

$$S_t^w \equiv R_t^b - r_t^{FI} = -\kappa_{K^b}\left(\frac{K_{t+1}^b}{BL_{t+1}} - v_t^b\right)\left(\frac{K_{t+1}^b}{BL_{t+1}}\right)^2 \ ,$$

where S_t^w is the spread prevailing at the wholesale level. The left-hand side of the equation represents the marginal benefit from increasing lending (an increase in profits equal to the spread); the right-hand side is the marginal cost of doing so (an increase in the costs of deviating from v_t^b). The bank thus chooses a level of loans that, at the margin, equalizes the costs and benefits of increasing the leverage.

3.3.2 Retail loan branch

The representative z-th bank maximizes its profits, taking as given the return (R_t^b) payable to the wholesale unit. In choosing the interest rate, each bank faces quadratic adjustment costs for changing over time the rates it charges on loans. These costs are parameterized by κ_b and are proportional to aggregate returns on loans. This assumption is a modeling shortcut for introducing sticky rates and thus to have an incomplete short-run pass-through of policy rates to retail loan rates. In fact, empirical studies (see *e.g.* de Bondt et al., 2005 and Gropp et al., 2014) have reported that the pass-through from money-market rates to retail lending rates is far from complete in several euro area countries. In Finland, the pass-through is expected to be relatively fast – but still incomplete – due to the fact that a majority of loan contracts are in terms of variable interest rates (see *e.g.* Kauko, 2005)

[18] Note that, by this assumption, an increase in the risk premium on government bonds is also fed into the banks' funding costs, reflecting the link between bank's and sovereign's financing costs.

At the end of period t, the z-th bank maximizes, over $r^b_{t+\tau}(z)$, the objective

$$E_0 \sum_{\tau=0}^{\infty} \beta^\tau \phi_{t+\tau} \left[\left(r^b_{t+\tau}(z) - R^b_{t+\tau} \right) bl_{t+1+\tau}(z) - \frac{\kappa_b}{2} \left(\frac{r^b_{t+\tau}(z)}{r^b_{t-1+\tau}(z)} - 1 \right)^2 r^b_{t+\tau} BL_{t+1+\tau} \right]$$

subject to

$$bl_{t+1+\tau}(z) = \left(\frac{r^b_{t+\tau}(z)}{r^b_{t+\tau}} \right)^{-\varepsilon^b_{t+\tau}} BL_{t+1+\tau} \quad .$$

Deriving the first-order condition, imposing a symmetric equilibrium and rearranging yields

$$1 - \varepsilon^b_t \frac{r^b_t - R^b_t}{r^b_t} - \kappa_b \left(\frac{r^b_t}{r^b_{t-1}} - 1 \right) \frac{r^b_t}{r^b_{t-1}} + \beta E_t \left[\frac{\phi_{t+1}}{\phi_t} \kappa_b \left(\frac{r^b_{t+1}}{r^b_t} - 1 \right) \left(\frac{r^b_{t+1}}{r^b_t} \right)^2 \frac{BL_{t+2}}{BL_{t+1}} \right] = 0 \quad .$$

Log-linearizing this equation yields

$$\tilde{r}^b_t = \frac{\varepsilon^b - 1}{\varepsilon^b - 1 + (1+\beta)\kappa_b} \tilde{R}^b_t - \frac{1}{\varepsilon^b - 1 + (1+\beta)\kappa_b} \tilde{\varepsilon}^b_t$$

$$\frac{\kappa_b}{\varepsilon^b - 1 + (1+\beta)\kappa_b} \tilde{r}^b_{t-1} + \frac{\beta \kappa_b}{\varepsilon^b - 1 + (1+\beta)\kappa_b} E_t \tilde{r}^b_{t+1} \tag{52}$$

where

$$\tilde{R}^b_t = \tilde{R}_t - \frac{\kappa_{K^b}}{R^b} \left(v^b \right)^3 \left(\tilde{k}^b_{t+1} - \tilde{bl}_{t+1} - \tilde{v}^b_t \right) \quad . \tag{53}$$

Equations (52) and (53) give the determinants of the loan interest rate. First, it depends on its past and future expected values because of the adjustment costs. Second, a temporary change in market power (*i.e.* a change in $\tilde{\varepsilon}^b_t$) moves the loan rate. Third, the bank capital position affects the loan interest rate: a sudden reduction in bank capital would force the bank to increase the loan interest rate so as to increase profits and restore the optimal bank capital level. The strength of this "bank capital" channel depends critically on the magnitude of the parameter κ_{K^b}, which will be estimated in section 4.

3.3.3 Bank profits

Overall bank profits are the sum of net earnings from the wholesale unit and the two retail branches. Deleting intragroup transactions, time-t profits are given by

$$J_t^B = r_{t-1}^b BL_t - r_{t-1}^{FI} D_t - \frac{\kappa_{K^b}}{2}\left(\frac{K_{t+1}^b}{BL_{t+1}} - v_t^b\right)^2 K_{t+1}^b - \frac{\kappa_b}{2}\left(\frac{r_t^b}{r_{t-1}^b} - 1\right)^2 r_t^b BL_{t+1} \ .$$

4 Bayesian estimation

We estimate *Aino 2.0* by employing Bayesian inference methods as outlined by *e.g.* Smets and Wouters (2003) and An and Schorfheide (2007). This involves obtaining the joint posterior distribution of the model's structural parameters based on its linear or log-linear state-space representation (which is reported in appendix A). Bayesian inference methods allow the use of prior information in the estimation of the structural parameters and help to alleviate at least some of the parameter identification problems and numerical difficulties due to the highly non-linear estimation problem. Since Bayesian estimation methods are nowadays standard tools of macroeconomists, we do not repeat the technical details here. In what follows we describe the data and the prior distributions used in its implementation. In this context, we also provide information on the structural shocks that we employ in the estimation and describe the calibration of the parameters that are kept fixed. We then present our estimation results.[19]

4.1 Data

We use a total of 24 observables in the estimation of the *Aino 2.0* model. Since the model is developed for use in forecasting, the set of observables contains all the demand components of GDP, as well as their deflators. The data for domestic real variables, price deflators, wages and hours are obtained from Statistic of Finland's Quarterly National Accounts, which are based on the newest European System of National and Regional Accounts, ESA 2010. The domestic real variables are based on chain-linked volume data for reference year 2010, all expressed in per-capita terms. The data for external demand index, foreign price index, oil prices, raw material prices, nominal effective exchange rate, euro area short term interest rate, total loans to non-financial corporations (NFC) and corresponding lending rates, are from the Bank of Finland and European Central Bank databases. The complete set of observables is provided in table 1.

The estimation sample period is from 1995Q2 to 2014Q4. Prior to the estimation, we transform the total output (private sector value added), private consumption, investment, exports and imports, government consumption, the associated deflators, total hours, hourly wages, as well as foreign demand and foreign prices into the quarter-on-quarter growth rates, approximated by the first difference in their logarithms. Furthermore, we match the sample

[19] The estimation was performed using Dynare version 4.4.3. See Adjemian et al. (2011) and www.dynare.org.

growth rates of all the components of GDP with the sample growth rate of total output, by removing the sample growth differentials of the real variables prior to the estimation. Effectively, this means that we remove the variable specific deterministic trends from the real variables such that all the observable real variables are consistent with the model's balanced growth path. As for the price deflators, we proceed in the same way in order to guarantee that all the observable price series are consistent with the model's assumption of stationary relative prices. Finally, all the transformed domestic price series share the same growth rate, which is equal to the first difference in logarithms of the private sector value added deflator. Figure 3 shows the time series of the transformed variables used in the estimation.

4.2 Shocks and exogenous processes

For the estimation, we specify 13 shocks and 11 exogenous processes, corresponding to 24 observables, which are divided into the following 5 categories:

- technology shocks
  - permanent labour productivity (ε_t^{μ}), temporary labour productivity ($\varepsilon_t^{\lambda l}$), temporary capital productivity ($\varepsilon_t^{\lambda k}$), productivity shifters in consumption (ε_t^{cy} and ε_t^{cm}) and productivity shifter in investment (ε_t^{iy});
- domestic markup shocks
  - price markup of intermediate good firms (ε_t^{v}), price markup of export producing firm (ε_t^{vx}) and wage markup ($\varepsilon_t^{\lambda w}$);
- domestic demand shocks
  - government consumption (ε_t^{cG}), public investment (ε_t^{iG}), hours in the public sector (ε_t^{hG}) and household consumption preference ($\varepsilon_t^{\zeta C}$);
- foreign/external shocks[20]
  - export demand (ε_t^{mW}), export share (ε_t^{x}), nominal exchange rate ($\varepsilon_t^{\Delta s}$), foreign inflation ($\varepsilon_t^{\pi W}$), price markup of import firms (ε_t^{vm}), oil price (ε_t^{OIL}) and price of raw materials (ε_t^{RAW});
- financial shocks

[20] The oil price and raw materials price shocks enter into the marginal cost term of the import goods' inflation equation (see equation A.37).

– domestic risk premium ($\varepsilon_t^{\zeta^{\text{€}}}$), euro area interest rate ($\varepsilon_t^{r^{\text{€}}}$), bank markup ($\varepsilon_t^{\bar{\varepsilon}^b}$) and bank capital ($\varepsilon_t^{\bar{\varepsilon}^{Kb}}$).

All the shocks and exogenous processes follow first order autoregressive processes, except for the price markup of intermediate goods firm and wage markup shocks, which are assumed to be serially uncorrelated in order to enable a better identification of the Calvo parameters and labor supply elasticity. As in Gerali et al. (2010), to avoid near stochastic singularity, we also allow a small serially uncorrelated shock (ε_t^{bl}) to the bank balance sheet. In addition, we account for measurement errors in the private sector value added, real imports and investment price deflator, latter of which are subject to large revisions. Measurement errors in private sector value added reflect both the revisions and the differences in the model's aggregate resource constraint and the construction of Quarterly National Accounts data for the corresponding variable.

4.3 Calibration and steady-state properties of the model

In calibrating the steady state, we fix the value of some structural parameters and allow a number of other parameters to be chosen optimally in order to match as closely as possible some key aggregate macro and financial steady-state ratios. Along the non-stochastic steady state, all the domestic transformed real variables are assumed to grow along the balanced growth path at a rate of 2.16% per year ($\mu = 1.0054$), corresponding to the sample average growth rate of output. The nominal transformed variables (apart from the nominal wage) grow at the rate of 1.24% per year ($\Pi = 1.0031$). All the quantity variables are expressed in per-capita terms; hence the growth rate of the domestic real variables, after removing the growth difference, correspond to the growth rate of labour-augmenting productivity. Consequently, along the balanced growth path, technical progress is labour-augmenting.

The discount rate is set at 0.998 to deliver an equilibrium annual nominal interest rate of about 4.3%. The elasticity of demand for funds ε^b is set at 3.82 so as to match the average spread between the lending rate and the risk-free rate. The price markup for intermediate good producing firms Υ is set at 1.08, and for export producing firms Υ^f and importing firms Υ_m at 1.05; the labor markup λ_w is 1.45. The value of the depreciation rate of physical capital δ is set at 0.014.

The substitution parameters (ρ_Y, ρ_c, ρ_i and ρ_x) of the CES production functions have been partially estimated and partially calibrated. The substitution parameter in the production of final consumption good between the domestic intermediate good and the imported good is set at 0.05, implying close to unitary elasticity of substitution. The parameter of substitution between the domestic intermediate investment good and the imported investment good is estimated at -0.78, which implies a very high elasticity of substitution in the production of investment goods. On the contrary, the substitution parameter in the production of export goods is estimated at 1.06, implying that

domestic intermediate goods and imported goods are gross complements in the production of export goods. Finally, the implied elasticity of substitution between capital and labour in the production of domestic intermediate goods is 0.85, a significant departure from the usual Cobb-Douglas specification.

The depreciation rate for bank capital δ^b is set at the value 0.062, which ensures that the steady-state bank capital-to-asset ratio v^b is 9%.[21] The survival probability of entrepreneurs γ is set at 0.988, which allows us to exactly match the non-financial-corporations loans-to-gdp ratio in the data. The initial transfer from households to entrepreneurs W^e is arbitrarily set at 0.01.

As for the fiscal variables, the tax rates on capital income (τ^K), on consumption (τ^C) and on labor income (τ^W) are set at 20%, 21% and 32%, respectively, close to their sample means. Also, the social security contribution rate of private sector firms τ^F is set at 16%. The share of government consumption ($\mathbf{s_{GCF}}$) and government investment ($\mathbf{s_{IG}}$) are, respectively, 0.068 and 0.171, based on their sample means. Hours worked in the government sector $\mathbf{s_{LGH}}$ represents 23.1% of the total hours.

We then allow a number of other parameters (*e.g.* quasi share parameters and steady state values of productivity shifters) to be chosen optimally in order to match as closely as possible the key aggregate macro ratios and financial variables (*e.g.* M^C/C). Table 2 shows the calibration of these parameters, and the key steady-state ratios are reported in table 3. The key aggregate ratios are matched with their empirical counterparts reasonably well over the sample period.

4.4 Prior distributions

The vertical panel in the middle of tables 4–6 summarises our assumptions regarding prior distributions for the parameters estimated using Bayesian methods. As this is the first paper estimating a fully-fledged DSGE model using Finnish data, we take a relatively agnostic approach and use fairly wide priors for the parameters. We use the beta distribution for all the parameters bounded between 0 and 1, and either a gamma or an inverse gamma distribution for the prior distributions of parameters that are bounded from below at zero.

For the external habit formation parameter, all the Calvo and the indexation parameters and all the autocorrelation parameters of the exogenous shocks, we adopt beta distributions with mean equal to 0.5 and standard deviation of 0.20. The standard errors of the shocks are assumed to follow an inverse-gamma distribution. All the standard

[21] The value of v^b could be thought of as comprising a minimum requirement established by the regulator (the 8% benchmark from the Basel regulation) plus a voluntary buffer that the bank decides to hold for precautionary reasons. In this paper we assume that the regulator can set v^b, which implies that the voluntary buffer is time invariant.

deviations are set at 2, whereas the precise mean for the prior distribution was based on previous estimation outcomes and trials with uninformative priors.

We assume a gamma distribution with mean 5 and standard deviation 2.5 for the investment adjustment costs parameter (γ_I). This prior encompasses a wide range of empirical findings in the literature. As for the parameter governing the loan interest rate adjustment costs (κ_b), the prior mean is set at 5, which implies a rather quick adjustment of the loan rate to movements in the short term money market rate. The prior on the parameter governing the adjustment costs in banking (κ_{K^b}) is difficult to set. We have experimented with alternative prior values for the mean and always found that this parameter value tends towards values smaller than those usually assumed or found in the literature (*e.g.* Gerali et al., 2010 and Paries et al., 2011). Accordingly, here we assume a gamma distribution with mean 1 and a standard deviation 0.5.

4.5 Estimation results

The right-hand columns in tables 4–6 report the mode, mean, median and 5th and 95th percentiles of the posterior distribution of the parameters, all computed via a posterior sampling algorithm based on 2 Markov chains with 8 million draws each, with the first 50% of draws being discarded as burn-in draws. Comparing the plots of the prior and posterior distributions in figure 4 gives some indication of how informative the observed data are for the structural parameters. For most of the parameters, the posterior distribution turns out to be quite different from the prior distribution, so the data seem to be rather informative.

The posterior mean of the parameter measuring the degree of external consumption habits is estimated to be very high (0.95). Private consumption thus reacts very sluggishly to external shocks. This may (at least partly) reflect the demographic trend whereby a large part of households' income is non-wage income and hence consumption is relatively insensitive to the business cycle.

The mean of investment adjustment costs is around 8.2, slightly larger than common findings such as in Smets and Wouters (2003). This value implies that investment increases on impact by 0.12% following a 1% temporary increase in the price of physical capital. A persistent change in the price of capital would induce a larger percentage change in investment because adjustment costs induce agents to be forward looking.

Concerning nominal rigidities, we find that wage stickiness in Finland is much stronger than price stickiness. On the basis of the Calvo wage parameter, the average duration of wage contracts is over 3 years, whereas prices change about every quarter. At the same time, we find a fairly high degree of price indexation (75%) to past inflation.

However, the posterior distribution is rather wide, indicating that there is substantial parameter uncertainty (recall that for wages we have assumed full indexing).

Exporters change their prices very often – almost every quarter, whereas importers change them less often – every two years on average. In particular, the latter result implies that the pass-through of oil and raw materials prices to import prices is low.

As to the indexation parameters, the estimation results suggest that the persistence of export price inflation is higher (but weakly estimated as the posterior is quite wide) than that of import price inflation; the estimated import price Phillips curve is indeed mostly forward-looking.

As regards the parameter driving the degree of exchange rate pass-through (ω_m), we estimate that 74% of foreign importers price their products in euro, the remaining 26% in their own (foreign) currency. The exchange rate pass-through is therefore quite low in Finland, as only 23% of an exchange rate movement is passed through to the price of imported goods.

Concerning the parameter measuring the degree of stickiness in bank loan rates, we find that the interest rate on loans adjusts rather quickly to shocks. In particular, the estimated mean value implies an interest-rate pass-through of about 4 quarters. Finally, the posterior distribution for the coefficient measuring the cost of deviating from targeted leverage is very low, both in absolute value and in comparison with previous findings using a similar modelling framework for the banking sector (*e.g.* Gerali et al., 2010 and Paries et al., 2011).

Finally, as regard the properties of the structural shocks, we observe that shocks exhibit either a quite high or a quite low persistence. The most persistent shocks are the permanent labour productivity and government hours shocks, with autoregressive coefficients of 0.97. In contrast, the persistence of the capital productivity and consumption preference shocks is relatively low (0.11).[22]

5 Model properties

5.1 Impulse response functions

Figures 5 to 9 show the impulse response functions for five distinct structural shocks.[23] In these figures, we report the mean (blue lines) and the 60 and 90 percent equal-tail uncertainty bands (grey-shaded areas) for the impulse

[22] Using the local identification approach methodology proposed by Iskrev (2010), we have verified that all estimated parameters reported in tables 4–6 are locally identified.

[23] Additional impulse response functions are reported in appendix B.

responses to shocks of one standard deviation. These uncertainty bands reflect the uncertainty about the model's structural parameters, as described by their posterior distributions. All the impulse responses are reported as percentage deviations from the model's non-stochastic steady state, except for inflation and the loan interest rate, which are reported in annual percentage points, the bank capital-to-asset ratio (reported as percent value) and trade balance to output, which is reported in percent deviation.

Price markup shock in intermediate-good production

Figure 5 shows the impulse responses following a shock that temporarily raises firms' price markup in the intermediate good sector. The shock induces intermediate good producers to increase their prices and so inflation increases. The price increase reduces expenditure on final output, and the main expenditure components all decline persistently. The fall in output reduces the demand for labour and capital and hence real factor prices also fall, at least initially. This pushes down the marginal cost initially, but inflation returns to its steady state level after the initial effect of the shock has worn off. Actually, inflation responds very quickly as, according to our estimates, the Phillips curve is quite steep (as prices are quite flexible). Consumption falls because the rise in inflation reduces labour income – as real wage cut – and so households' consumption falls. The muted consumption response reflects the high external habit persistence. The cut in investment leads to a decrease in lending, despite a (small) reduction in the interest rate on loans paid by entrepreneurs. The increase in inflation also generates an appreciation of the real exchange rate – which reduces exports – and improves the terms of trade.

Temporary capital productivity shock

Figure 6 presents the impulse responses following a temporary capital productivity shock. The short run can be interpreted as a period of excess supply, as a positive capital productivity shock increases firms' output for a given level of inputs. The direct result is an increase in final output. We note that capital and labour are gross complements due to the less-than-unitary elasticity of substitution. Hence, an increase in the productivity of capital increases the marginal product of labour by more than the marginal product of capital. As a consequence, increase in the productivity of capital eventually generates excess demand for labour. It is in this sense that the increase in capital productivity is biased towards labour. Due to the capital adjustment costs, however, an increase in capital productivity leads to an initial decrease in hours.[24]

[24] Figure 17 in appendix B shows the reaction of the economy to the temporary labour productivity shock. The domestic intermediate good firms respond to the labour productivity shock also by initially decreasing the hours and increasing the capital. As a result of the increase in the labour productivity, the relative factor costs (W_t/R_t^K) increase, and the intermediate good firms decrease the labour demand relative to capital, and the capital-labour ratio increases. In contrast to the capital augmenting productivity shock, the increase

The adjustment is however quite fast, as the shock is short-lived (the AR parameter is 0.14). Marginal cost falls not only as a result of the direct effect of the shock, but also because of the lower initial capital rental cost. In addition, the initial decrease in hours worked further increases the marginal productivity of labor. All these effects, which dampen the marginal cost, dominate the initial increase in the real wage, which results from the income effect on labor supply and from high nominal wage rigidity.

The decline in the marginal cost causes domestic inflation to fall. The fact that i) the estimated shock is quite large and ii) prices are very flexible and, consequently, the Phillips curve is very sensitive to changes in the marginal cost explains why the reaction of inflation, on impact, is negative. However, deflation turns into inflation from the second quarter onwards since the persistence of inflation is quite low, *i.e.* inflation is very forward-looking.

Demand increases across all the expenditure components. Consumption increases as a result of the income effect, even if the real interest rate initially falls, due to the lowering of inflation. Investment is particularly forward-looking due to the high adjustment costs and the long time needed to build up the capital stock. Therefore, although in the very short run the capital rental costs fall, Tobin's Q increases right away at once, as it accounts for the expectation of higher capital rental costs in the future.

The fall in domestic prices also leads to a the deterioration of the terms of trade which, along with the depreciation of the real exchange rate, leads to expenditure switching away from foreign towards domestic goods, thereby boosting exports significantly (imports also increase, but by less).

An appealing feature of the capital productivity shock is that it generates a boom in both quantities (*e.g.* investment and consumption) and prices (*i.e.* the price of capital or Tobin's Q). An investment-specific technology shock of the type normally used in estimated DSGE models (such as ζ_t^I in equation 31) would have the counterfactual implication of moving quantity and prices in the opposite directions (*i.e.* it would generate an investment boom with falling asset prices).

Government consumption shock

Figure 7 shows the effects of a positive shock to government consumption expenditure. An increase in government consumption expenditure raises final output, but it crowds out private consumption (as a result of lower wage income) and private investment (as a result of a lower expected Tobin's Q), as is typical in the models like this. The crowding out of private consumption is rather muted, however, reflecting a strong habit persistence of consumption.

in labour productivity leads to excess demand for capital. See also Cantore et al. (2014) who study the responses of the New Keynesian economy to labour productivity shocks.

The short-run (first year) government consumption multiplier is 0.64, which is in line with estimates reported by Kilponen et al. (2015). Total hours also increase initially to meet the increased demand for output. The increased aggregate demand pushes up factor prices and increases the marginal costs of production, which in turn leads to a rise in domestic inflation. This generates the real exchange rate appreciation, which reduces exports.

Euro area interest rate shock

Figure 8 reports the dynamics following a shock to the euro area interest rate. As Finland is part of the euro area, this shock can be seen as the relevant monetary policy shock for Finland. The estimated size of the shock is such that, on impact, the euro area interest rate goes up by 44 basis points. By construction, the pass-through of monetary policy to bank loan rates is incomplete on impact. Namely, the interest rate on loans rises by only 21 basis points. The loan interest rate displays a persistent (and hump-shaped) response due to both the high persistence of the shock itself and quite high interest rate adjustment cost. The increased cost of borrowing induces entrepreneurs to reduce the amount of borrowing and hence to cut capital expenditures, so that private investment declines. The shock leads to a hump-shaped fall in output and to domestic inflation as well. After an initial positive (but small) reaction, real wages fall in response to the shock, and hours is also negatively affected. A muted, but persistent reaction of consumption reflects the estimated strong habit persistence. As the real exchange rate depreciates, Finnish products become more attractive to foreign investors, so that exports rise and imports decline. This eventually also boosts output. Overall, the impulse responses are well in line with the literature on using VARs to study the effects of interest rate (*i.e.* monetary policy) shocks.[25]

Bank capital shock

Figure 9 reports the impulse responses following a negative unexpected shock to bank capital, which can be interpreted as an unexpected increase in banks' loan losses. The estimated persistence of the shock is quite low – the AR parameter is 0.49 – and the estimated size of the shock is such that, on impact, the bank capital-to-asset ratio drops by about 0.4%. This is also roughly the mean of the ratio between the banks' net impairment losses (that destroy bank capital) and banks' total capital over the 1999-2013 sample. Relative to the destruction of bank capital that occurred during the global financial crises, this shock is rather small. At the end of 2009, the banks' net impairment losses in fact peaked at about 840 mil €, which was roughly 3.5% of the banks' total capital at the time.

[25] We note, however, that it is quite likely that the model underestimates the effect of the monetary policy shock, as it does not account for the the indirect channel due to the effect of the euro area interest rate on the exchange rate, and of euro area output and inflation.

After the shock, the banks are too leveraged and, accordingly, have to pay a higher "penalty" cost. In order to re-establish their target leverage ratio, they raise the interest rate on loans by charging a higher interest rate margin, which in turn reduces lending and hence output and investment. The negative impact on output is quite persistent – despite the shock being rather short-lived – but the overall effect is very modest. The peak effect on the interest rate on loans is only about 10 basis points. Investment decreases by a larger amount, though the reaction still seems to be rather small. This is mainly due to the fact that the bank capital channel – which depends on the parameter κ_{K^b} measuring banks' cost of deviating from the targeted capital-to-assets ratio – is muted as, according to our estimates, κ_{K^b} is very low.

To better highlight the role of the bank capital channel, we ran a simulation in which we exogenously increase the parameter κ_{K^b}. In particular, we consider two different values for κ_{K^b} (10 and 25), which are similar to those estimated and used by Gerali et al. (2010) and Paries et al. (2011). This simulation mimics a stress scenario in which banks are poorly capitalized (so that they have major difficulties in reducing further, even temporarily, their capital-to-assets ratio) and cannot easily raise new capital in the market. Results are reported in figure 10.[26] In the stress scenario in which we increase the cost of deviating from the target capital-to-assets ratio, all the responses are more harsh, as banks can no longer afford prolonged periods of undercapitalization and have instead strong incentives to quickly close the gap between the capital-to-assets ratio and its target level. Such harsh deleveraging in the financial sector results in a significantly larger increase in loan rates and in a larger contraction of credit, investment and output.

5.2 Drivers of business cycle fluctuations in Finland

The origins of business cycles are still controversial among macroeconomists. According to the real business cycle literature of the 1980s, business cycle fluctuations are caused mainly by exogenous total factor productivity (TFP) shocks. More recently, several authors find that other shocks outperform TFP shocks. For example, Christiano et al. (2014) show that financial shocks account for a large share of the fluctuations of macroeconomic variables in a DSGE model with the Bernanke et al. (1999) financial accelerator. Similarly, Gerali et al. (2010), Gilchrist and Zakrajsek (2012), Jorda et al. (2013) and Kaihatsu and Kurozumi (2014), among many others, find that shocks arising in the financial sector are important drivers of business cycle fluctuations. Furthermore, Justiniano et al. (2010, 2011) show that an investment shock that determines the efficiency of newly produced investment goods is the key driver of business cycles in a medium-scale estimated DSGE model. As regards the importance of

[26] In this simulation, in order to avoid having an excessively volatile loan interest rate, we also increase the value of the parameter determining the stickiness of the lending rate (to $\kappa_b = 200$).

foreign-sourced disturbances for (small) open economies, Christiano et al. (2011) show that financial shocks are still (slightly) more important than foreign shocks in Sweden. On the other hand, Lombardo and McAdam (2012) find that movements in foreign and technology shocks are the drivers of euro area GDP growth, with financial shocks playing a relatively small role. As for Canada, the evidence is mixed, as Justiniano and Preston (2010) find that U.S. shocks (*i.e.* foreign shocks) account for less than 3% of the variability observed in several Canadian series, while Bergholt and Sveen (2015) attributes an important role to foreign disturbances.[27]

Four papers analyze – and disagree on – the drivers of business cycle fluctuations in Finland. Conesa et al. (2007) find that the sharp drop in real GDP over the period 1990-1993 was driven by a combination of a drop in TFP during 1990-1992 and of increases in taxes on labor and consumption and increases in government consumption during 1989-1994. Freystatter (2010) builds and estimates a DSGE model that allows for several shocks arising from both domestic sources and the international economy. According to Freystatter's estimates, domestic financial market shocks were key drivers of historical investment fluctuations in Finland in the 1995-2008 period. Gorodnichenko et al. (2012) claim that the major causes of the Finnish Great Depression (1991-1993) were the collapse of the Finnish-Soviet trade and an adverse oil price shock, which were amplified by a rigid labor market. Gulan et al. (2014) challenge Gorodnichenko et al. (2012) results. They run a SVAR model, where real and financial shocks are identified through sign restrictions, and find that domestic financial factors did indeed play an important role in the 1991 recession, but not in the recent one, which was mainly driven by international financial shocks and negative shocks to world demand.

In what follows, we use the *Aino 2.0* model to provide an interpretation of business cycle fluctuations by analyzing the smoothed shock processes, the historical variance decomposition of output growth and inflation rate, as well as the forecast-error-variance decomposition of a selection of variables.

5.2.1 Smoothed shock processes and historical decomposition

Figure 11 presents the smoothed values for the shock processes considered in the model.

The bank markup shock was negative before the peak of the recession and then turned positive just after the peak. This matches well with the evidence that the spread between the domestic loan rate and risk-free rate was narrowing in the period before the peak (or, in other words, that the markup (competition) in the banking sector was decreasing (increasing)). However, at the end of 2008 the ECB aggressively cut the nominal interest rate and

[27] Other shocks that are found to be important are *e.g.* uncertainty shocks (Bloom, 2009), news (or anticipated) shocks (Schmitt-Grohe and Uribe, 2012) and belief shocks (Farmer, 2013).

Finnish banks only responded with a delay to those cuts (which in the model is captured by the incomplete short-run pass-through of policy rates to retail loan rates). As a results, the spread (and hence the markup) increased substantially around the peak of the recession, as can be seen in figure 11.

The bank capital shock captures remarkably well the dynamics of bank leverage and net impairment losses in the Finnish economy, especially considering the fact that we do not include any variables related to bank capital or bank losses in the estimation. At the beginning of the sample the shock was positive (see equation 31), which seems to be consistent with the fact that bank losses were still quite high in that period, as banks were still recovering from the early 1990s' crises. Banks were indeed required to recapitalize and many were merged in the aftermath of the Finnish great depression. Afterwards, a gradual deleveraging process – that lasted until the end of 2006 and was characterized by very moderate bank losses – took place in the banking sector. However, the situation changed suddenly at the beginning of 2007. Bank loan losses started increasing and spiked at the end of 2009.[28] Banks had to cover the losses with their own capital, which in turn led to an increase in the banks' leverage positions. The increase in leverage was also partly due to the fact that, after the Lehman Brothers problems started in the second half of 2007, the corporate bond market in Finland froze. As a consequence, large companies turned to banks for funding that was no longer available from the capital markets. From 2010 onwards, bank losses started decreasing (and hence profits started increasing, also boosted by a widening loan spread) and stabilized after 2012.

In addition, the stagnant growth since the global financial crises shows up in the slowdown of labour productivities (both temporary and permanent), in the loss of export shares and decline of external demand. Declining productivity performance and loss of export shares were manifested in the dramatic fall of the electronics industry as well as in problems in the forestry industry that started well before the global financial crisis. The boom period preceding the global financial crisis was mainly driven by the same factors – booming labour productivity and a strong increase in export shares, again related to the rise of the electronics industry and the ICT sector in general. Finally, a fall in the terms of trade observed in the data until about 2010 is captured by the fall in the price markup of export producing firms.

The historical variance decomposition of Finnish private sector output is shown in figure 12.[29] We decompose the observed private sector output into the contributions of its structural shocks and, to facilitate the presentation, we group the structural shocks into the five categories described in section 4.2 (technology shocks, domestic demand shocks, domestic markup shocks, external/foreign shocks and financial shocks). According to the *Aino 2.0* model, throughout the entire sample period output fluctuations in Finland were primarily due to external shocks. Technol-

[28] At the end of 2009, banks' total net impairment losses amounted to 6% of non-financial corporation's loans stock and 3.5% of the banks' own capital stock.

[29] Note that the bars do not sum up to actual output due to measurement errors, which are not shown in the figure.

ogy shocks also played an important role, especially after 2007. In particular, the model interprets the large part of the stagnant growth and problems within the ICT sector and in the forest industry that was due to the negative contributions of technology shocks since 2008.

Demand and markup shocks played a (less important) role, while financial shocks played a relatively minor role in output fluctuations in Finland. Similar results hold for other real variables such as investment and consumption growth.

Three possible explanations for the quantitatively small role played by financial shocks in Finnish business cycle fluctuations are as follows. First, the model is estimated for a period (1996-2014) in which financial shocks, if any, were probably quite small. This is consistent with the fact that Finnish banks have been well capitalized throughout the period, and there is no evidence of a major disruption in bank lending, not even during and after the global financial crisis, as suggested also by Gulan et al. (2014).[30] In fact, except for the bank capital shock, the estimated sizes of the financial shocks are quite small. As regards the bank capital shock, the size of the shock is not negligible, but the bank capital channel is muted due to the very low estimates of κ_{K^b}.

Second, two of these financial shocks (bank capital and bank markup) have a direct effect on the loan interest rate, and only after that do the shocks spread throughout the economy. Third, the model economy does not feature any (shocks to) quantity restrictions (*e.g.* loan-to-value ratios requirements), which have usually been found to have large effects on the real economy. Moreover, the model does not feature a housing market nor financial intermediation of mortgages to households. The latter may mean that the model underestimates the importance of financial shocks on the Finnish business cycle.

The historical variance decomposition of the inflation rate, shown in figure 13, reveals very important roles for technology and external shocks, along with markup shocks driving inflation developments. At the same time, domestic demand and financial shocks play a minor role, similarly in the case of output. An interesting feature of the historical decomposition is that technology and external shocks seem to drive inflation in opposite directions throughout the sample.

5.2.2 Forecast-error-variance decomposition

An alternative and complementary way to evaluate the importance of a shock is to study the forecast-error-variance decomposition (FEVD). Tables 7 and 10 report the contributions of the structural shocks to the forecast error

[30] The main financial crisis of 1991 is excluded from the estimation because of the different monetary policy regime in that period, so that the model is not appropriate for that period.

variances of GDP growth and loan interest rate, respectively. In particular, we report mean estimates and 90% equal-tail uncertainty bands for the contributions to the forecast error variances over different horizons. As compared to the impulse response function analysis, not only parameter but also shock uncertainty is taken into account in the FEVD analysis. In fact, uncertainty is relative large as revealed by the width of the 90% uncertainty bands.

As regards output, the importance of technology shocks increases over time, from 17% in the first quarter to 85% in the long run. This is a typical feature of the model as specified here. In the short run, wage and price rigidities render demand shocks important. In the longer run, however, output is driven by supply factors as in the classical real business cycle framework. External shocks, which are primarily demand shocks, are indeed very important in the very short run (up to one year), after which their contributions gradually decline. The importance of markup shocks is fairly constant over the forecast horizon, ranging between 10 and 20%. The last column confirms that financial shocks indeed play no significant role for output fluctuations, as their total contribution is close to 0.

Tables 8 and 9 further decompose the contribution of the technology and foreign shock groups, respectively. As regards technology shocks, in the short run, the temporary capital and the labour productivity shocks are approximately equally important. However, while the importance of the capital productivity shock falls to less than 2% in the long run, the contribution of the labour productivity shock becomes increasingly important and accounts for most of the variability in output at the longest (32-quarter) horizon. This fact can be explained by the very high persistence of the labour productivity process. Also, the other productivity shifters do not make any noticeable contributions at any horizon. As regards the foreign shocks, at all horizons the export share shock is by far the most important shock, while the export demand, foreign inflation and exchange rate shocks are roughly equally important.

Turning to the loan interest rates (table 10), up to four years, the financial shocks are the most important shocks, while in the long run technology shocks explain a larger share of interest loan rate variation. All the other shocks play only very modest roles. Table 11 decomposes the contributions of the financial shock group. Among the four financial shocks, the euro area interest rate shock is by far the most important. The bank markup shock is also quite important, especially in the very short run (up to one year), while the bank capital shock has almost no impact on loan interest rate fluctuations at any horizon.

5.3 Rolling window estimation

During the estimation sample, the Finnish economy experienced a remarkable rise and dramatic fall of the electronics industry. In particular, during the last years of the estimation sample, the growth came to a halt, and private

investment and exports fell substantially as a share of total output. A large part of the recent stagnant growth reflects structural problems in the economy. It is thus interesting to see if any of the parameters feature temporal instability, which could be related to the structural changes in the Finnish economy during the sample period.

Accordingly, in this subsection we study the stability of the estimated structural parameters by means of rolling window estimations of the posterior mode.[31] In particular, the first sample considered is 1995Q2 - 2008Q4, so that the estimation window has 55 observations. We then keep the size of the window fixed and move it by one year at a time (so that the second sample is 1996Q2 - 2009Q4, and so on). Blue lines in figure 14 show the results of the rolling window estimates, and grey-shaded areas represent the 90% confidence band around the posterior estimates using the entire sample. Overall, we observe that most of the structural parameters are relatively stable (*e.g.* the habit persistence parameter, the Calvo parameter on wage, and import and export prices, and the share of FCP firms). However, for some parameters the changes are substantial. Domestic prices have become more sticky over the sample period, which in turn implies that the slope of the Phillips curve for domestic intermediate goods' inflation has substantially declined. At the same time, inflation has become increasingly more forward looking. The price elasticity of exports have also increased over time – also quite substantially – from below 0.9 to about 1.2. Another interesting feature is that the strength of the "bank capital" channel, which depends on the magnitude of the parameter κ_{K^b}, has declined over time. This provides further evidence that the Finnish economy was indeed still suffering from the negative effects of the Finnish Great Depression at the beginning of the sample period, and that these effects have gradually vanished over time.

6 Conclusions

In this paper we have provided a detailed description of *Aino 2.0*, an estimated DSGE model for the Finnish economy. In a nutshell, the model features a monopolistically competitive banking sector in the spirit of Gerali et al. (2010) within a small open economy setting similar to that in Adolfson et al. (2005, 2007, 2008) and Christoffel et al. (2008). The model was estimated using Bayesian methods for the period 1995-2014. *Aino 2.0* has already proved itself useful for practical purposes, both in identifying the economic forces driving the Finnish economy and as a macroeconomic forecasting tool. As the current version of the model features the bank capital requirements, it can also be used for macroprudential policy simulations. For instance, it would be possible to gauge the effects of bank capital requirements or countercyclical capital buffers in dampening business cycle volatility (as done by *e.g.* Clerc et al., 2015), or to analyze the dynamics during the transition to a more well-capitalized banking sector (as

[31] We do not run the full MCMC estimation and instead only report the posterior mode for each estimation.

in *e.g.* Paries et al., 2011 and Kiley and Sim, 2014).

Building and improving models for policy analysis is a continuous process, and no model can ever be considered "the final" model, as further improvements should always be envisaged. In terms of modelling, there are many directions in which the model could be enriched or adjusted. Among these, at least three refinements seem to be worthwhile.

First, given the importance of the labour markets for cushioning the asymmetric shocks in a small currency union member state like Finland, it would be desirable to include a fully developed model of the labour market into the *Aino 2.0* model. A more detailed description of the labour market would offer new possibilities to analyze the effects of policies and disturbances on key labour market variables including unemployment, as well as to inspect the importance of wage formation mechanism for the overall stability of the macroeconomy. Some variant of the search and matching framework of Pissarides (2000), including wage rigidity, would seem to be the most promising way forward.

Second, the model could be extended to include the so-called cost channel as in *e.g.* Christiano et al. (2005) and Ravenna and Walsh (2006). In *Aino 2.0*, financial frictions in the real sector affect access to longer term physical capital financing. In Finland, however, a significant part (about 40%) of bank loans to non-financial sector corporations are short-term loans, which are used to provide short-term working capital financing to firms. Usually, when problems in the financial sector arise, firms have trouble meeting their short-term financing needs as well. It would be relatively easy to modify the model and assume that intermediate goods firms have to pay their wage bills in advance and borrow working capital from the banks. It would then be possible to analyze how frictions in the market for very short-term financing exacerbate (or dampen) the recessions. It is likely that the financial variables and shocks would have larger effects on the real economy, since firms' marginal cost (hence inflation and production) would depend directly on the interest rate set by the banks, which in turn would be a function of the risk-free rate, the degree of competition in the banking sector and banks' leverage.

Third, one can incorporate a housing market along the lines of Iacoviello (2005), given the importance of the housing wealth of Finnish households.[32] The model would then feature collateral/borrowing constraints tied to housing values, and it would be possible to analyze how (negative) shocks to house price are propagated across the economy, as well as the macroeconomic effects of loan-to-value ratio policies (see *e.g.* Mendicino and Punzi, 2014 and Rubio and Carrasco-Gallego, 2014, 2015). Moreover, as there would be two types of loans in the model – mortgage and corporate loans – it would be possible to account for the risk-sensitive regulation of bank capital

[32] According to the Statistics of Finland's Household's Wealth Survey (available at http://www.stat.fi/til/vtutk/2013/vtutk_2013_2015-04-01_kat_002_fi.html), at the end of 2013 the ratio of housing wealth to total (gross) wealth of Finnish households was 69%. That figure includes all the housing wealth of the households *i.e.* houses used as main residences of the households, holiday homes as well as houses owned by the households but rented out. Housing wealth that includes only houses used as primary residences of households comprises 53% of the total (gross) wealth.

(Basel II) by simply replacing total loans by the sum of risk-weighted loans to entrepreneurs and to households, as is done by Angelini et al. (2014).

References

Adjemian, S., H. Bastani, F. Karame, M. Juillard, J. Maih, F. Mihoubi, G. Perendia, J. Pfeifer, M. Ratto, and S. Villemot: 2011, 'Dynare: Reference Manual Version 4'. Dynare Working Papers 1, CEPREMAP.

Adolfson, M., S. Laseen, J. Linde, and M. Villani: 2005, 'The Role of Sticky Prices in an Open Economy DSGE Model: A Bayesian Investigation'. *Journal of the European Economic Association* **3**(2-3), 444–457.

Adolfson, M., S. Laseen, J. Linde, and M. Villani: 2007, 'Bayesian estimation of an open economy DSGE model with incomplete pass-through'. *Journal of International Economics* **72**(2), 481–511.

Adolfson, M., S. Laseen, J. Linde, and M. Villani: 2008, 'Evaluating an estimated new Keynesian small open economy model'. *Journal of Economic Dynamics and Control* **32**(8), 2690–2721.

Agenor, P.-R., K. Alper, and L. A. Pereira da Silva: 2012, 'Capital requirements and business cycles with credit market imperfections'. *Journal of Macroeconomics* **34**(3), 687–705.

Agenor, P.-R., K. Alper, and L. A. Pereira da Silva: 2013, 'Capital Regulation, Monetary Policy, and Financial Stability'. *International Journal of Central Banking* **9**(3), 198–243.

Agenor, P.-R. and L. A. Pereira da Silva: 2014, 'Macroprudential regulation and the monetary transmission mechanism'. *Journal of Financial Stability* **13**(C), 44–63.

An, S. and F. Schorfheide: 2007, 'Bayesian Analysis of DSGE Models'. *Econometric Reviews* **26**(2-4), 113–172.

Angelini, P., S. Neri, and F. Panetta: 2014, 'The interaction between capital requirements and monetary policy'. *Journal of Money, Credit and Banking* **46**(6), 1073–1112.

Angeloni, I. and E. Faia: 2013, 'Capital regulation and monetary policy with fragile banks'. *Journal of Monetary Economics* **60**(3), 311–324.

Atkinson, A. and J. Stiglitz: 1969, 'A new view of technological change'. *The Economic Journal* **79**(315), 573–578.

Bergholt, D. and T. Sveen: 2015, 'Can Sticky Price Models Account for International Disturbances in Small Open Economies?'. mimeo.

Bernanke, B. S., M. Gertler, and S. Gilchrist: 1999, 'The financial accelerator in a quantitative business cycle framework'. In: J. B. Taylor and M. Woodford (eds.): *Handbook of Macroeconomics*, Vol. 1. Chapt. 21, pp. 1341–1393.

Bloom, N.: 2009, 'The Impact of Uncertainty Shocks'. *Econometrica* **77**(3), 623–685.

Brubakk, L. and P. Gelain: 2014, 'Financial factors and the macroeconomy - a policy model'. Staff Memo 10/2014, Norges Bank.

Brzoza-Brzezina, M. and M. Kolasa: 2013, 'Bayesian Evaluation of DSGE Models with Financial Frictions'. *Journal of Money, Credit and Banking* **45**(8), 1451–1476.

Brzoza-Brzezina, M., M. Kolasa, and K. Makarski: 2013, 'The anatomy of standard DSGE models with financial frictions'. *Journal of Economic Dynamics and Control* **37**(1), 32–51.

Calvo, G. A.: 1983, 'Staggered prices in a utility-maximizing framework'. *Journal of Monetary Economics* **12**(3), 383–398.

Cantore, C., M. A. Leon-Ledesma, P. McAdam, and A. Willman: 2014, 'Shocking stuff: technology, hours, and factor substitution'. *Journal of the European Economic Association* **12**(1), 108–128.

Chang, R., A. Fernandez, and A. Gulan: 2016, 'Bond finance, bank credit, and aggregate fluctuations in an open economy'. mimeo.

Christiano, L. J., M. Eichenbaum, and C. L. Evans: 2005, 'Nominal Rigidities and the Dynamic Effects of a Shock to Monetary Policy'. *Journal of Political Economy* **113**(1), 1–45.

Christiano, L. J., R. Motto, and M. Rostagno: 2003, 'The Great Depression and the Friedman-Schwartz Hypothesis'. *Journal of Money, Credit, and Banking* **35**(6 - part 2), 1119–1197.

Christiano, L. J., R. Motto, and M. Rostagno: 2008, 'Shocks, Structures or Monetary Policies? The Euro Area and US After 2001'. *Journal of Economic Dynamics and Control* **32**(8), 2476–2506.

Christiano, L. J., R. Motto, and M. Rostagno: 2014, 'Risk Shocks'. *American Economic Review* **104**(1), 27–65.

Christiano, L. J., M. Trabandt, and K. Walentin: 2011, 'Introducing financial frictions and unemployment into a small open economy model'. *Journal of Economic Dynamics and Control* **35**(12), 1999–2041.

Christoffel, K., G. Coenen, and A. Warne: 2008, 'The new area-wide model of the euro area - A micro-founded open-economy model for forecasting and policy analysis'. Working Paper Series 944, European Central Bank.

Clerc, L., A. Derviz, C. Mendicino, S. Moyen, K. Nikolov, L. Stracca, J. Suarez, and A. P. Vardoulakis: 2015, 'Capital Regulation in a Macroeconomic Model with Three Layers of Default'. *International Journal of Central Banking* **11**(3), 9–63.

Conesa, J. C., T. J. Kehoe, and K. J. Ruhl: 2007, 'Modeling great depressions: the depression in Finland in the 1990s'. *Quarterly Review* (Nov), 16–44.

Covas, F. and S. Fujita: 2010, 'Procyclicality of Capital Requirements in a General Equilibrium Model of Liquidity Dependence'. *International Journal of Central Banking* **6**(34), 137–173.

Curdia, V. and M. Woodford: 2010, 'Credit Spreads and Monetary Policy'. *Journal of Money, Credit, and Banking* **42**(Supplement s1), 3–35.

de Bondt, G., B. Mojon, and N. Valla: 2005, 'Term structure and the sluggishness of retail bank interest rates in euro area countries'. Working Paper Series 0518, European Central Bank.

de Walque, G., O. Pierrard, and A. Rouabah: 2010, 'Financial (in)stability, supervision and liquidity injections: a dynamic general equilibrium approach'. *The Economic Journal* **120**(549), 1234–1261.

Dieppe, A. and P. Guarda: 2015, 'Public debt, ageing and medium term growth'. ECB Occasional Paper Series 165, European Central Bank.

Dixit, A. K. and J. E. Stiglitz: 1977, 'Monopolistic Competition and Optimum Product Diversity'. *American Economic Review* **67**(3), 297–308.

Farmer, R. E.: 2013, 'Animal Spirits, Financial Crises and Persistent Unemployment'. *Economic Journal* **123**(May), 317–340.

Freystatter, H.: 2010, 'Financial market disturbances as sources of business cycle fluctuations in Finland'. Research Discussion Papers 5/2010, Bank of Finland.

Freystatter, H.: 2012, 'Essays on small open economy macroeconomics'. Scientific Monographs E:43-2012, Bank of Finland.

Fujiwara, I. and Y. Teranishi: 2011, 'Real exchange rate dynamics revisited: A case with financial market imperfections'. *Journal of International Money and Finance* **30**(7), 1562–1589.

Gambacorta, L. and F. M. Signoretti: 2014, 'Should monetary policy lean against the wind?'. *Journal of Economic Dynamics and Control* **43**(C), 146–174.

Gelain, P. and P. Ilbas: 2014, 'Monetary and macroprudential policies in an estimated model with financial intermediation'. Working Paper Research 258, National Bank of Belgium.

Gerali, A., S. Neri, L. Sessa, and F. M. Signoretti: 2010, 'Credit and Banking in a DSGE Model of the Euro Area'. *Journal of Money, Credit, and Banking* **42**(6), 107–141.

Gertler, M.: 1999, 'Government debt and social security in a life-cycle economy'. *Carnegie-Rochester Conference Series on Public Policy* **50**(1), 61–110.

Gertler, M. and P. Karadi: 2011, 'A model of unconventional monetary policy'. *Journal of Monetary Economics* **58**(1), 17–34.

Gilchrist, S. and E. Zakrajsek: 2012, 'Credit Spreads and Business Cycle Fluctuations'. *American Economic Review* **102**(4), 1692–1720.

Goodfriend, M. and B. T. McCallum: 2007, 'Banking and interest rates in monetary policy analysis: A quantitative exploration'. *Journal of Monetary Economics* **54**(5), 1480–1507.

Gorodnichenko, Y., E. G. Mendoza, and L. L. Tesar: 2012, 'The Finnish Great Depression: From Russia with Love'. *American Economic Review* **102**(4), 1619–1644.

Gropp, R., C. Kok, and J.-D. Lichtenberger: 2014, 'The Dynamics of Bank Spreads and Financial Structure'. *Quarterly Journal of Finance* **4**(4).

Gulan, A., M. Haavio, and J. Kilponen: 2014, 'Kiss me deadly: From Finnish great depression to great recession'. Research Discussion Papers 24/2014, Bank of Finland.

Iacoviello, M.: 2005, 'House Prices, Borrowing Constraints, and Monetary Policy in the Business Cycle'. *American Economic Review* **95**(3), 739–764.

Iskrev, N.: 2010, 'Local identification in DSGE models'. *Journal of Monetary Economics* **57**(2), 189–202.

Jalava, J., M. Pohjola, A. Ripatti, and J. Vilmunen: 2006, 'Biased Technical Change and Capital-Labour Substitution in Finland, 1902-2003'. *The B.E. Journal of Macroeconomics* **6**(1), 1–20.

Jones, C. I.: 2005, 'The Shape of Production Functions and the Direction of Technical Change'. *The Quarterly Journal of Economics* **120**(2), 517–549.

Jorda, O., M. Schularick, and A. M. Taylor: 2013, 'When Credit Bites Back'. *Journal of Money, Credit and Banking* **45**(s2), 3–28.

Justiniano, A. and B. Preston: 2010, 'Can structural small open-economy models account for the influence of foreign disturbances?'. *Journal of International Economics* **81**(1), 61–74.

Justiniano, A., G. E. Primiceri, and A. Tambalotti: 2010, 'Investment shocks and business cycles'. *Journal of Monetary Economics* **57**(2), 132–145.

Justiniano, A., G. E. Primiceri, and A. Tambalotti: 2011, 'Investment Shocks and the Relative Price of Investment'. *Review of Economic Dynamics* **14**(1), 101–121.

Kaihatsu, S. and T. Kurozumi: 2014, 'Sources of Business Fluctuations: Financial or Technology Shocks?'. *Review of Economic Dynamics* **17**(2), 224–242.

Kamber, G. and C. Thoenissen: 2013, 'Financial Exposure and the International Transmission of Financial Shocks'. *Journal of Money, Credit and Banking* **45**(s2), 127–158.

Kannan, P., P. Rabanal, and A. M. Scott: 2012, 'Monetary and Macroprudential Policy Rules in a Model with House Price Booms'. *The B.E. Journal of Macroeconomics* **12**(1), 1–44.

Kauko, K.: 2005, 'Bank interest rates in a small European economy: Some exploratory macro level analyses using Finnish data'. Research Discussion Papers 9/2005, Bank of Finland.

Kiley, M. T. and J. W. Sim: 2014, 'Bank capital and the macroeconomy: Policy considerations'. *Journal of Economic Dynamics and Control* **43**(C), 175–198.

Kilponen, J., H. Kinnunen, and P. Maki-Franti: 2014, 'Finland's long-term growth outlook has deteriorated'. Bank of Finland Bulletin 5, Bank of Finland.

Kilponen, J., M. Pisani, S. Schmidt, V. Corbo, T. Hledik, J. Hollmayr, S. Hurtado, P. Julio, D. Kulikov, M. Lemoine, M. Lozej, H. Lundvall, J. R. Maria, B. Micallef, D. Papageorgiou, J. Rysanek, D. Sideris, C. Thomas, and G. de Walque: 2015, 'Comparing fiscal multipliers across models and countries in Europe'. Working Paper Series 1760, European Central Bank.

Kilponen, J. and A. Ripatti: 2006, 'Labour and product market competition in a small open economy, Simulation results using a DGE model of the Finnish economy'. Research Discussion Papers 5/2006, Bank of Finland.

Kiyotaki, N. and J. Moore: 1997, 'Credit Cycles'. *Journal of Political Economy* **105**(2), 211–248.

Klump, R., P. McAdam, and A. Willman: 2012, 'The normalized CES production function: theory and empirics'. *Journal of Economic Surveys* **26**(5), 769–799.

Kobayashi, T.: 2008, 'Incomplete Interest Rate Pass-Through and Optimal Monetary Policy'. *International Journal of Central Banking* **4**(3), 77–118.

Kolasa, M. and G. Lombardo: 2014, 'Financial Frictions and Optimal Monetary Policy in an Open Economy'. *International Journal of Central Banking* **10**(1), 43–94.

Kollmann, R.: 2013, 'Global Banks, Financial Shocks, and International Business Cycles: Evidence from an Estimated Model'. *Journal of Money, Credit and Banking* **45**(s2), 159–195.

Lombardo, G. and P. McAdam: 2012, 'Financial market frictions in a model of the Euro area'. *Economic Modelling* **29**(6), 2460–2485.

Meh, C. A. and K. Moran: 2010, 'The role of bank capital in the propagation of shocks'. *Journal of Economic Dynamics and Control* **34**(3), 555–576.

Mendicino, C. and M. T. Punzi: 2014, 'House prices, capital inflows and macroprudential policy'. *Journal of Banking & Finance* **49**(C), 337–355.

Paries, M. D., C. K. Sorensen, and D. Rodriguez-Palenzuela: 2011, 'Macroeconomic Propagation under Different Regulatory Regimes: Evidence from an Estimated DSGE Model for the Euro Area'. *International Journal of Central Banking* **7**(4), 49–113.

Pissarides, C. A.: 2000, *Equilibrium Unemployment Theory, 2nd Edition*, Vol. 1 of *MIT Press Books*. The MIT Press.

Quint, D. and P. Rabanal: 2014, 'Monetary and Macroprudential Policy in an Estimated DSGE Model of the Euro Area'. *International Journal of Central Banking* **10**(2), 169–236.

Ravenna, F. and C. E. Walsh: 2006, 'Optimal monetary policy with the cost channel'. *Journal of Monetary Economics* **53**(2), 199–216.

Ripatti, A. and J. Vilmunen: 2001, 'Declining labour share - Evidence of a change in underlying production technology?'. Research Discussion Papers 10/2001, Bank of Finland.

Rubio, M. and J. A. Carrasco-Gallego: 2014, 'Macroprudential and monetary policies: Implications for financial stability and welfare'. *Journal of Banking & Finance* **49**(C), 326–336.

Rubio, M. and J. A. Carrasco-Gallego: 2015, 'Macroprudential and monetary policy rules: a welfare analysis'. *Manchester School* **83**(2), 127–152.

Schmitt-Grohe, S. and M. Uribe: 2003, 'Closing small open economy models'. *Journal of International Economics* **61**(1), 163–185.

Schmitt-Grohe, S. and M. Uribe: 2012, 'What's News in Business Cycles'. *Econometrica* **80**(6), 2733–2764.

Smets, F. and R. Wouters: 2003, 'An Estimated Dynamic Stochastic General Equilibrium Model of the Euro Area'. *Journal of the European Economic Association* **1**(5), 1123–1175.

Smets, F. and R. Wouters: 2007, 'Shocks and Frictions in US Business Cycles: A Bayesian DSGE Approach'. *American Economic Review* **97**(3), 586–606.

Unsal, D. F.: 2013, 'Capital Flows and Financial Stability: Monetary Policy and Macroprudential Responses'. *International Journal of Central Banking* **9**(1), 233–285.

Van den Heuvel, S. J.: 2008, 'The welfare cost of bank capital requirements'. *Journal of Monetary Economics* **55**(2), 298–320.

Verona, F., M. M. F. Martins, and I. Drumond: 2013, '(Un)anticipated monetary policy in a DSGE model with a shadow banking system'. *International Journal of Central Banking* **9**(3), 73–117.

Willman, A., M. Kortelainen, H.-L. Mannisto, and M. Tujula: 2000, 'The BOF5 Macroeconomic Model of Finland, Structure and Equations'. *Economic Modelling* **17**, 275–303.

Private sector value added (Y)	Private sector value added deflator (P^Y)
Private consumption (C^H)	Private consumption deflator (P^{CH})
Private investment (I^H)	Private investment deflator (P^I)
Public investment (I^G)*	Export deflator (P^X)
Government consumption(C^G)*	Import deflator (P^M)
Total exports (X)	Foreign prices (P^W)*
Total imports (M)	Oil prices (P^{OIL})*
External demand (M^W)*	Prices of raw materials, excluding oil (P^{MX})*
Hours, private sector (H^F)	Nominal effective exchange rate (S)*
Hours, public sector (H^G)*	Domestic short term interest rate (R^{FI})
Compensation per hour (W)	Euro area short term interest rate $\left(R^{€}\right)^*$
Total loans to non financial sector corporations (BL)	Lending rate to financial sector corporations (R^B)

Table 1: Observables

Note. The variables denoted with $*$ are exogenous, and specified as first order autoregressive processes.

Parameter	Value	Description
Households		
β	0.998	discount factor
λ_w	1.45	markup, workers
δ	0.014	depreciation rate on capital
ϕ_a	0.0005	elasticity of return w.r.t. net foreign asset position
Firms		
μ	1.0054	gross growth rate permanent labor productivity
Π	1.0031	gross steady-state inflation rate
Λ_l	1.1	steady-state labor productivity
Λ_k	0.31	steady-state capital productivity
δ_Y	0.58	share parameter in the production function
ρ_Y	0.18	substitution parameter in the production function
$\Upsilon = -1/\rho^z$	1.08	price markup of intermediate good producing firms
δ_c	0.79	share parameter in the production function
ρ_c	0.05	substitution parameter in the production function
Λ_{cy}	2	productivity shifter
Λ_{cm}	1.69	productivity shifter
δ_i	0.29	share parameter in the production function
ρ_i	-0.78	substitution parameter in the production function
Λ_{iy}	4.8	productivity shifter
Λ_{im}	1.44	productivity shifter
δ_x	0.95	share parameter in the production function
ρ_x	1.06	substitution parameter in the production function
Λ_{xy}	4.31	productivity shifter
Λ_{xm}	0.21	productivity shifter
$\Upsilon^f = -1/\rho^f$	1.05	price markup of export producing firms
$\Upsilon_m = -1/\rho_m$	1.05	price markup of FCP and PCP firms
Entrepreneurs		
γ	0.988	survival probability entrepreneurs
W^e	0.01	transfer from households
Banks		
ε^b	3.82	steady-state elasticity of the demand for funds
υ^b	0.09	bank capital-to-asset ratio
δ^b	0.062	depreciation rate bank capital
Policy		
$\mathbf{s_{GCF}}$	0.068	share of government consumption
$\mathbf{s_{IG}}$	0.171	share of government investment
$\mathbf{s_{LGH}}$	0.231	share of hours worked in government sector
τ^W	0.32	tax on labor income
τ^F	0.16	social security contribution
τ^C	0.21	tax on consumption
τ^K	0.20	tax on capital income
Others		
ω^{OIL}	0.15	share of oil imports of total imports
ω^{RAW}	0.5	share of raw materials in total imports

Table 2: Model parameters (time unit of model: quarterly)

Variable	Data†	Model
C/Y	0.75	0.70
I/Y	0.28	0.27
X/Y	0.52	0.45
M^C/C	0.17	0.16
M^I/I	0.38	0.39
M^X/X	0.50	0.51
non-financial corporations loans-to-gdp ratio	1.50	1.50
spread (loan rate - risk-free rate), annual (%)	1.5	1.5

† Sample period: 1995Q2 – 2014Q4

Table 3: Steady-state properties, model versus Finnish data

Parameter		Prior distribution			Posterior distribution				
		type	mean	std	mode	mean	median	5%	95%
External habit formation	b_c	β	0,50	0,20	0,95	0,95	0,95	0,93	0,98
Calvo wages	ξ_w	β	0,50	0,20	0,93	0,94	0,94	0,92	0,96
Calvo prices	ζ	β	0,50	0,20	0,38	0,39	0,39	0,33	0,46
Indexation prices	θ	β	0,50	0,20	0,77	0,74	0,76	0,56	0,95
Calvo import prices	ζ_m	β	0,50	0,20	0,86	0,86	0,86	0,83	0,89
Indexation import prices	θ_m	β	0,50	0,20	0,11	0,16	0,15	0,03	0,28
Share of FCP firms	ω_m	β	0,50	0,20	0,75	0,74	0,74	0,58	0,90
Calvo export prices	ζ_x	β	0,50	0,20	0,08	0,12	0,10	0,02	0,21
Indexation export prices	θ_x	β	0,50	0,20	0,32	0,36	0,34	0,06	0,66
Investment adjustment cost	γ_I	Γ	5,00	2,50	7,20	8,20	8,12	6,36	9,99
Adjustment cost function	γ_{cm}	Γ	2,00	1,00	0,15	0,24	0,21	0,04	0,43
Adjustment cost function	γ_{im}	Γ	5,00	2,50	5,07	5,12	5,03	3,64	6,57
Elasticity of substitution - export demand	σ_w	N	1,50	0,20	0,96	0,96	0,94	0,80	1,11
Frisch elasticity	σ_l	Γ	1,00	0,50	0,61	0,87	0,84	0,29	1,44
Loan rate adjustment cost	κ_b	Γ	5,00	2,50	4,70	4,55	4,45	3,08	5,97
Leverage deviation cost	κ_{K^b}	Γ	1,00	0,50	0,07	0,08	0,07	0,03	0,12

Table 4: Prior and posterior distributions of the structural parameters

Parameter		Prior distribution			Posterior distribution				
AR(1) shock		type	mean	std	mode	mean	median	5%	95%
Technology shocks									
permanent labour productivity	ρ_{μ}	β	0,50	0,20	0,98	0,97	0,97	0,94	0,99
temporary labour productivity	$\rho_{\lambda l}$	β	0,50	0,20	0,93	0,94	0,94	0,91	0,96
temporary capital productivity	$\rho_{\lambda k}$	β	0,50	0,20	0,12	0,14	0,14	0,05	0,23
productivity shifter in consumption	ρ_{cy}	β	0,50	0,20	0,76	0,75	0,76	0,64	0,87
productivity shifter in consumption	ρ_{cm}	β	0,50	0,20	0,33	0,43	0,41	0,10	0,74
productivity shifter in investment	ρ_{iy}	β	0,50	0,20	0,57	0,57	0,58	0,28	0,86
Domestic markup shock									
price markup, export producing firm	ρ_{vx}	β	0,50	0,20	0,66	0,59	0,60	0,39	0,79
Domestic demand shocks									
government consumption	ρ_{cG}	β	0,50	0,20	0,86	0,82	0,82	0,70	0,94
government investment	ρ_{iG}	β	0,50	0,20	0,79	0,81	0,81	0,69	0,92
government hours	ρ_{hG}	β	0,50	0,20	0,97	0,97	0,97	0,94	0,99
household consumption preference	$\rho_{\zeta C}$	β	0,50	0,20	0,08	0,11	0,10	0,02	0,19
Foreign/external shocks									
foreign export demand	ρ_{mW}	β	0,50	0,20	0,94	0,93	0,93	0,89	0,97
export share	ρ_{x}	β	0,50	0,20	0,93	0,90	0,91	0,84	0,96
nominal exchange rate	$\rho_{\Delta s}$	β	0,50	0,20	0,16	0,18	0,18	0,07	0,29
foreign inflation shock	$\rho_{\pi W}$	β	0,50	0,20	0,19	0,20	0,20	0,08	0,32
price markup of import firms	ρ_{vm}	β	0,50	0,20	0,31	0,29	0,29	0,12	0,46
oil price	ρ_{OIL}	β	0,50	0,20	0,85	0,85	0,85	0,79	0,91
prices of raw materials	ρ_{RAW}	β	0,50	0,20	0,88	0,88	0,88	0,84	0,91
Financial shocks									
domestic risk premium	$\rho_{\zeta€}$	β	0,50	0,20	0,79	0,79	0,80	0,69	0,90
bank markup	$\rho_{\varepsilon b}$	β	0,50	0,20	0,70	0,63	0,65	0,36	0,89
bank capital	ρ_{Kb}	β	0,50	0,20	0,66	0,49	0,49	0,18	0,78
euro area interest rate	$\rho_{r€}$	β	0,50	0,20	0,97	0,95	0,95	0,92	0,98

Table 5: Prior and posterior distributions of the structural parameters – exogenous processes

Parameter		Prior distribution			Posterior distribution				
Standard deviations		type	mean	std	mode	mean	median	5%	95%
Technology shocks									
permanent labour productivity	σ_{μ}	Γ^{-1}	0,005	2	0,0029	0,0037	0,0035	0,0023	0,0051
temporary labour productivity	$\sigma_{\lambda l}$	Γ^{-1}	0,025	2	0,0433	0,0442	0,0439	0,0373	0,0511
temporary capital productivity	$\sigma_{\lambda k}$	Γ^{-1}	0,025	2	0,0514	0,0532	0,0528	0,0448	0,0614
productivity shifter in consumption	σ_{cy}	Γ^{-1}	0,01	2	0,0071	0,0073	0,0073	0,0062	0,0084
productivity shifter in consumption	σ_{cm}	Γ^{-1}	0,01	2	0,0076	0,0074	0,0071	0,0031	0,0116
productivity shifter in investment	σ_{iy}	Γ^{-1}	0,025	2	0,0074	0,0075	0,0075	0,0058	0,0092
Domestic markup shocks									
price markup, intermediate good firms	σ_{v}	Γ^{-1}	0,01	2	0,0258	0,0272	0,0268	0,0216	0,0326
price markup, export producing firm	σ_{vx}	Γ^{-1}	0,05	2	0,0193	0,0222	0,0213	0,0161	0,0280
wage markup	$\sigma_{\lambda w}$	Γ^{-1}	2	2	2,0630	2,7482	2,5588	1,3068	4,1530
Domestic demand shocks									
government consumption	σ_{cG}	Γ^{-1}	0,05	2	0,0607	0,0613	0,0610	0,0533	0,0693
government investment	σ_{iG}	Γ^{-1}	0,05	2	0,0540	0,0556	0,0554	0,0481	0,0629
government hours	σ_{hG}	Γ^{-1}	0,005	2	0,0034	0,0035	0,0035	0,0030	0,0040
household consumption preference	$\sigma_{\zeta C}$	Γ^{-1}	0,05	2	0,2271	0,2393	0,2250	0,1327	0,3433
Foreign/external shocks									
foreign export demand	σ_{mW}	Γ^{-1}	0,02	2	0,0204	0,0208	0,0207	0,0181	0,0235
export share	σ_{x}	Γ^{-1}	0,05	2	0,0483	0,0488	0,0485	0,0418	0,0555
nominal exchange rate	$\sigma_{\Delta s}$	Γ^{-1}	0,01	2	0,0159	0,0161	0,0161	0,0141	0,0182
foreign inflation	$\sigma_{\pi W}$	Γ^{-1}	0,02	2	0,0177	0,0180	0,0179	0,0156	0,0203
price markup of import firms	σ_{vm}	Γ^{-1}	0,7	2	0,4550	0,5377	0,5071	0,2726	0,7905
oil price	σ_{OIL}	Γ^{-1}	0,1	2	0,1462	0,1492	0,1484	0,1296	0,1686
prices of raw materials	σ_{RAW}	Γ^{-1}	0,08	2	0,0811	0,0829	0,0825	0,0715	0,0940
Financial shocks									
domestic risk premium	$\sigma_{\zeta €}$	Γ^{-1}	0,0005	2	0,0004	0,0004	0,0004	0,0004	0,0005
bank markup	$\sigma_{\varepsilon b}$	Γ^{-1}	0,002	2	0,0018	0,0017	0,0017	0,0012	0,0023
bank capital	σ_{Kb}	Γ^{-1}	0,05	2	0,0276	0,0477	0,0404	0,0133	0,0836
euro area interest rate	$\sigma_{r€}$	Γ^{-1}	0,005	2	0,0011	0,0011	0,0011	0,0009	0,0012

Table 6: Prior and posterior distributions of the structural parameters – exogenous processes

forecast horizons (quarters)	**shocks**														
	technology			domestic demand			domestic markup			external			financial		
	mean	5%	95%	mean	5%	95%	mean	5%	95%	mean	5%	95%	mean	5%	95%
1	16,9	9,5	24,5	10,2	4,3	15,9	18,4	8,2	28,8	54,2	44,1	65,1	0,2	0,0	0,5
2	32,2	22,2	42,3	6,9	2,8	11,1	18,7	6,4	30,2	41,9	30,7	53,0	0,3	0,0	0,6
4	56,3	43,9	68,6	2,6	1,1	4,2	21,5	6,6	34,7	19,5	12,0	26,5	0,2	0,0	0,3
8	70,4	55,8	84,1	1,0	0,4	1,6	21,1	5,9	33,9	7,4	4,7	10,1	0,1	0,0	0,2
16	76,7	61,2	92,8	0,6	0,2	1,1	17,3	4,7	27,9	5,1	3,3	6,9	0,2	0,0	0,4
32	80,3	61,5	100,0	0,5	0,2	1,0	14,5	4,3	23,6	4,4	2,5	6,1	0,2	0,1	0,4
∞	84,9	46,7	122,1	0,5	0,1	0,9	10,6	2,9	18,1	3,7	1,3	5,8	0,4	0,0	0,7

Table 7: Forecast-error-variance decompositions, output

forecast horizons (quarters)	**technology shocks**						
	total	temporary capital	temporary labor	permanent labor	shifter in consumption	shifter in consumption	shifter in investment
1	16,9	6,5	5,7	2,2	1,9	0,0	0,6
2	32,2	10,3	18,0	2,3	1,3	0,0	0,3
4	56,3	10,1	44,2	1,1	0,7	0,0	0,1
8	70,4	4,8	60,2	5,1	0,4	0,0	0,1
16	76,7	2,7	57,2	16,5	0,2	0,0	0,0
32	80,3	2,2	51,4	26,5	0,2	0,0	0,0
∞	84,9	1,6	38,9	44,2	0,2	0,0	0,0

Table 8: Forecast-error-variance decompositions, output, mean contribution of each technology shock

forecast horizons (quarters)	**foreign shocks**							
	total	oil price	prices of raw materials	export demand	foreign inflation	exchange rate	price markup of import firms	export share
1	54,2	0,0	0,1	7,7	7,6	6,9	0,3	31,7
2	41,9	0,0	0,1	5,6	7,5	6,4	0,1	22,1
4	19,5	0,0	0,0	2,3	4,2	3,7	0,4	8,8
8	7,4	0,0	0,1	0,8	1,3	1,2	0,6	3,3
16	5,1	0,0	0,1	0,6	0,8	0,7	0,4	2,4
32	4,4	0,0	0,2	0,5	0,7	0,6	0,4	2,0
∞	3,7	0,0	0,2	0,6	0,5	0,4	0,3	1,7

Table 9: Forecast-error-variance decompositions, output, mean contribution of each foreign shock

forecast horizons (quarters)	**shocks**														
	technology			domestic demand			domestic markup			external			financial		
	mean	5%	95%	mean	5%	95%	mean	5%	95%	mean	5%	95%	mean	5%	95%
1	4,1	0,5	7,8	0,1	0,0	0,1	0,4	0,1	0,7	0,9	0,1	1,9	94,6	82,5	107,6
2	6,5	0,8	12,4	0,0	0,0	0,1	0,8	0,2	1,4	1,2	0,1	2,6	91,5	74,9	109,3
4	12,2	1,6	22,6	0,1	0,0	0,1	2,2	0,4	4,0	2,1	0,1	4,3	83,5	61,1	105,4
8	23,4	5,5	40,2	0,3	0,0	0,6	5,5	0,7	10,3	4,2	0,4	7,7	66,6	40,7	91,7
16	37,3	10,0	63,4	0,5	0,0	1,0	6,7	0,9	12,7	6,9	1,6	11,8	48,5	23,3	72,9
32	59,6	29,6	96,6	0,3	0,0	0,7	4,1	0,2	8,2	5,9	0,7	11,4	30,0	8,9	51,9
∞	77,0	46,8	107,6	0,4	0,0	0,8	2,5	0,1	5,3	3,7	0,2	7,8	16,5	1,3	33,6

Table 10: Forecast-error-variance decompositions, interest rate on loans

forecast horizons (quarters)	**financial shocks**				
	total	domestic risk premium	euro area interest rate	bank markup	bank capital
1	94,6	5,9	74,3	12,7	1,7
2	91,5	5,2	74,3	9,8	2,2
4	83,5	3,9	70,6	6,3	2,8
8	66,6	2,3	58,1	3,3	3,0
16	48,5	1,2	43,1	1,7	2,5
32	30,0	0,6	26,8	0,9	1,7
∞	16,5	0,3	14,7	0,5	1,0

Table 11: Forecast-error-variance decompositions, interest rate on loans, mean contribution of each financial shock

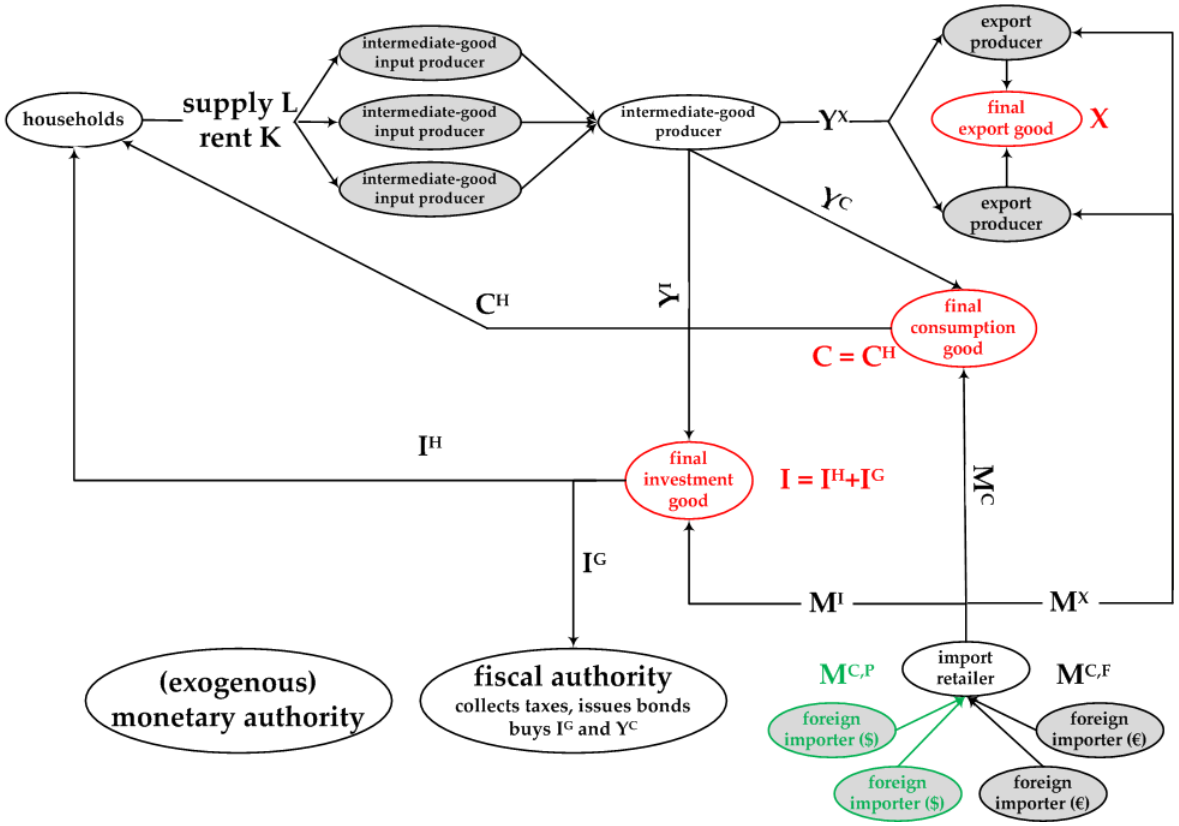

Figure 1: Sketch of the model

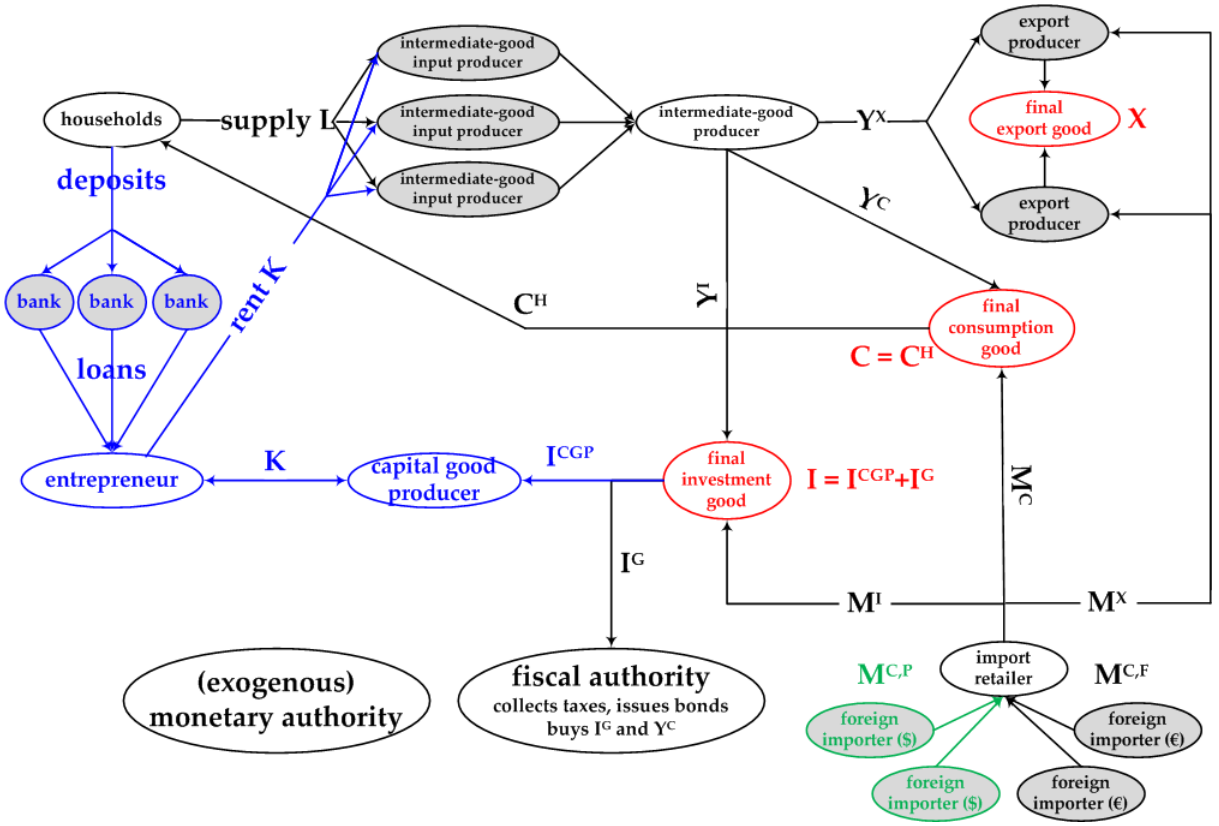

Figure 2: The model with the banking sector

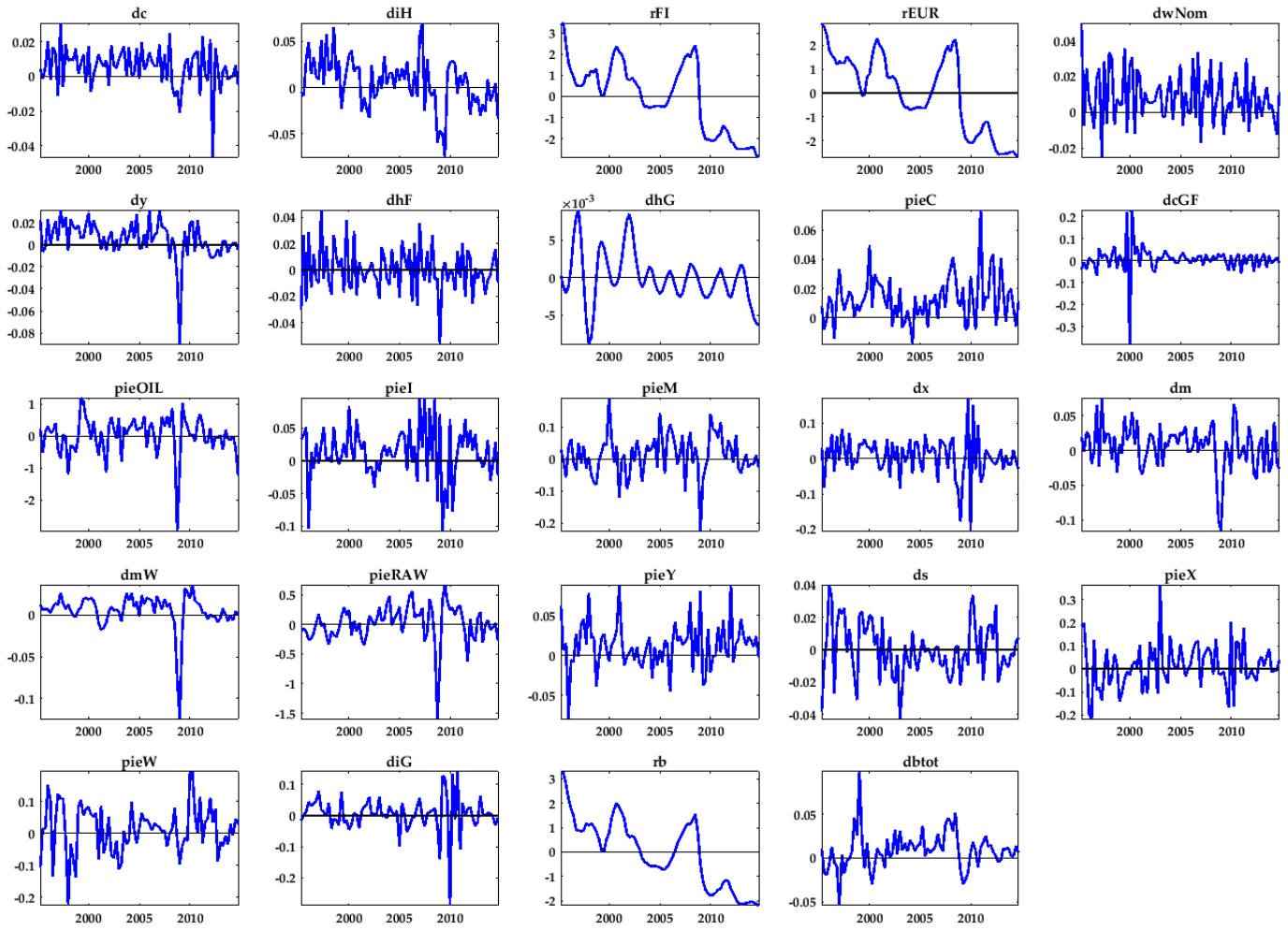

Figure 3: the data

Note. This figure shows the time series of the observed variables used in the estimation of *Aino 2.0*.

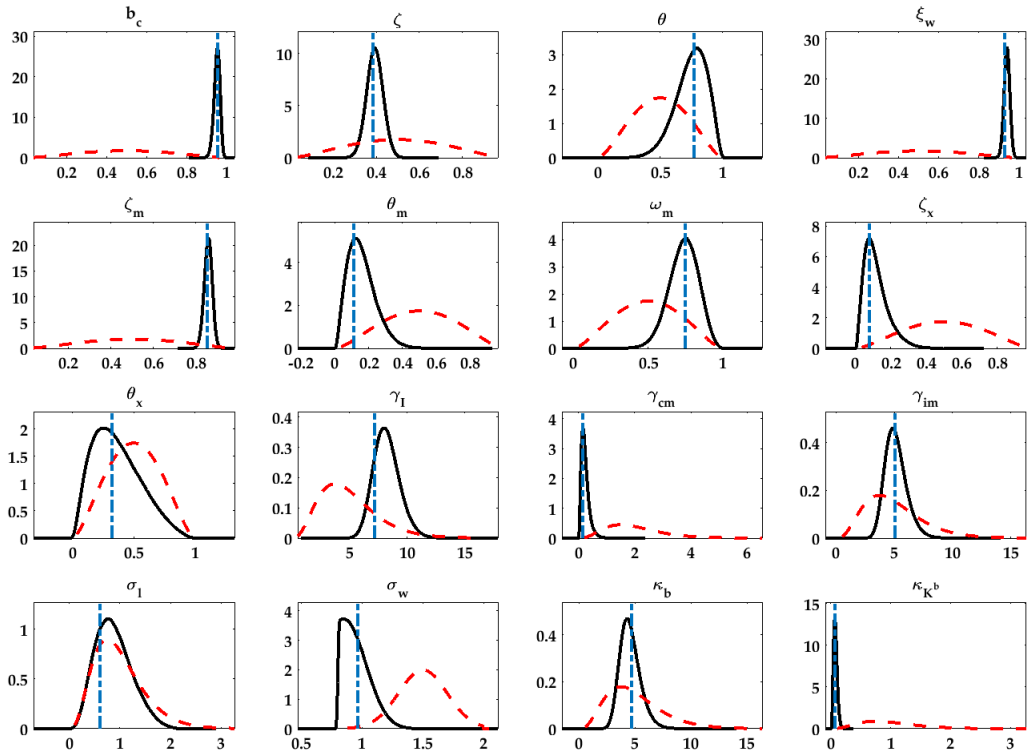

Figure 4: Prior and posterior distributions of the structural parameters

Note. This figure shows the marginal posterior distributions of the structural parameters based on two Markov chains with 8 million draws each (black solid lines) against their marginal prior distributions (red dashed lines), with 50% of the draws being discarded as burn-in draws. The blue dashed-dotted vertical line indicates the posterior mode.

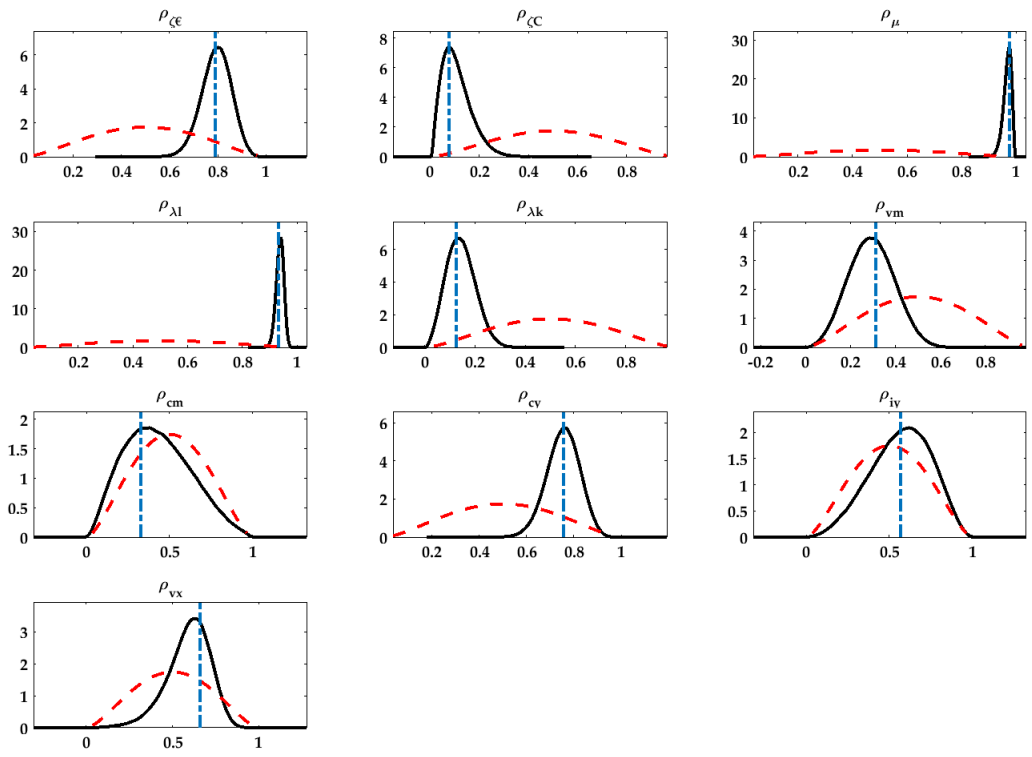

Figure 4: Prior and posterior distributions of the structural parameters (continued)

Note. This figure shows the marginal posterior distributions of the structural parameters based on two Markov chains with 8 million draws each (black solid lines) against their marginal prior distributions (red dashed lines), with 50% of the draws being discarded as burn-in draws. The blue dashed-dotted vertical line indicates the posterior mode.

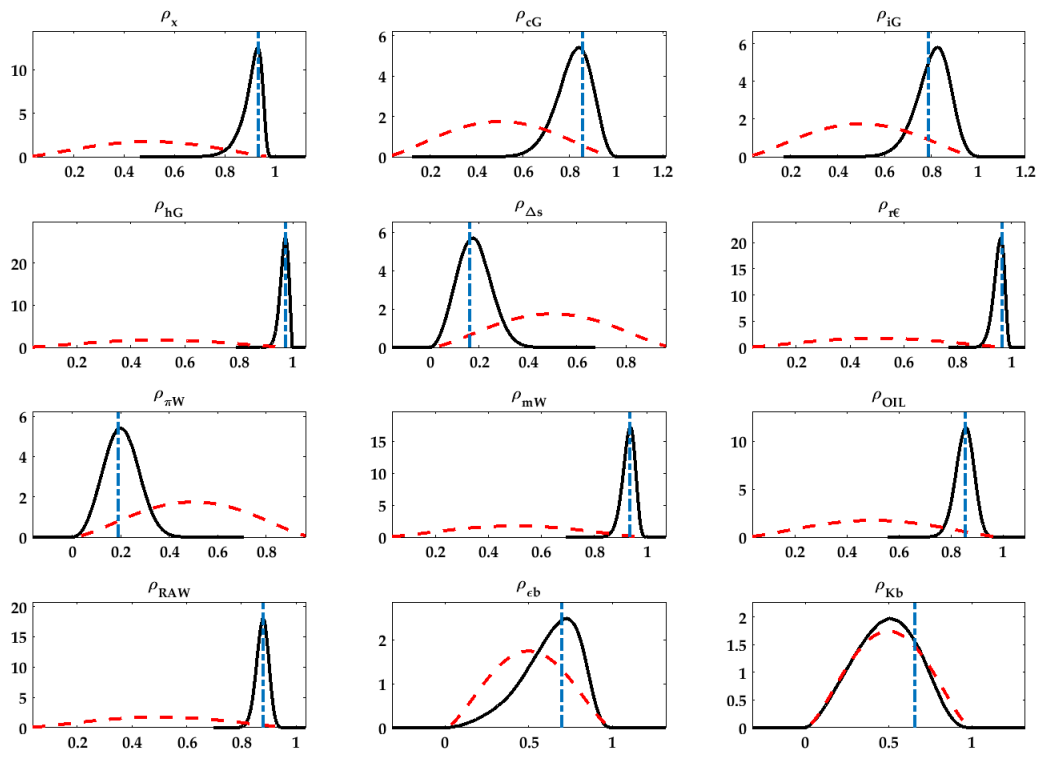

Figure 4: Prior and posterior distributions of the structural parameters (continued)

Note. This figure shows the marginal posterior distributions of the structural parameters based on two Markov chains with 8 million draws each (black solid lines) against their marginal prior distributions (red dashed lines), with 50% of the draws being discarded as burn-in draws. The blue dashed-dotted vertical line indicates the posterior mode.

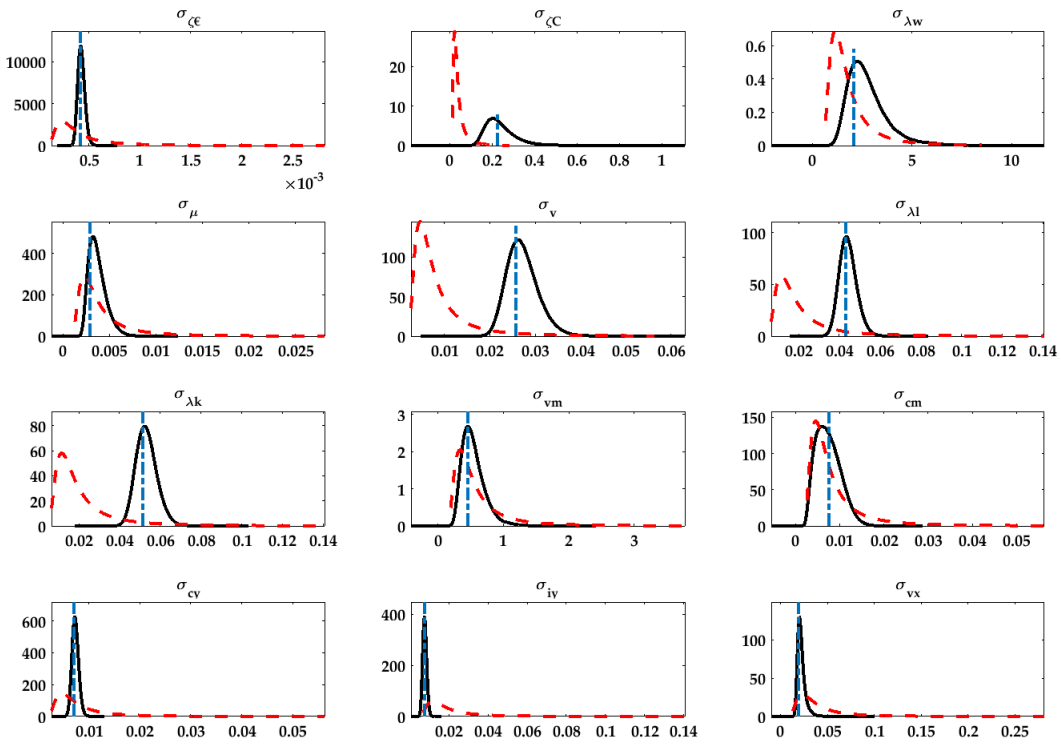

Figure 4: Prior and posterior distributions of the structural parameters (continued)

Note. This figure shows the marginal posterior distributions of the structural parameters based on two Markov chains with 8 million draws each (black solid lines) against their marginal prior distributions (red dashed lines), with 50% of the draws being discarded as burn-in draws. The blue dashed-dotted vertical line indicates the posterior mode.

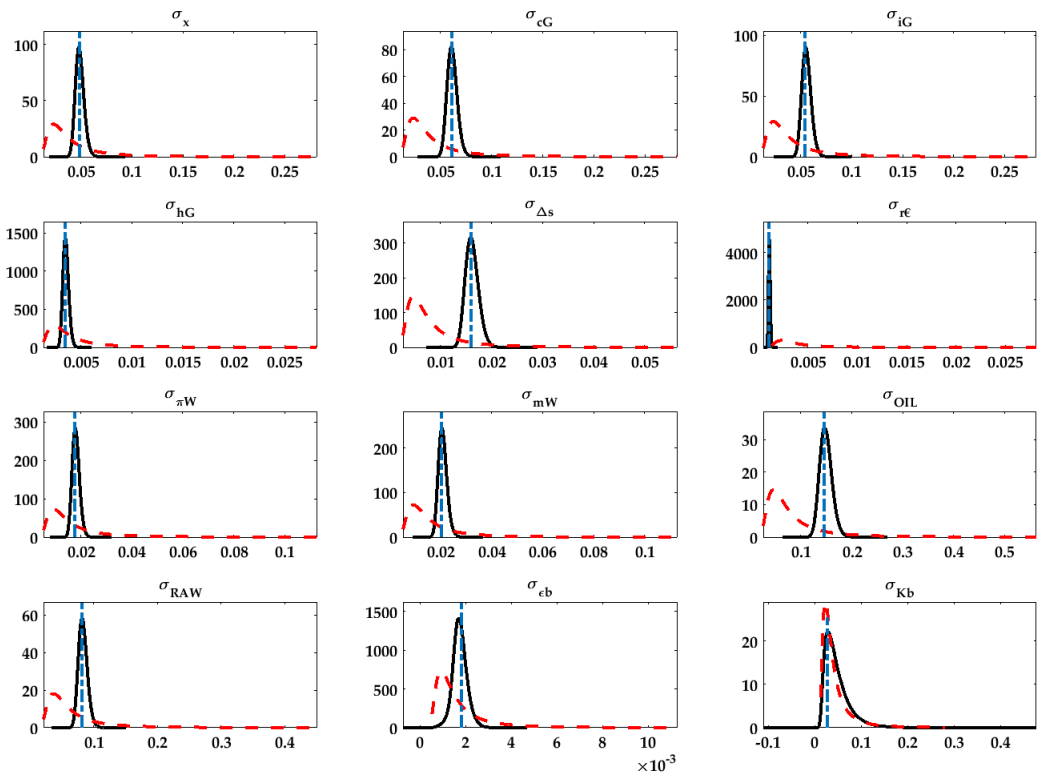

Figure 4: Prior and posterior distributions of the structural parameters (continued)

Note. This figure shows the marginal posterior distributions of the structural parameters based on two Markov chains with 8 million draws each (black solid lines) against their marginal prior distributions (red dashed lines), with 50% of the draws being discarded as burn-in draws. The blue dashed-dotted vertical line indicates the posterior mode.

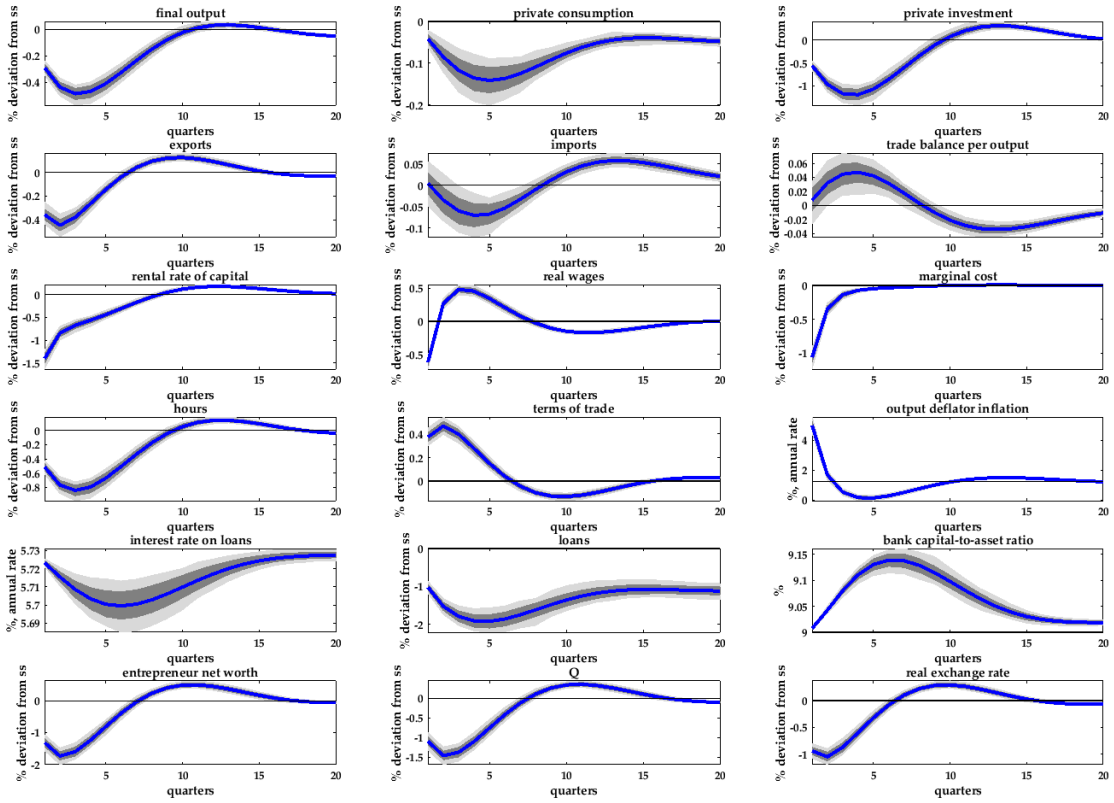

Figure 5: Impulse response functions - price markup intermediate good firms shock

Note. This figure shows the mean (blue solid line) and the 60 and 90 percent equal-tail uncertainty bands (grey-shaded areas) of the impulse responses of selected observed variables to a one standard deviation shock. All impulse responses are reported as percentage deviations from the non-stochastic steady state, except for the impulse responses of the inflation and the loan interest rate which are reported as annual percentage points, and the bank capital-to-asset ratio which is reported as percent value. The results are based on 40000 draws from the posterior distribution of the model's parameters.

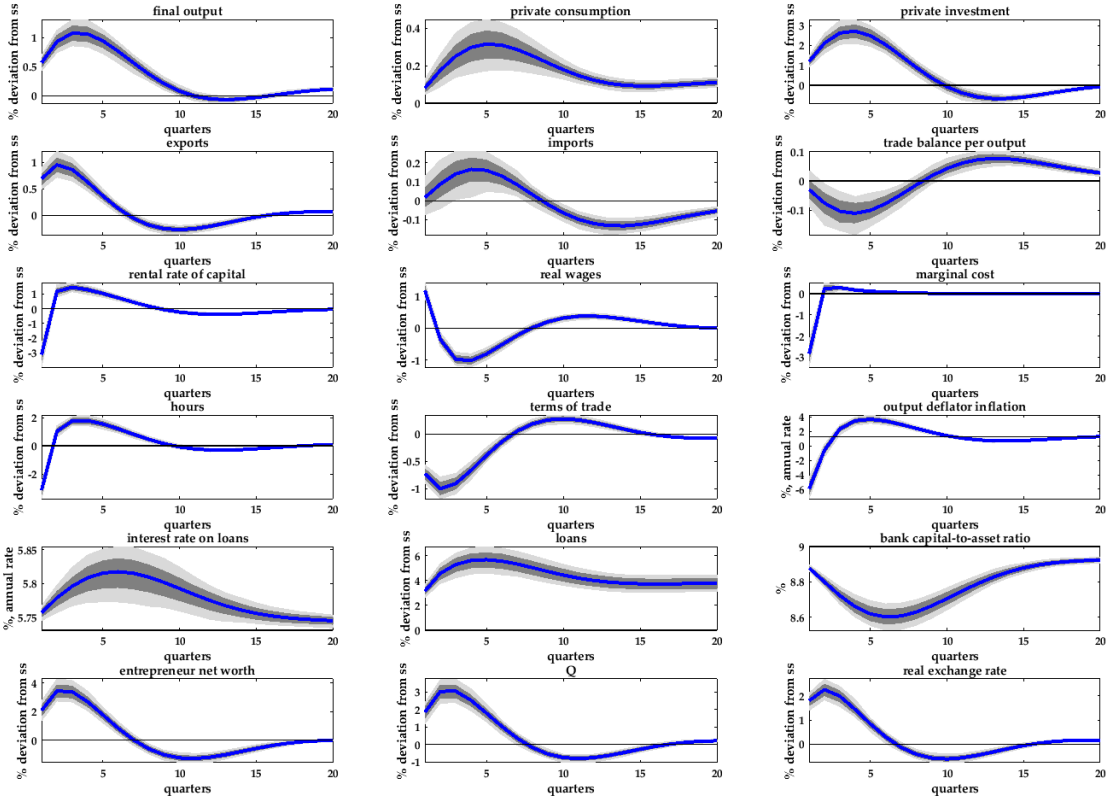

Figure 6: Impulse response functions - temporary capital productivity shock

Note. This figure shows the mean (blue solid line) and the 60 and 90 percent equal-tail uncertainty bands (grey-shaded areas) of the impulse responses of selected observed variables to a one standard deviation shock. All impulse responses are reported as percentage deviations from the non-stochastic steady state, except for the impulse responses of the inflation and the loan interest rate which are reported as annual percentage points, and the bank capital-to-asset ratio which is reported as percent value. The results are based on 40000 draws from the posterior distribution of the model's parameters.

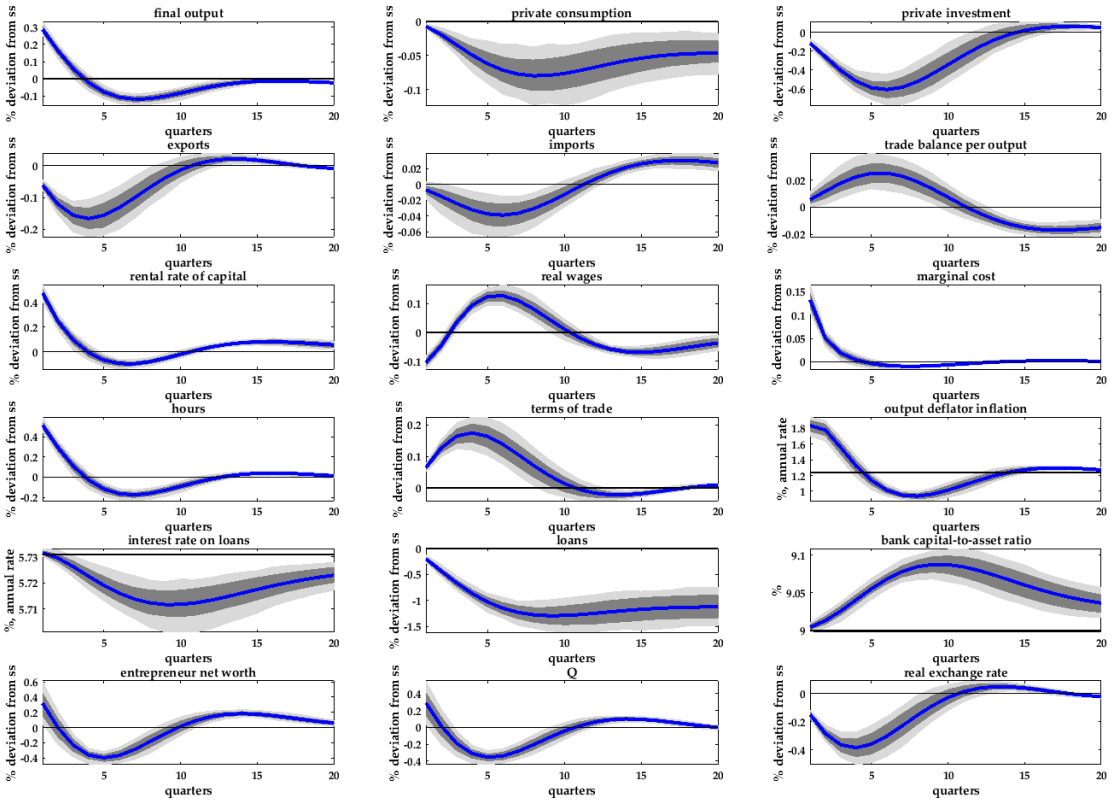

Figure 7: Impulse response functions - government consumption shock

Note. This figure shows the mean (blue solid line) and the 60 and 90 percent equal-tail uncertainty bands (grey-shaded areas) of the impulse responses of selected observed variables to a one standard deviation shock. All impulse responses are reported as percentage deviations from the non-stochastic steady state, except for the impulse responses of the inflation and the loan interest rate which are reported as annual percentage points, and the bank capital-to-asset ratio which is reported as percent value. The results are based on 40000 draws from the posterior distribution of the model's parameters.

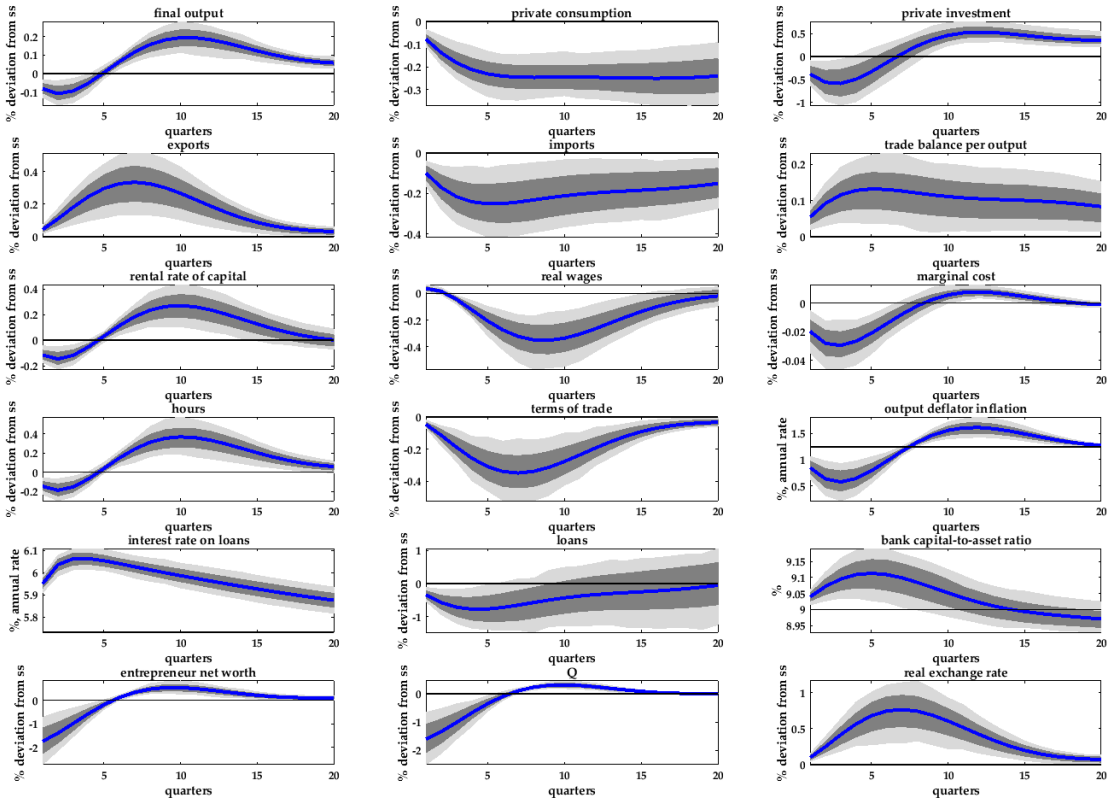

Figure 8: Impulse response functions - euro area interest rate shock

Note. This figure shows the mean (blue solid line) and the 60 and 90 percent equal-tail uncertainty bands (grey-shaded areas) of the impulse responses of selected observed variables to a one standard deviation shock. All impulse responses are reported as percentage deviations from the non-stochastic steady state, except for the impulse responses of the inflation and the loan interest rate which are reported as annual percentage points, and the bank capital-to-asset ratio which is reported as percent value. The results are based on 40000 draws from the posterior distribution of the model's parameters.

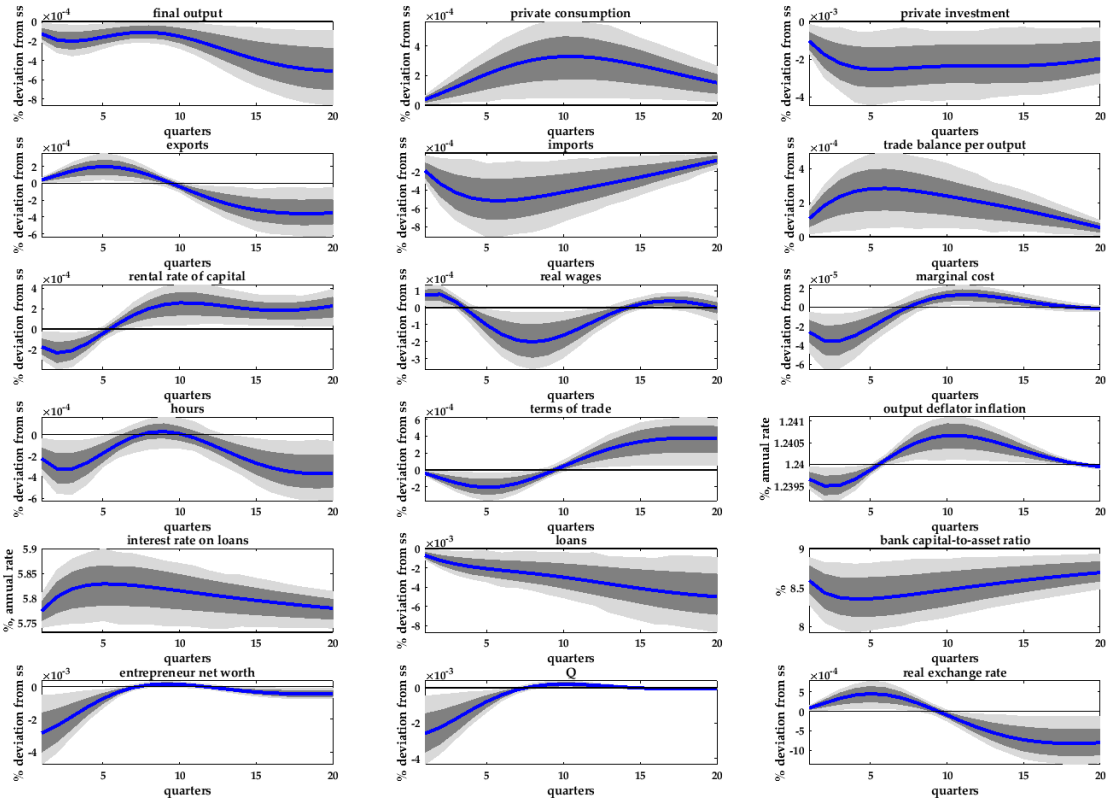

Figure 9: Impulse response functions - bank capital shock

Note. This figure shows the mean (blue solid line) and the 60 and 90 percent equal-tail uncertainty bands (grey-shaded areas) of the impulse responses of selected observed variables to a one standard deviation shock. All impulse responses are reported as percentage deviations from the non-stochastic steady state, except for the impulse responses of the inflation and the loan interest rate which are reported as annual percentage points, and the bank capital-to-asset ratio which is reported as percent value. The results are based on 40000 draws from the posterior distribution of the model's parameters.

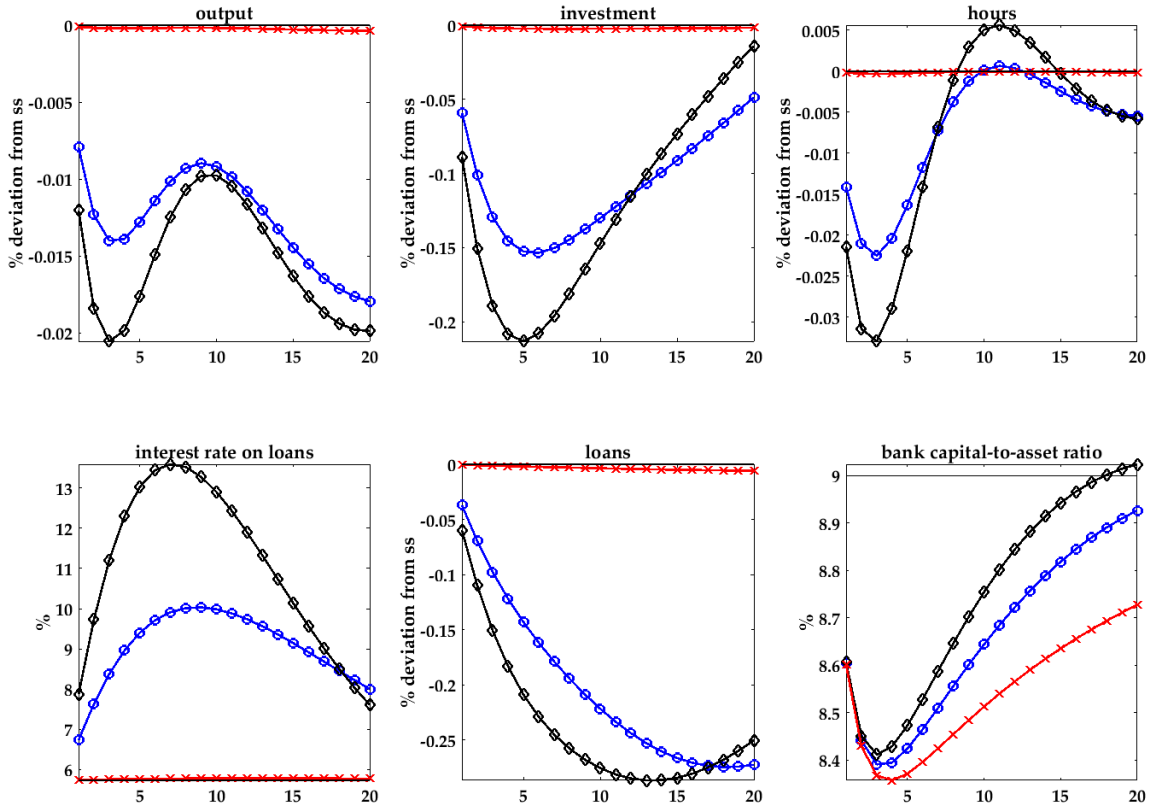

Figure 10: Impulse response functions - bank capital shock for different values of κ_{K^b}

Note. This figure shows the impulse responses of selected observed variables to a one standard deviation bank capital shock for different values of κ_{K^b} (we also set κ_b to 200). Red lines: $\kappa_{K^b} = 0.08$ (baseline estimated value); blue lines: $\kappa_{K^b} = 10$; black lines: $\kappa_{K^b} = 25$. All impulse responses are reported as percentage deviations from the non-stochastic steady state, except for the impulse responses of the loan interest rate which are reported as annual percentage points, and the bank capital-to-asset ratio which are reported as percent value.

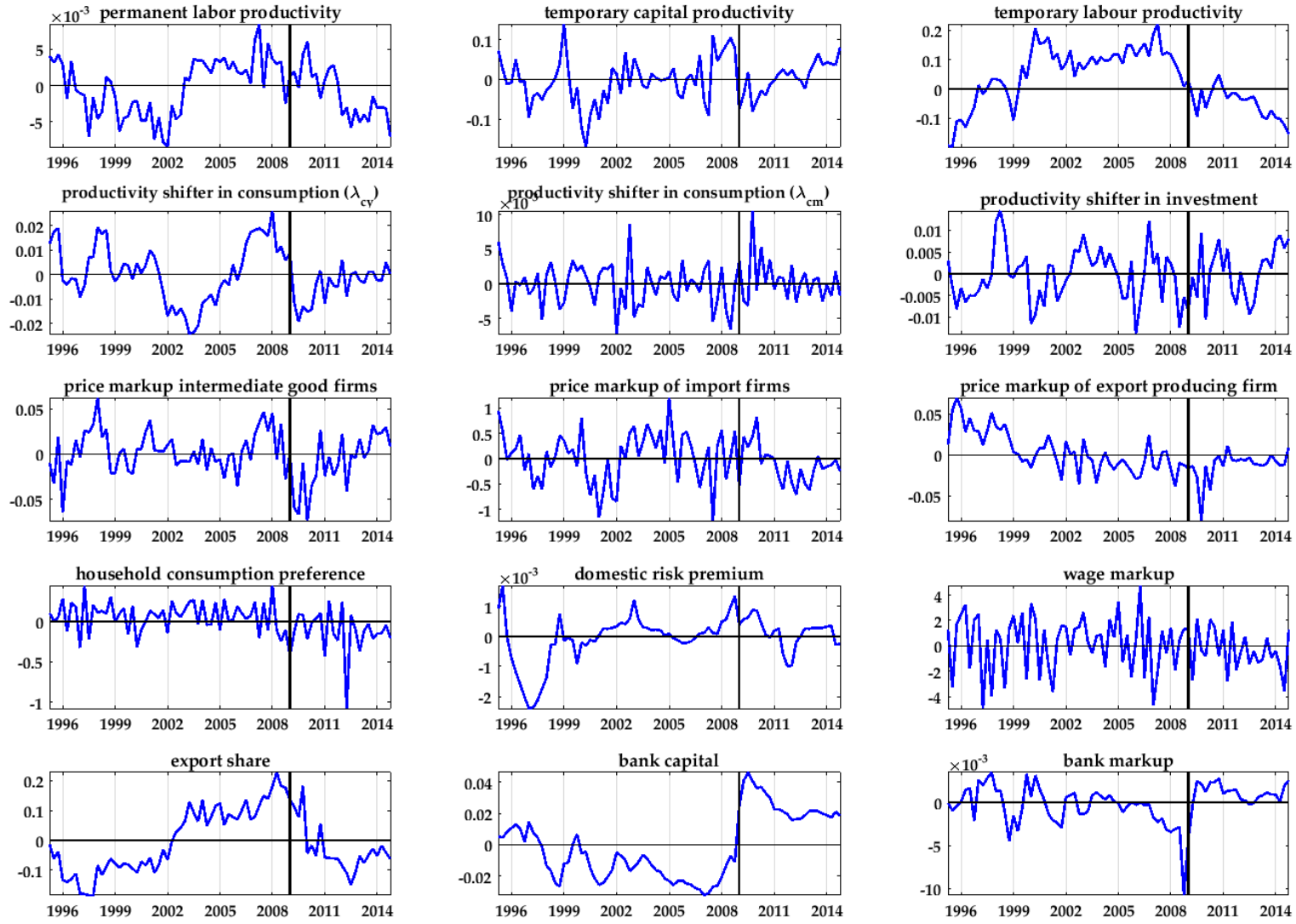

Figure 11: Smoothed estimates of the structural shocks

Note. This figure shows the smoothed estimates of the structural shocks. The vertical line – at 2009Q1 – corresponds to the peak of the recession (GDP growth rate). For the bank markup shock, we report the bank markup – computed as $\tilde{\varepsilon}_t^b / \left(\tilde{\varepsilon}_t^b - 1\right)$ – instead of the elasticity of substitution ($\tilde{\varepsilon}_t^b$).

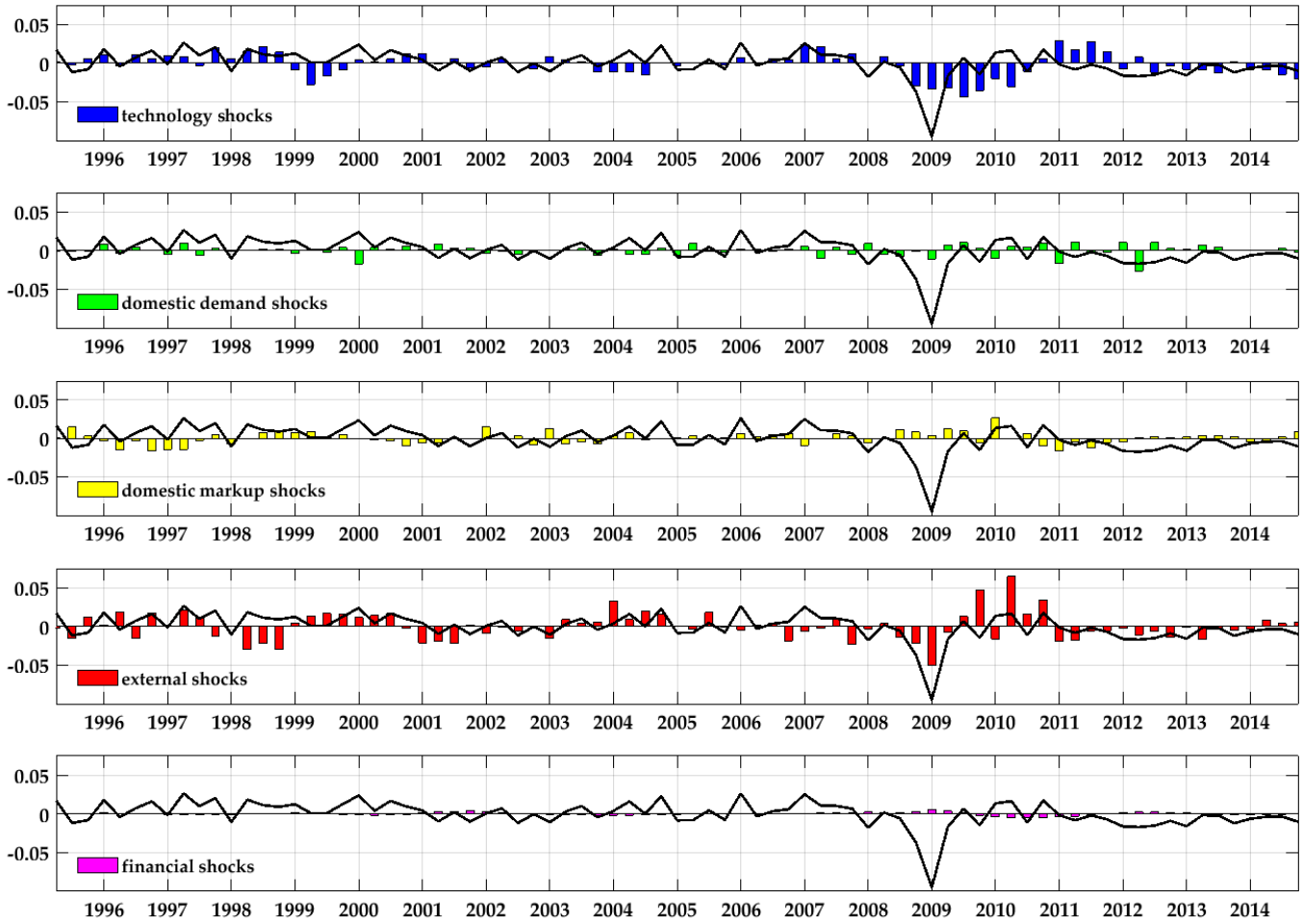

Figure 12: Historical decomposition of Finnish GDP growth rate

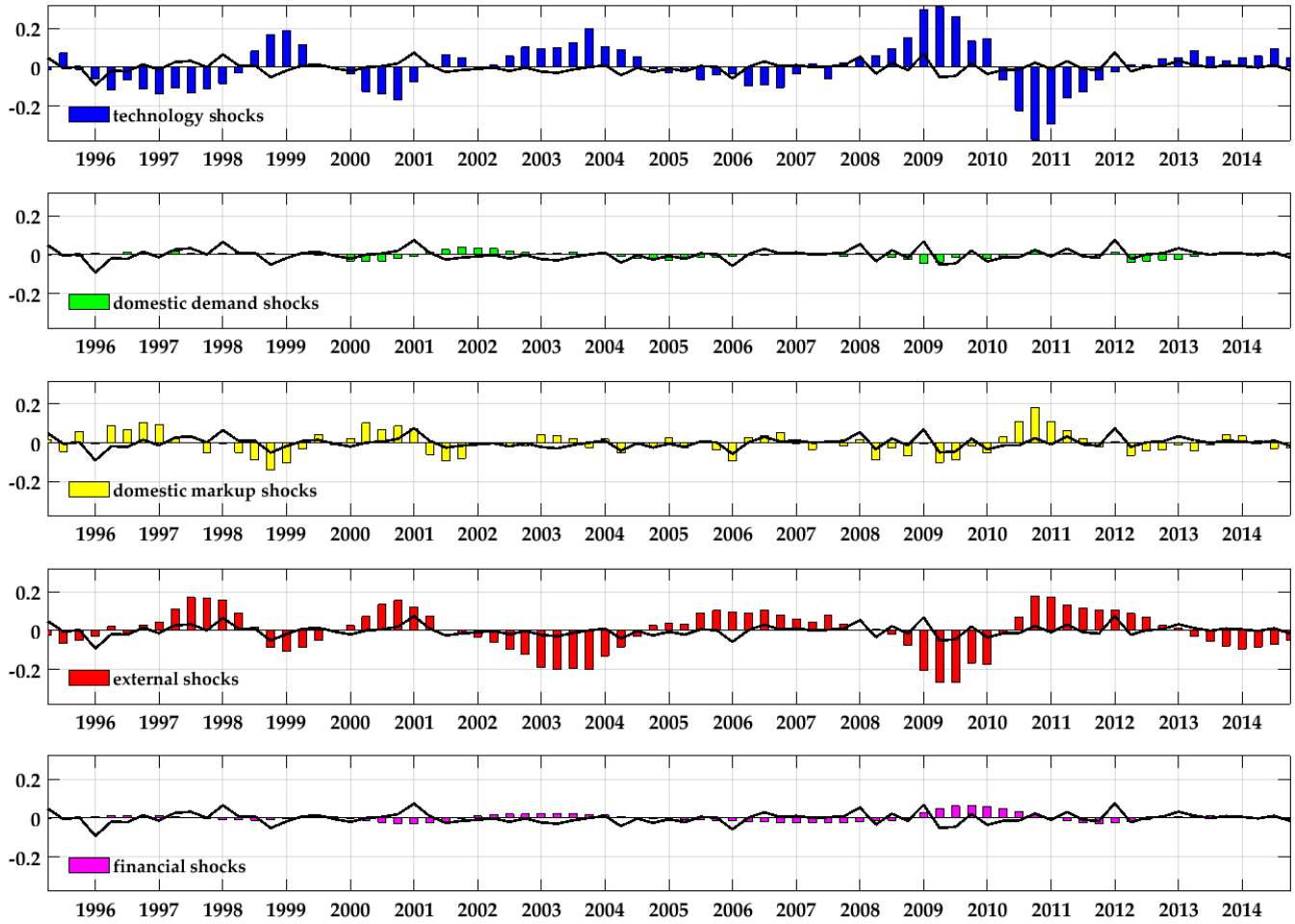

Figure 13: Historical decomposition of Finnish inflation rate

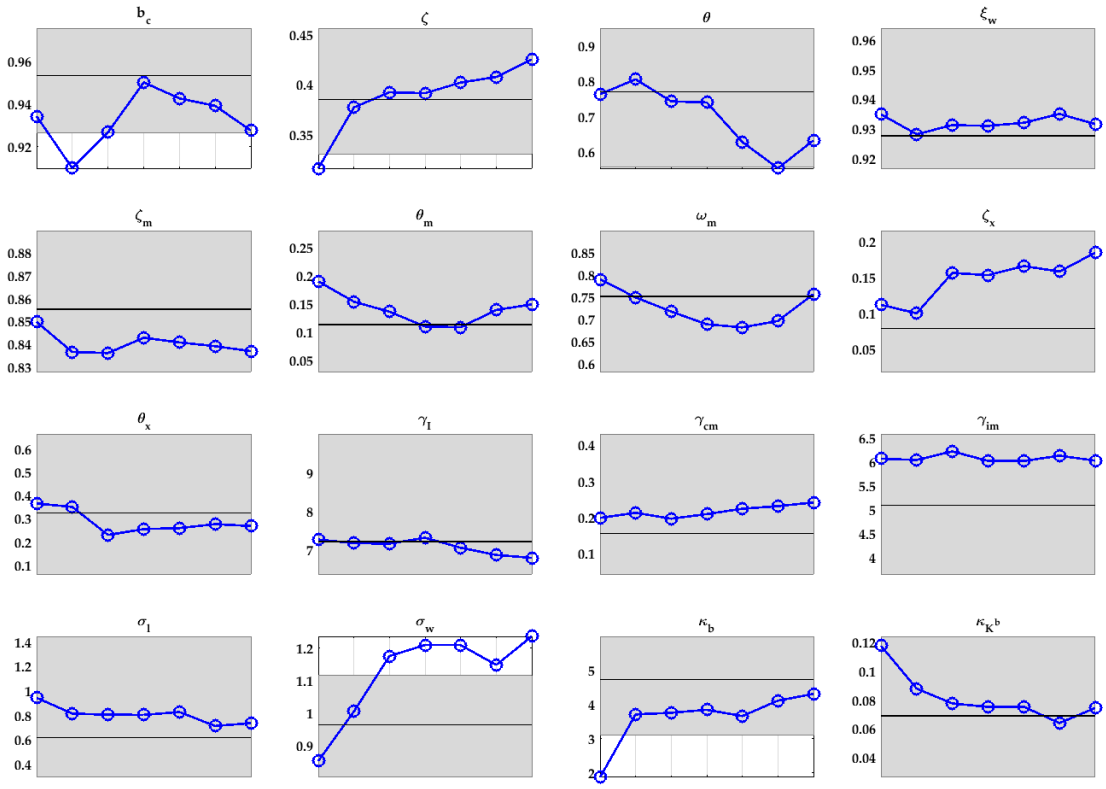

Figure 14: Rolling window posterior mode estimates of the structural parameters

Note. This figure shows the posterior mode of the structural parameters estimated using rolling window shifted by one year (blue lines). The first point is obtained by estimating the model for the period 1995Q2-2008Q4, and grey-shaded areas represent the 90% confidence band of the posterior distribution of the parameters.

Appendix A

This appendix shows the linearised model equations and the shock processes.[33] Before the log-linearising the model, we scale all the real variables by the permanent component of labour productivity ($\Lambda^P_{l,t}$) in order to render the transformed variable stationary. So, for any real variable V_t, $\widetilde{V}_t = V_t/\Lambda^P_{l,t}$ is the corresponding stationary variable. Finally, lower case letters with tilde (*e.g.* $\tilde{y}_t$, $\tilde{p}^C_t$) denote the log-linearised normalized variables. For trade balance, net foreign assets and tax rates, we use differences denoted by $\widehat{\ }$.

The linearised model

$$\tilde{bl}_{t+1} = \frac{Q\widetilde{P}^C\tilde{K}}{\tilde{BL}}\left(\tilde{q}_t + \tilde{p}^C_t + \tilde{k}_{t+1}\right) - \frac{\tilde{N}}{\tilde{BL}}\tilde{n}_{t+1} \tag{A.1}$$

$$\begin{aligned}\tilde{q}_t = {} & \frac{1}{1+\beta r^b}\left\{\beta\Pi\left[1-\delta+\delta\tau^K\right]E_t\tilde{q}_{t+1} - \beta r^b\tilde{r}^b_t\right. \\ & \left. + \frac{\beta\Pi}{Q}\left[\frac{\tilde{R}^K}{\widetilde{P}^C}\left(1-\tau^K\right)\left(E_t\tilde{r}^K_{t+1} - E_t\tilde{p}^C_{t+1}\right) - \left(\frac{\tilde{R}^K}{\widetilde{P}^C} - \delta Q\right)E_t\hat{\tau}^K_{t+1}\right]\right\} \\ & + E_t\tilde{\pi}_{t+1} + E_t\tilde{p}^C_{t+1} - \tilde{p}^C_t\end{aligned} \tag{A.2}$$

$$n_1\tilde{n}_{t+1} = n_2\tilde{k}_t + n_3\tilde{r}^K_t + n_4\tilde{q}_t + n_5\tilde{q}_{t-1} + n_6\tilde{n}_t + n_7\tilde{r}^b_{t-1} + n_8\tilde{\pi}_t + n_9\tilde{\mu}_t + n_{10}\hat{\tau}^K_t + n_{11}\tilde{p}^C_t + n_{12}\tilde{p}^C_{t-1} \tag{A.3}$$

where $c^*_1 = \tilde{R}^K\left(1-\tau^K\right) + \left(1-\delta+\delta\tau^K\right)Q\widetilde{P}^C$, $n_1 = \Pi\tilde{N}\mu/\gamma$, $n_2 = \Pi\tilde{K}c^*_1 - \left(1+r^b\right)\tilde{K}Q\widetilde{P}^C$, $n_3 = \Pi\tilde{K}\tilde{R}^K\left(1-\tau^K\right)$, $n_4 = \Pi\tilde{K}Q\widetilde{P}^C\left(1-\delta+\delta\tau^K\right)$, $n_5 = -Q\tilde{K}\widetilde{P}^C\left(1+r^b\right)$, $n_6 = \tilde{N}\left(1+r^b\right)$, $n_7 = -r^b\left(Q\tilde{K}\widetilde{P}^C - \tilde{N}\right)$, $n_8 = \Pi\tilde{K}c^*_1 - \frac{\Pi\mu}{\gamma}\left(\tilde{N} - \tilde{W}^e\right)$, $n_9 = -\frac{\Pi\mu}{\gamma}\left(\tilde{N} - \tilde{W}^e\right)$, $n_{10} = \Pi\tilde{K}\left(\delta Q\widetilde{P}^C - \tilde{R}^K\right)$, $n_{11} = n_4$ and $n_{12} = n_5$.

$$\begin{aligned}\tilde{r}^b_t = {} & \frac{\kappa_b}{\varepsilon^b - 1 + (1+\beta)\kappa_b}\tilde{r}^b_{t-1} + \frac{\beta\kappa_b}{\varepsilon^b - 1 + (1+\beta)\kappa_b}E_t\tilde{r}^b_{t+1} \\ & + \frac{\varepsilon^b - 1}{\varepsilon^b - 1 + (1+\beta)\kappa_b}\tilde{R}^b_t - \frac{1}{\varepsilon^b - 1 + (1+\beta)\kappa_b}\tilde{\varepsilon}^b_t\end{aligned} \tag{A.4}$$

[33] The detailed derivation of the linearised model and the model's steady state is provided in the separate technical appendix, which is available from the authors upon request.

$$\tilde{R}_t^b = \tilde{R}_t - \frac{\kappa_{K^b}}{R^b}\left(v^b\right)^3\left(\tilde{k}_{t+1}^b - \tilde{bl}_{t+1} - \tilde{v}_t^b\right) \tag{A.5}$$

$$\tilde{k}_{t+1}^b = \frac{1-\delta^b}{\Pi\mu}\left(\tilde{k}_t^b - \tilde{\pi}_t - \tilde{\mu}_t - \tilde{\varepsilon}_t^{Kb}\right) + \left(1 - \frac{1-\delta^b}{\Pi\mu}\right)\tilde{j}_t^b \tag{A.6}$$

$$\tilde{j}_t^b = \frac{r^b}{r^b - r^{FI}\left(1-v^b\right)}\left(\tilde{r}_{t-1}^b + \tilde{bl}_t\right) - \frac{r^{FI}\left(1-v^b\right)}{r^b - r^{FI}\left(1-v^b\right)}\left(\tilde{R}_{t-1} + \tilde{d}_t\right) - \tilde{\pi}_t - \tilde{\mu}_t \tag{A.7}$$

$$\tilde{bl}_{t+1} = \left(1-v^b\right)\tilde{d}_{t+1} + v^b\tilde{k}_{t+1}^b + \varepsilon_t^{bl} \tag{A.8}$$

$$\tilde{bka}_t = \tilde{k}_{t+1}^b - \tilde{bl}_{t+1} \tag{A.9}$$

$$\tilde{lev}_t = \tilde{q}_t + \tilde{k}_{t+1} + \tilde{p}_t^C - \tilde{n}_{t+1} \tag{A.10}$$

$$\tilde{by}_t = \tilde{bl}_{t+1} - \tilde{y}_t \tag{A.11}$$

$$\tilde{\psi}_{\Lambda,t} = -\frac{1}{1-\mu^{-1}b_c}\left(\tilde{c}_t^H - \mu^{-1}b_c\tilde{c}_{t-1}^H\right) - \frac{\mu^{-1}b_c}{1-\mu^{-1}b_c}\hat{\mu}_t - \frac{1}{1+\tau^C}\hat{\tau}_t^C + \tilde{\zeta}_t^C \tag{A.12}$$

$$\tilde{i}_t^H = \frac{1}{1+\beta}\left(\beta E_t\tilde{i}_{t+1}^H + \tilde{i}_{t-1}^H\right) - \frac{1}{\gamma_I\mu^2\left(1+\beta\right)}\left(\tilde{p}_t^I - \tilde{p}_t^C - \tilde{q}_t - \tilde{\zeta}_t^I\right) + \frac{1}{1+\beta}\left(\beta E_t\hat{\mu}_{t+1} - \hat{\mu}_t\right) \tag{A.13}$$

$$\begin{aligned}\tilde{c}_t^H = {} & \frac{1}{1+\mu^{-1}b_c}E_t\tilde{c}_{t+1}^H + \frac{\mu^{-1}b_c}{1+\mu^{-1}b_c}\tilde{c}_{t-1}^H + \frac{1}{1+\mu^{-1}b_c}\left(E_t\hat{\mu}_{t+1} - \mu^{-1}b_c\hat{\mu}_t\right) \\ & + \frac{1}{1+\tau^C}\frac{1-\mu^{-1}b_c}{1+\mu^{-1}b_c}\left(E_t\hat{\tau}_{t+1}^C - \hat{\tau}_t^C\right) - \frac{1-\mu^{-1}b_c}{1+\mu^{-1}b_c}\left(\tilde{R}_t + E_t\tilde{\zeta}_{t+1}^C - \tilde{\zeta}_t^C - E_t\tilde{\pi}_{t+1}^C\right)\end{aligned} \tag{A.14}$$

$$\tilde{R}_t - \tilde{r}_t^{\text{€}} = -E_t\left(\phi_a\hat{a}_{t+1}^*\right) + \tilde{\zeta}_t^{\text{€}} \tag{A.15}$$

$$\tilde{k}_{t+1} = \frac{1-\delta}{\mu}\left(\tilde{k}_t - \hat{\mu}_t\right) + \left(1 - \frac{1-\delta}{\mu}\right)\left(\tilde{i}_t^H + \tilde{\zeta}_t^I\right) \tag{A.16}$$

$$\begin{aligned}
&\tilde{w}_t - \tilde{p}_t^C = \frac{1}{1+\beta}\left(\tilde{w}_{t-1} - \tilde{p}_{t-1}^C\right) - \frac{1}{1+\beta}\left(\tilde{p}_t^C - \tilde{p}_{t-1}^C + \tilde{\pi}_t - \tilde{\pi}_{t-1}\right) \\
&+\frac{\beta}{1+\beta}\left(E_t\tilde{p}_{t+1}^C - \tilde{p}_t^C + E_t\tilde{\pi}_{t+1} - \tilde{\pi}_t + E_t\tilde{w}_{t+1} - E_t\tilde{p}_{t+1}^C\right) \\
&+\kappa_{\mathbf{wc}}\left\{\frac{1}{1+\tau^w}\hat{\tau}_t^w + \hat{\zeta}_t^L + \sigma_l\left[\left(1 - \mathbf{s_{LGH}}\right)\tilde{h}_t^F + \mathbf{s_{LGH}}\tilde{h}_t^G\right] - \tilde{\psi}_{\Lambda,t} + \hat{\lambda}_{w,t} + \tilde{p}_t^C - \tilde{w}_t\right\}
\end{aligned} \tag{A.17}$$

where $\kappa_{\mathbf{wc}} = \frac{(1-\xi_w)(1-\xi_w\beta)}{\xi_w(1+\beta)\left(1-\sigma_l\mathbf{s_{LGH}}\frac{\lambda_w}{1-\lambda_w}\right)}$.

$$\tilde{real\,wage}_t = \tilde{w}_t - \tilde{p}_t^C \tag{A.18}$$

$$\sigma_Y\tilde{r}_t^K = \tilde{l}_t^F + \hat{\mu}_t - \tilde{k}_t + \sigma_Y\left[\tilde{w}_t + \frac{1}{1+\tau^F}\hat{\tau}_t^F + \rho_Y\left(\hat{\lambda}_{l,t}^T - \hat{\lambda}_{k,t}\right)\right] \tag{A.19}$$

$$\widetilde{mc}_t = \alpha_k\left(\tilde{r}_t^K - \hat{\lambda}_{k,t}\right) + \alpha_l\left[\tilde{w}_t + \left(1+\tau^F\right)^{-1}\hat{\tau}_t^F - \hat{\lambda}_{l,t}^T\right] \tag{A.20}$$

where $\alpha_k = \frac{\tilde{K}}{\tilde{Y}\mu}\frac{\tilde{R}^K}{\widetilde{\mathcal{MC}}}$ and $\alpha_l = \frac{L^F}{\tilde{Y}}\frac{\left(1+\tau^F\right)\tilde{W}}{\widetilde{\mathcal{MC}}}$.

$$\tilde{y}_t = \alpha_k\left(\hat{\lambda}_{k,t} + \tilde{k}_t - \hat{\mu}_t\right) + \alpha_l\left(\hat{\lambda}_{l,t}^T + \tilde{l}_t^F\right) \tag{A.21}$$

$$\tilde{\pi}_t = \frac{\theta}{1+\beta\theta}\tilde{\pi}_{t-1} + \frac{\beta}{1+\beta\theta}E_t\tilde{\pi}_{t+1} + \frac{\left(1-\zeta\beta\right)\left(1-\zeta\right)}{\zeta\left(1+\beta\theta\right)}\left(\widetilde{mc}_t + \tilde{v}_t\right) \tag{A.22}$$

$$\begin{aligned}
&\tilde{Y}\tilde{y}_t = \widetilde{P}^C\tilde{C}^H\left(\tilde{p}_t^C + \tilde{c}_t^H\right) + \widetilde{C}^G\tilde{c}_t^G + \widetilde{P}^I\left[\left(\widetilde{I}^H + \widetilde{I}^G\right)\tilde{p}_t^I + \widetilde{I}^H\tilde{i}_t^H + \widetilde{I}^G\tilde{i}_t^G\right] \\
&+RS\widetilde{P}^X\tilde{X}\left(\tilde{rs}_t + \tilde{p}_t^X + \tilde{x}_t\right) - \widetilde{P}^M\left[\left(\widetilde{M}^C + \widetilde{M}^I + \widetilde{M}^X\right)\tilde{p}_t^M + \widetilde{M}^C\tilde{m}_t^C + \widetilde{M}^I\tilde{m}_t^I + \widetilde{M}^X\tilde{m}_t^X\right]
\end{aligned} \tag{A.23}$$

$$\widetilde{Y}^C\tilde{y}_t^C = s_{YCZ}^*\tilde{C}^H\left[\widetilde{c}_t^H + \sigma_c\left(\tilde{p}_t^C - \rho_c\hat{\lambda}_{cy,t}\right)\right] + \tilde{C}^G\widetilde{c}_t^G \tag{A.24}$$

$$\tilde{m}_t^C = \frac{\sigma_c\gamma_{cm}}{1+\sigma_c\gamma_{cm}}\left(\widetilde{c}_t^H - \widetilde{c}_{t-1}^H + \tilde{m}_{t-1}^C\right) + \frac{1}{1+\sigma_c\gamma_{cm}}\widetilde{c}_t^H - \frac{\sigma_c}{1+\sigma_c\gamma_{cm}}\left(\tilde{p}_t^M - \tilde{p}_t^C\right) - \frac{\sigma_c\rho_c}{1+\sigma_c\gamma_{cm}}\hat{\lambda}_{cm,t} \tag{A.25}$$

$$\tilde{p}_t^C = -s_{YCZ}^*\hat{\lambda}_{cy,t} + s_{MCZ}^*\left\{\tilde{p}_t^{MC} - \hat{\lambda}_{cm,t} + \gamma_{cm}\left[\left(\tilde{m}_t^C - \widetilde{c}_t^H\right) - \left(\tilde{m}_{t-1}^C - \widetilde{c}_{t-1}^H\right)\right]\right\} \tag{A.26}$$

where $s_{YCZ}^* = \frac{s_{YCZ}}{\widetilde{P}^C}$ and $s_{MCZ}^* = s_{MCZ}\frac{\widetilde{P}^{MC}}{\widetilde{P}^C}$.

$$\widetilde{c}_t = \left(1 - \mathbf{s_{GCF}}\right)\widetilde{c}_t^H + \mathbf{s_{GCF}}\widetilde{c}_t^G \tag{A.27}$$

$$\tilde{y}_t^I = \tilde{i}_t + \sigma_i\left(\tilde{p}_t^I - \rho_i\hat{\lambda}_{iy,t}\right) \tag{A.28}$$

$$\tilde{m}_t^I = \frac{\sigma_i\gamma_{im}}{1+\sigma_i\gamma_{im}}\left(\tilde{i}_t - \tilde{i}_{t-1} + \tilde{m}_{t-1}^I\right) + \frac{1}{1+\sigma_i\gamma_{im}}\tilde{i}_t - \frac{\sigma_i}{1+\sigma_i\gamma_{im}}\left(\tilde{p}_t^M - \tilde{p}_t^I\right) - \frac{\sigma_i\rho_i}{1+\sigma_i\gamma_{im}}\hat{\lambda}_{im,t} \tag{A.29}$$

$$\tilde{p}_t^I = -s_{YII}^*\hat{\lambda}_{iy,t} + s_{MII}^*\left\{\tilde{p}_t^M - \hat{\lambda}_{im,t} + \gamma_{im}\left[\left(\tilde{m}_t^I - \tilde{i}_t\right) - \left(\tilde{m}_{t-1}^I - \tilde{i}_{t-1}\right)\right]\right\} \tag{A.30}$$

where $s_{YII}^* = \frac{s_{YII}}{\widetilde{P}^I}$ and $s_{MII}^* = s_{MII}\frac{\widetilde{P}^M}{\widetilde{P}^I}$.

$$\widetilde{i}_t = \left(1 - \mathbf{s_{IG}}\right)\widetilde{i}_t^H + \mathbf{s_{IG}}\widetilde{i}_t^G \tag{A.31}$$

$$\tilde{y}_t^X = \tilde{x}_t + \sigma_x\left(\widetilde{mc}_{x,t} - \rho_x\hat{\lambda}_{xy,t}\right) \tag{A.32}$$

$$\tilde{m}_t^X = \tilde{x}_t + \sigma_x\left(\widetilde{mc}_{x,t} - \tilde{p}_t^M - \rho_x\hat{\lambda}_{xm,t}\right) \tag{A.33}$$

$$\widetilde{mc}_{x,t} = -s_{YXX}^*\hat{\lambda}_{xy,t} + s_{MXX}^*\left(\tilde{p}_t^M - \hat{\lambda}_{xm,t}\right) \quad , \tag{A.34}$$

where $s^*_{YXX} = \frac{s_{YXX}}{\widetilde{mc}_x}$ and $s^*_{MXX} = s_{MXX}\frac{\widetilde{P}^M}{\widetilde{mc}_x}$.

$$\tilde{x}_t = \widetilde{m}^W_t - \sigma_w \widetilde{p}^X_t + \hat{\epsilon}_{x,t} \tag{A.35}$$

$$\tilde{\pi}_{x,t} = \frac{\theta_x}{1+\beta\theta_x}\tilde{\pi}_{x,t-1} + \frac{\beta}{1+\beta\theta_x}E_t\tilde{\pi}_{x,t+1} + \frac{(1-\zeta_x\beta)(1-\zeta_x)}{\zeta_x(1+\beta\theta_x)}\left(\widetilde{mc}_{x,t} - \widetilde{p}^X_t - r\tilde{s}_t + \tilde{v}_{x,t}\right) \tag{A.36}$$

$$\begin{aligned}\tilde{\pi}_{m,t} = {} & \frac{\theta_m}{1+\beta\theta_m}\tilde{\pi}_{m,t-1} + \frac{\beta}{1+\beta\theta_m}E_t\tilde{\pi}_{m,t+1} + \\ & \frac{(1-\zeta_m\beta)(1-\zeta_m)}{\zeta_m(1+\beta\theta_m)}\left(r\tilde{s}_t - \tilde{p}^M_t + \omega^{OIL}\tilde{p}^{OIL}_t + \omega^{RAW}\tilde{p}^{RAW}_t + \tilde{v}_{m,t}\right) + \frac{1-\omega_m}{1+\beta\theta_m}\left(\Delta\tilde{s}_t - \beta E_t\Delta\tilde{s}_{t+1}\right)\end{aligned} \tag{A.37}$$

$$\begin{aligned}\widehat{tb}_{Y,t} = {} & \frac{RS\widetilde{P}^X\tilde{X}}{\tilde{Y}}\left(r\tilde{s}_t + \widetilde{p}^X_t + \tilde{x}_t - \tilde{y}_t\right) \\ & -\frac{\widetilde{P}^M\widetilde{M}^C}{\tilde{Y}}\left(\widetilde{p}^M_t + \widetilde{m}^C_t - \tilde{y}_t\right) - \frac{\widetilde{P}^M\widetilde{M}^I}{\tilde{Y}}\left(\widetilde{p}^M_t + \widetilde{m}^I_t - \tilde{y}_t\right) - \frac{\widetilde{P}^M\widetilde{M}^X}{\tilde{Y}}\left(\widetilde{p}^M_t + \widetilde{m}^X_t - \tilde{y}_t\right)\end{aligned} \tag{A.38}$$

$$\tilde{tot}_t = r\tilde{s}_t + \widetilde{p}^X_t - \widetilde{p}^M_t \tag{A.39}$$

$$\widetilde{m}_t = \frac{\widetilde{P}^M\widetilde{M}^C}{RS\widetilde{P}^X\tilde{X}}\widetilde{m}^C_t + \frac{\widetilde{P}^M\widetilde{M}^I}{RS\widetilde{P}^X\tilde{X}}\widetilde{m}^I_t + \frac{\widetilde{P}^M\widetilde{M}^X}{RS\widetilde{P}^X\tilde{X}}\widetilde{m}^X_t \tag{A.40}$$

$$\begin{aligned}\hat{b}^*_{t+1} = {} & \frac{\hat{b}^*_t}{\beta} + RS\widetilde{P}^X\tilde{X}\left(r\tilde{s}_t + \widetilde{p}^X_t + \tilde{x}_t\right) \\ & -\widetilde{P}^M\widetilde{M}^C\left(\widetilde{p}^M_t + \widetilde{m}^C_t\right) - \widetilde{P}^M\widetilde{M}^I\left(\widetilde{p}^M_t + \widetilde{m}^I_t\right) - \widetilde{P}^M\widetilde{M}^X\left(\widetilde{p}^M_t + \widetilde{m}^X_t\right)\end{aligned} \tag{A.41}$$

$$\hat{a}^*_{t+1} = \frac{\hat{b}^*_{t+1}}{\tilde{Y}} - \tilde{y}_t \tag{A.42}$$

$$\frac{\widetilde{C}^G}{\tilde{Y}}\left(\widetilde{c}_t^G-\tilde{y}_t\right)+\frac{\widetilde{P}^I\widetilde{I}^G}{\tilde{Y}}\left(\widetilde{p}_t^I+\widetilde{i}_t^G-\tilde{y}_t\right)+\frac{\left(1-\tau^W\right)\widetilde{W}L^G}{\tilde{Y}}\left(\widetilde{w}_t+\tilde{l}_t^G-\tilde{y}_t-\frac{1}{1-\tau^W}\hat{\tau}_t^W\right)$$
$$=$$
$$\frac{\widetilde{P}^C\tilde{C}^H}{\tilde{Y}}\left[\tau^C\left(\widetilde{p}_t^C+\tilde{c}_t^H-\tilde{y}_t\right)+\hat{\tau}_t^C\right]+\frac{\widetilde{W}L^F}{\tilde{Y}}\left[\hat{\tau}_t^W+\hat{\tau}_t^F+\left(\tau^W+\tau^F\right)\left(\widetilde{w}_t+\tilde{l}_t^F-\tilde{y}_t\right)\right]$$
$$+\frac{\tilde{K}\left(\tilde{R}^K-\delta\widetilde{P}^I\right)}{\mu\tilde{Y}}\left[\hat{\tau}_t^K+\tau^K\left(\frac{\tilde{R}^K}{\tilde{R}^K-\delta\widetilde{P}^I}\tilde{r}_t^K-\frac{\delta\widetilde{P}^I}{\tilde{R}^K-\delta\widetilde{P}^I}\widetilde{p}_t^I+\tilde{k}_t-\hat{\mu}_t-\tilde{y}_t\right)\right]+tr\,\tilde{tr}_{Y,t} \tag{A.43}$$

$$\tilde{h}_t=\left(1-\mathbf{s_{LGH}}\right)\tilde{h}_t^F+\mathbf{s_{LGH}}\tilde{h}_t^G \tag{A.44}$$

The shock processes

- technology shocks
  - permanent labour productivity: $\hat{\mu}_t\equiv\Delta\log\left(\Lambda_t^P/\mu\right)=\rho_\mu\hat{\mu}_{t-1}+\varepsilon_t^\mu$, $\varepsilon_t^\mu\sim N\left(0,\sigma_\mu^2\right)$
  - temporary labour productivity: $\hat{\lambda}_{l,t}^T\equiv\log\left(\Lambda_{l,t}^T/\Lambda_l^T\right)=\rho_{\lambda l}\hat{\lambda}_{l,t-1}^T+\varepsilon_t^{\lambda l}$, $\varepsilon_t^{\lambda l}\sim N\left(0,\sigma_{\lambda l}^2\right)$
  - temporary capital productivity: $\hat{\lambda}_{k,t}\equiv\log\left(\Lambda_{k,t}/\Lambda_k\right)=\rho_{\lambda k}\hat{\lambda}_{k,t}+\varepsilon_t^{\lambda k}$, $\varepsilon_t^{\lambda k}\sim N\left(0,\sigma_{\lambda k}^2\right)$
  - productivity shifters in consumption: $\hat{\lambda}_{cy,t}\equiv\log\left(\Lambda_{cy,t}/\Lambda_{cy}\right)=\rho_{cy}\hat{\lambda}_{cy,t-1}+\varepsilon_t^{cy}$, $\varepsilon_t^{cy}\sim N\left(0,\sigma_{cy}^2\right)$ and $\hat{\lambda}_{cm,t}\equiv\log\left(\Lambda_{cm,t}/\Lambda_{cm}\right)=\rho_{cm}\hat{\lambda}_{cm,t-1}+\varepsilon_t^{cm}$, $\varepsilon_t^{cm}\sim N\left(0,\sigma_{cm}^2\right)$
  - productivity shifter in investment: $\hat{\lambda}_{iy,t}\equiv\log\left(\Lambda_{iy,t}/\Lambda_{iy}\right)=\rho_{iy}\hat{\lambda}_{iy,t-1}+\varepsilon_t^{iy}$, $\varepsilon_t^{iy}\sim N\left(0,\sigma_{iy}^2\right)$
- domestic markup shocks
  - price markup intermediate good firms: $\tilde{v}_t=\varepsilon_t^v$, $\varepsilon_t^v\sim N\left(0,\sigma_v^2\right)$
  - price markup of export producing firm: $\tilde{v}_{x,t}=\rho_{vx}\tilde{v}_{x,t-1}+\varepsilon_t^{vx}$, $\varepsilon_t^{vx}\sim N\left(0,\sigma_{vx}^2\right)$
  - wage markup: $\hat{\lambda}_{w,t}=\varepsilon_t^{\lambda w}$, $\varepsilon_t^{\lambda w}\sim N\left(0,\sigma_{\lambda w}^2\right)$
- domestic demand shocks
  - government consumption: $\widetilde{c}_t^G=\rho_{cG}\widetilde{c}_{t-1}^G+\varepsilon_t^{cG}$, $\varepsilon_t^{cG}\sim N\left(0,\sigma_{cG}^2\right)$
  - government investment: $\widetilde{i}_t^G=\rho_{iG}\widetilde{i}_{t-1}^G+\varepsilon_t^{iG}$, $\varepsilon_t^{iG}\sim N\left(0,\sigma_{iG}^2\right)$
  - government hours: $\widetilde{h}_t^G=\rho_{hG}\widetilde{h}_{t-1}^G+\varepsilon_t^{hG}$, $\varepsilon_t^{hG}\sim N\left(0,\sigma_{hG}^2\right)$

- household consumption preference: $\tilde{\zeta}_t^C = \rho_{\zeta C}\tilde{\zeta}_{t-1}^C + \varepsilon_t^{\zeta C}$, $\varepsilon_t^{\zeta C} \sim N\left(0, \sigma_{\zeta C}^2\right)$

- foreign/external shocks
  - foreign export demand: $\widetilde{m}_t^W = \rho_{mW}\widetilde{m}_{t-1}^W + \varepsilon_t^{mW}$, $\varepsilon_t^{mW} \sim N\left(0, \sigma_{mW}^2\right)$
  - export share: $\hat{\epsilon}_{x,t} = \rho_x \hat{\epsilon}_{x,t-1} + \varepsilon_t^x$, $\varepsilon_t^x \sim N\left(0, \sigma_x^2\right)$
  - nominal effective exchange rate: $\Delta\tilde{s}_t = \rho_{\Delta s}\Delta\tilde{s}_{t-1} + \varepsilon_t^{\Delta s}$, $\varepsilon_t^{\Delta s} \sim N\left(0, \sigma_{\Delta s}^2\right)$
  - foreign inflation shock: $\tilde{\pi}_t^W = \rho_{\pi W}\tilde{\pi}_{t-1}^W + \varepsilon_t^{\pi W}$, $\varepsilon_t^{\pi W} \sim N\left(0, \sigma_{\pi W}^2\right)$
  - price markup of import firms: $\tilde{v}_{m,t} = \rho_{vm}\tilde{v}_{m,t-1} + \varepsilon_t^{vm}$, $\varepsilon_t^{vm} \sim N\left(0, \sigma_{vm}^2\right)$
  - oil price: $p_t^{OIL} = \rho_{OIL}p_{t-1}^{OIL} + \varepsilon_t^{OIL}$, $\varepsilon_t^{OIL} \sim N\left(0, \sigma_{OIL}^2\right)$
  - price of raw materials: $p_t^{RAW} = \rho_{RAW}p_{t-1}^{RAW} + \varepsilon_t^{RAW}$, $\varepsilon_t^{RAW} \sim N\left(0, \sigma_{RAW}^2\right)$

- financial shocks
  - domestic risk premium: $\tilde{\zeta}_t^{€} = \rho_{\zeta €}\tilde{\zeta}_{t-1}^{€} + \varepsilon_t^{\zeta €}$, $\varepsilon_t^{\zeta €} \sim N\left(0, \sigma_{\zeta €}^2\right)$
  - euro area interest rate: $\tilde{r}_t^{€} = \rho_{r €}\tilde{r}_{t-1}^{€} + \varepsilon_t^{r €}$, $\varepsilon_t^{r €} \sim N\left(0, \sigma_{r €}^2\right)$
  - bank markup: $\tilde{\varepsilon}_t^b = \rho_{\varepsilon b}\tilde{\varepsilon}_{t-1}^b + \varepsilon_t^{\varepsilon b}$, $\varepsilon_t^{\varepsilon b} \sim N\left(0, \sigma_{\varepsilon b}^2\right)$
  - bank capital: $\tilde{\varepsilon}_t^{Kb} = \rho_{Kb}\tilde{\varepsilon}_{t-1}^{Kb} + \varepsilon_t^{\varepsilon Kb}$, $\varepsilon_t^{\varepsilon Kb} \sim N\left(0, \sigma_{Kb}^2\right)$

Appendix B - Other impulse response functions

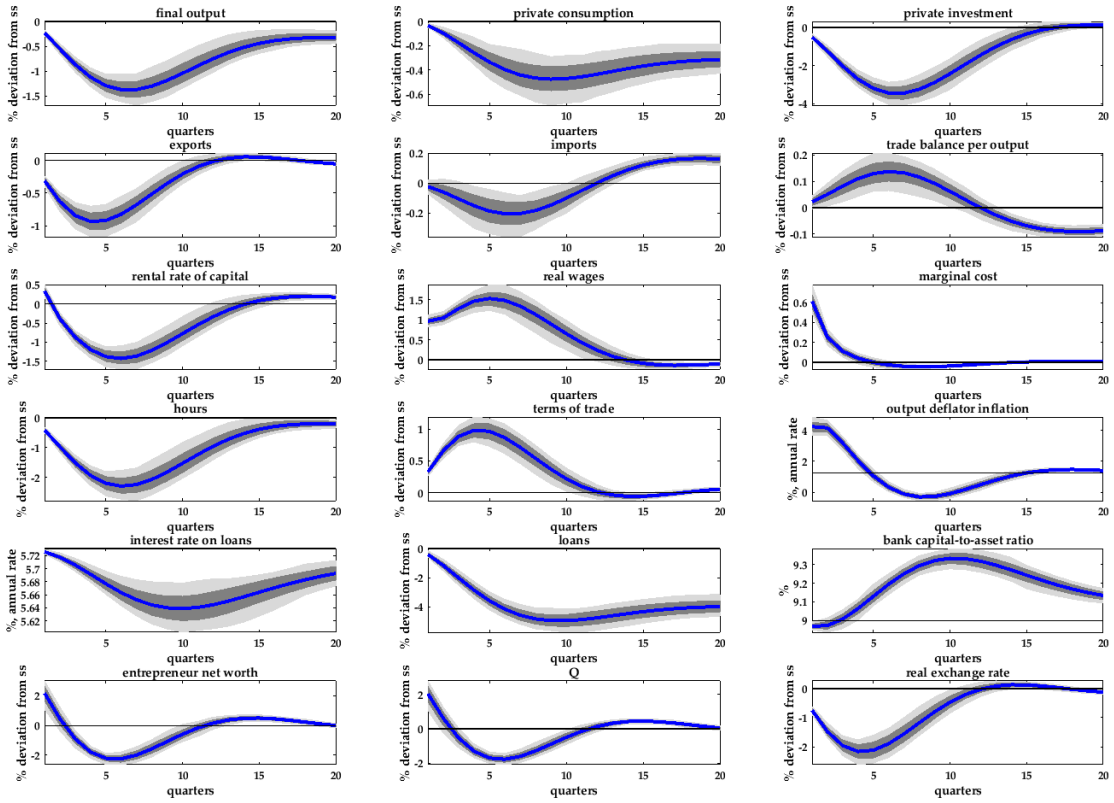

Figure 15: Impulse response functions - labor markup shock

Note. This figure shows the mean (blue solid line) and the 60 and 90 percent equal-tail uncertainty bands (grey-shaded areas) of the impulse responses of selected observed variables to a one standard deviation shock. All impulse responses are reported as percentage deviations from the non-stochastic steady state, except for the impulse responses of the inflation and the loan interest rate which are reported as annual percentage points, and the bank capital-to-asset ratio which is reported as percent value. The results are based on 40000 draws from the posterior distribution of the model's parameters.

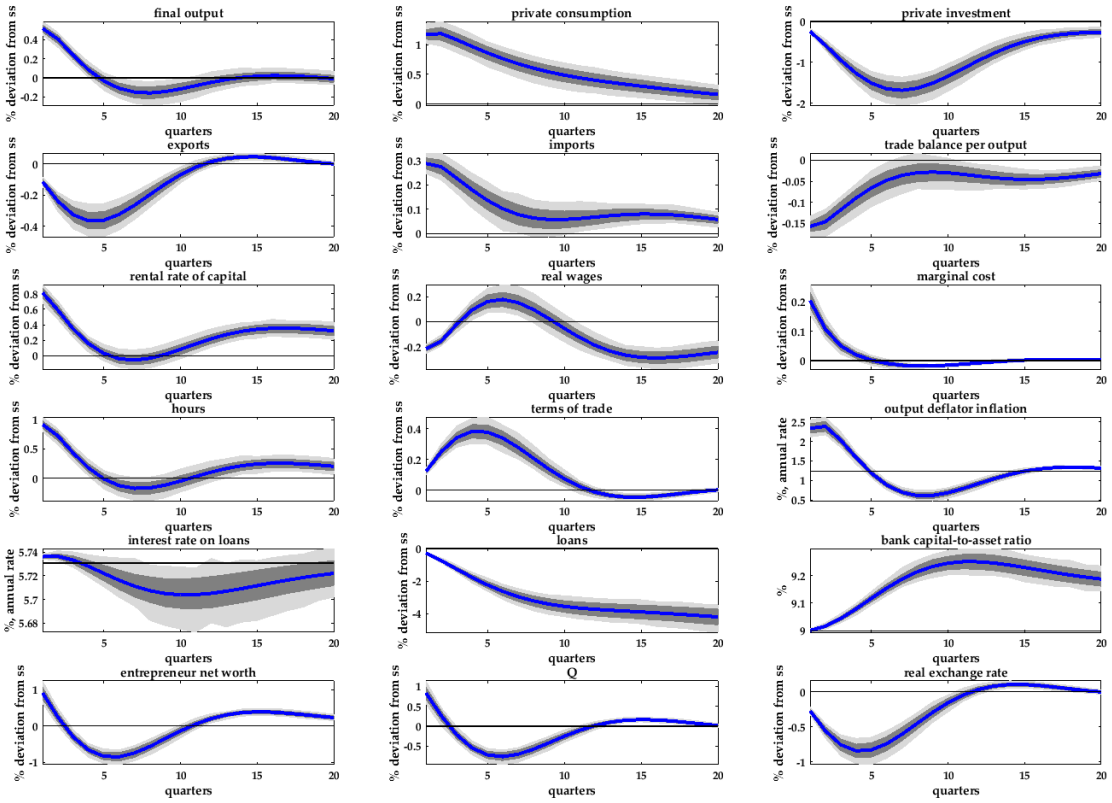

Figure 16: Impulse response functions - consumption preference shock

Note. This figure shows the mean (blue solid line) and the 60 and 90 percent equal-tail uncertainty bands (grey-shaded areas) of the impulse responses of selected observed variables to a one standard deviation shock. All impulse responses are reported as percentage deviations from the non-stochastic steady state, except for the impulse responses of the inflation and the loan interest rate which are reported as annual percentage points, and the bank capital-to-asset ratio which is reported as percent value. The results are based on 40000 draws from the posterior distribution of the model's parameters.

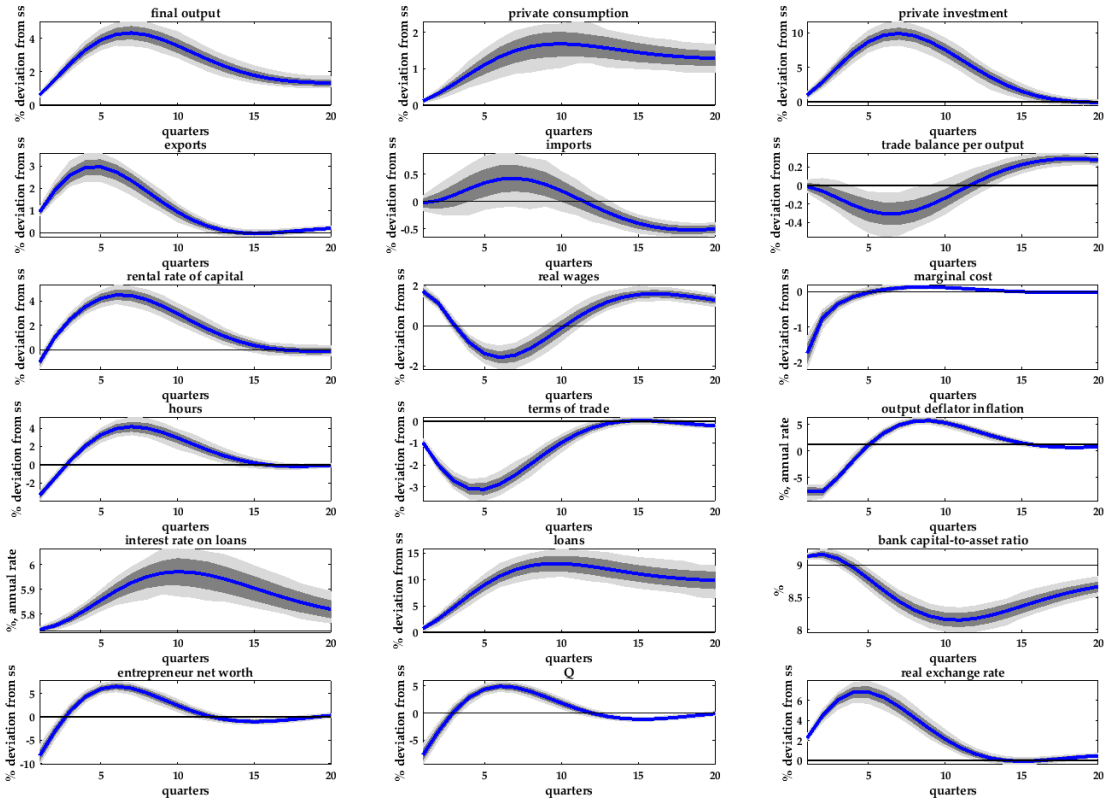

Figure 17: Impulse response functions - temporary labor productivity shock

Note. This figure shows the mean (blue solid line) and the 60 and 90 percent equal-tail uncertainty bands (grey-shaded areas) of the impulse responses of selected observed variables to a one standard deviation shock. All impulse responses are reported as percentage deviations from the non-stochastic steady state, except for the impulse responses of the inflation and the loan interest rate which are reported as annual percentage points, and the bank capital-to-asset ratio which is reported as percent value. The results are based on 40000 draws from the posterior distribution of the model's parameters.

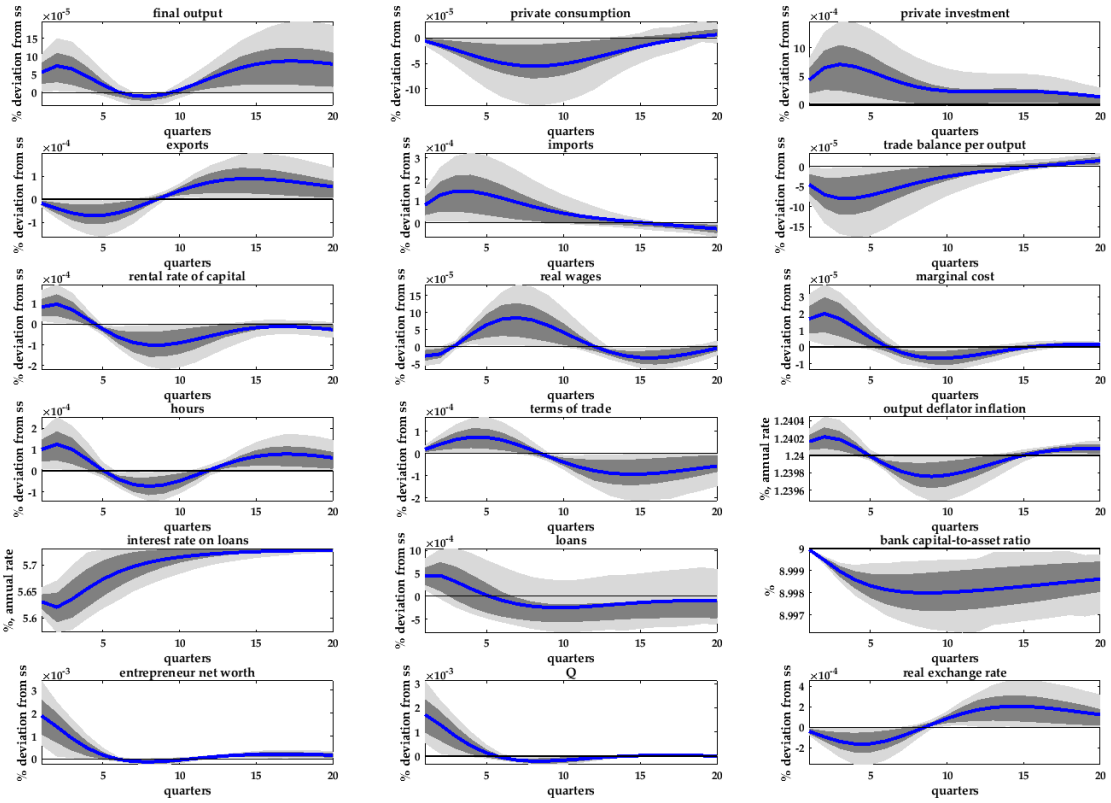

Figure 18: Impulse response functions - bank markup shock

Note. This figure shows the mean (blue solid line) and the 60 and 90 percent equal-tail uncertainty bands (grey-shaded areas) of the impulse responses of selected observed variables to a one standard deviation shock. All impulse responses are reported as percentage deviations from the non-stochastic steady state, except for the impulse responses of the inflation and the loan interest rate which are reported as annual percentage points, and the bank capital-to-asset ratio which is reported as percent value. The results are based on 40000 draws from the posterior distribution of the model's parameters.

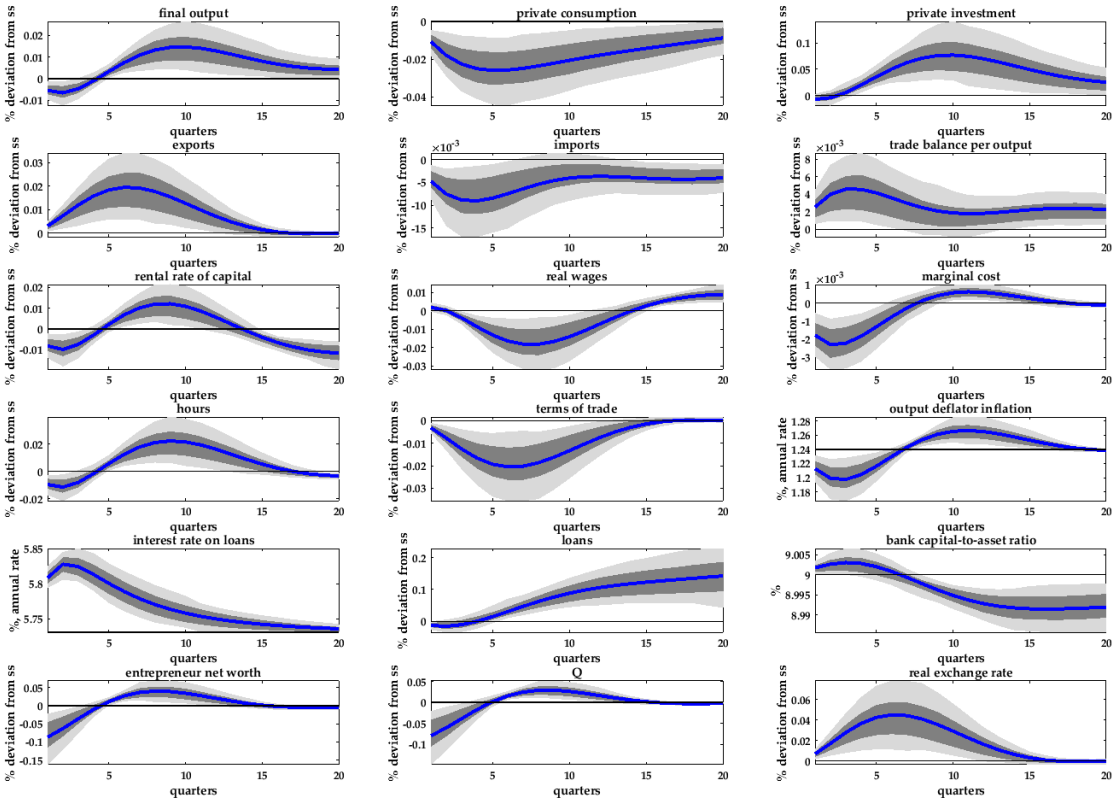

Figure 19: Impulse response functions - domestic risk premium shock

Note. This figure shows the mean (blue solid line) and the 60 and 90 percent equal-tail uncertainty bands (grey-shaded areas) of the impulse responses of selected observed variables to a one standard deviation shock. All impulse responses are reported as percentage deviations from the non-stochastic steady state, except for the impulse responses of the inflation and the loan interest rate which are reported as annual percentage points, and the bank capital-to-asset ratio which is reported as percent value. The results are based on 40000 draws from the posterior distribution of the model's parameters.

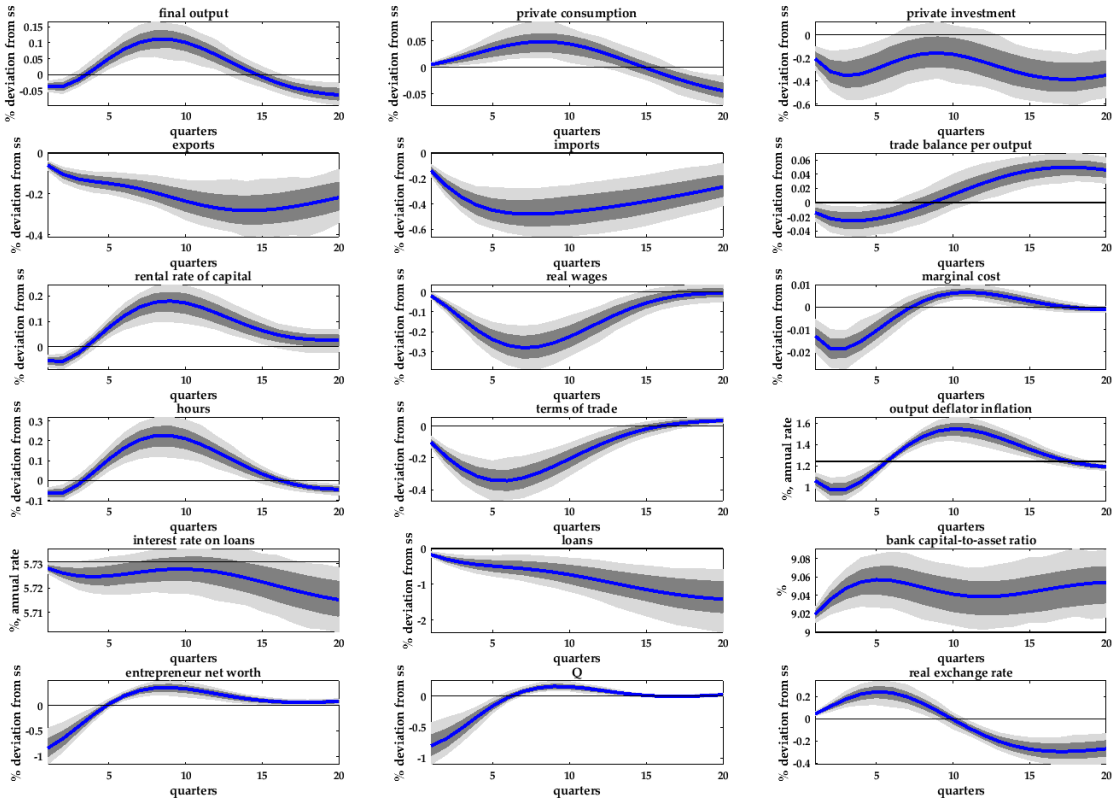

Figure 20: Impulse response functions - oil price shock

Note. This figure shows the mean (blue solid line) and the 60 and 90 percent equal-tail uncertainty bands (grey-shaded areas) of the impulse responses of selected observed variables to a one standard deviation shock. All impulse responses are reported as percentage deviations from the non-stochastic steady state, except for the impulse responses of the inflation and the loan interest rate which are reported as annual percentage points, and the bank capital-to-asset ratio which is reported as percent value. The results are based on 40000 draws from the posterior distribution of the model's parameters.

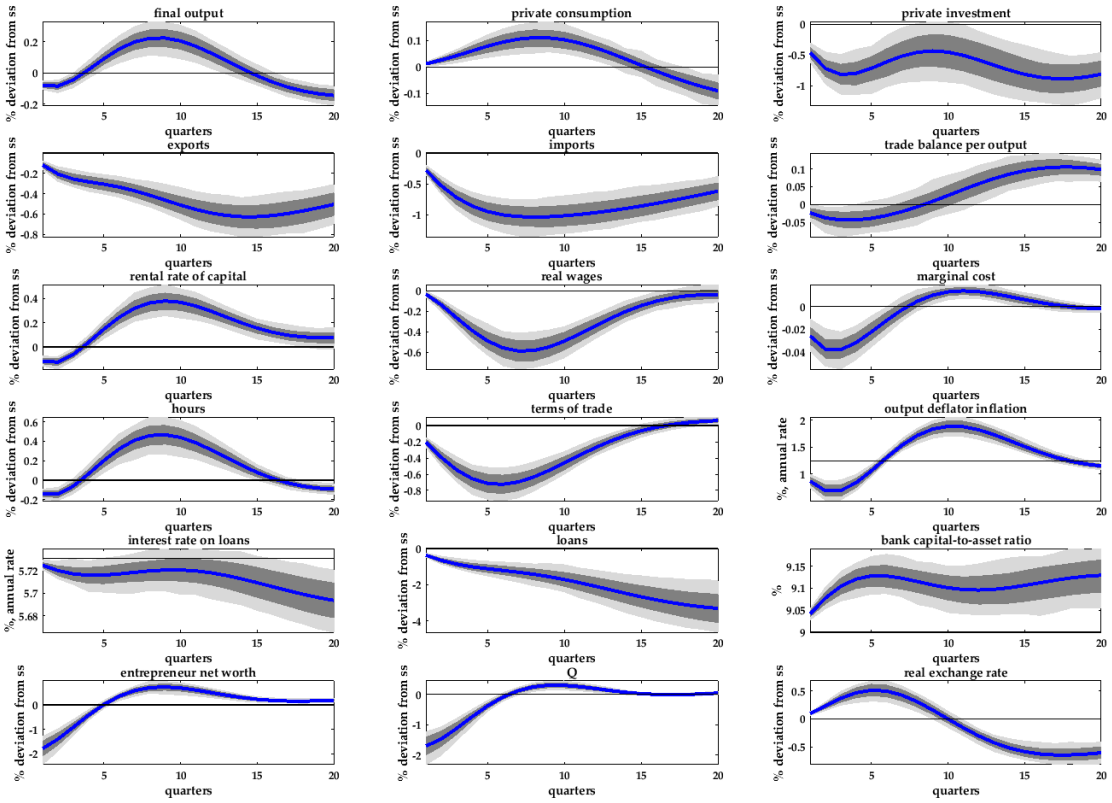

Figure 21: Impulse response functions - raw materials price shock

Note. This figure shows the mean (blue solid line) and the 60 and 90 percent equal-tail uncertainty bands (grey-shaded areas) of the impulse responses of selected observed variables to a one standard deviation shock. All impulse responses are reported as percentage deviations from the non-stochastic steady state, except for the impulse responses of the inflation and the loan interest rate which are reported as annual percentage points, and the bank capital-to-asset ratio which is reported as percent value. The results are based on 40000 draws from the posterior distribution of the model's parameters.

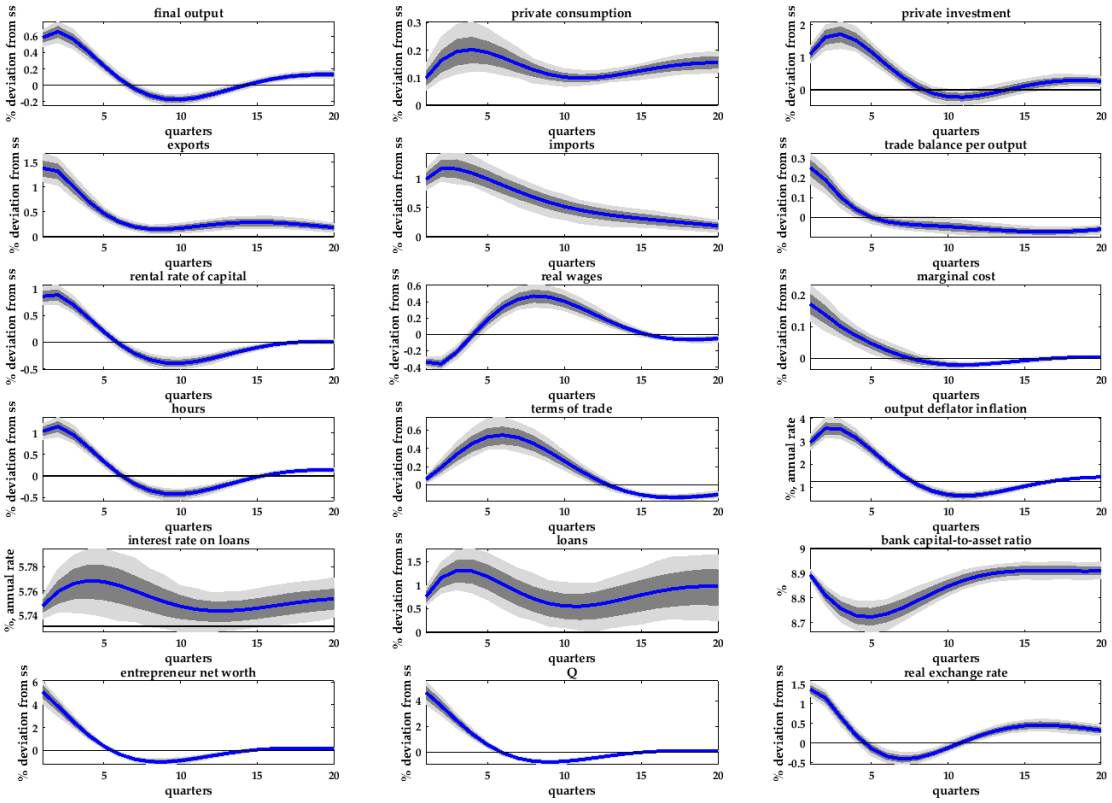

Figure 22: Impulse response functions - foreign inflation shock

Note. This figure shows the mean (blue solid line) and the 60 and 90 percent equal-tail uncertainty bands (grey-shaded areas) of the impulse responses of selected observed variables to a one standard deviation shock. All impulse responses are reported as percentage deviations from the non-stochastic steady state, except for the impulse responses of the inflation and the loan interest rate which are reported as annual percentage points, and the bank capital-to-asset ratio which is reported as percent value. The results are based on 40000 draws from the posterior distribution of the model's parameters.

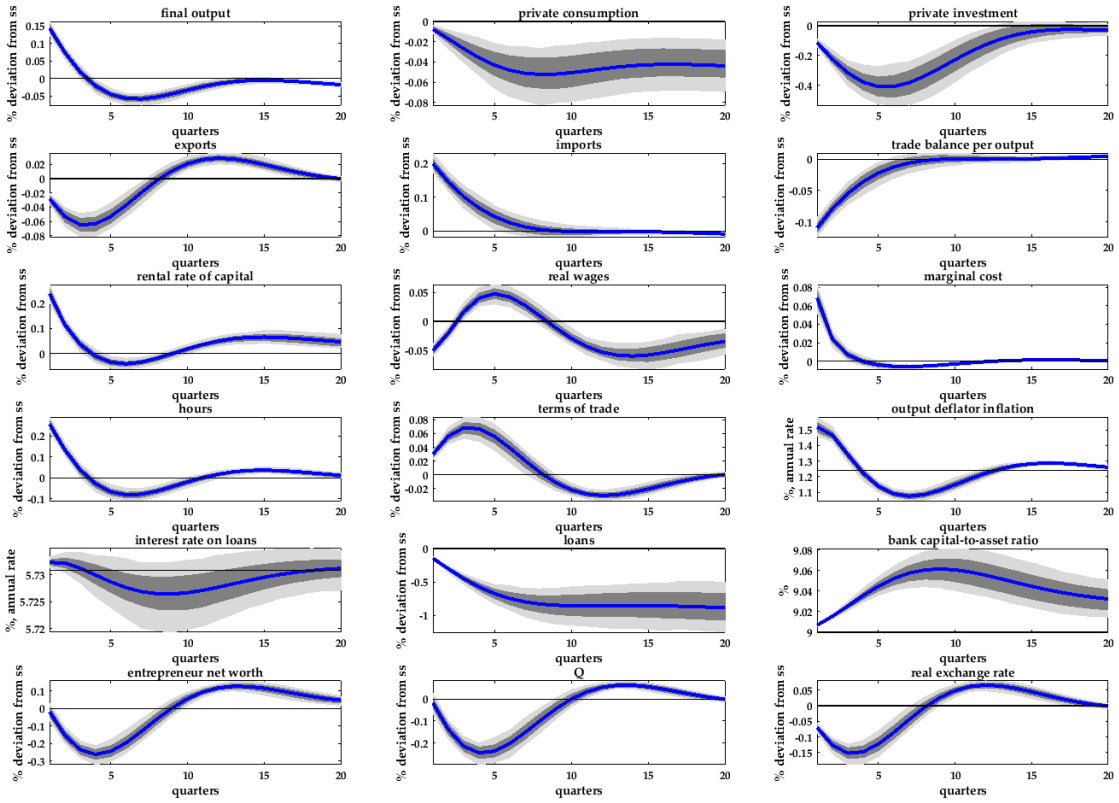

Figure 23: Impulse response functions - public investment shock

Note. This figure shows the mean (blue solid line) and the 60 and 90 percent equal-tail uncertainty bands (grey-shaded areas) of the impulse responses of selected observed variables to a one standard deviation shock. All impulse responses are reported as percentage deviations from the non-stochastic steady state, except for the impulse responses of the inflation and the loan interest rate which are reported as annual percentage points, and the bank capital-to-asset ratio which is reported as percent value. The results are based on 40000 draws from the posterior distribution of the model's parameters.

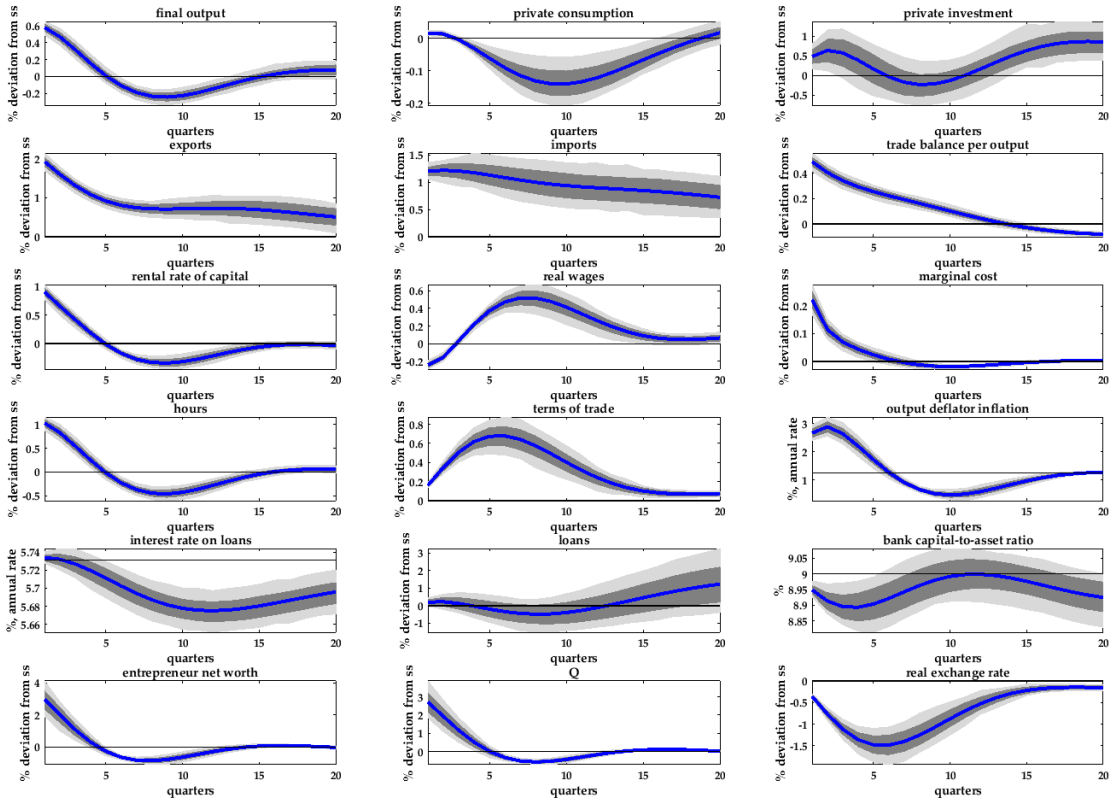

Figure 24: Impulse response functions - foreign export demand shock

Note. This figure shows the mean (blue solid line) and the 60 and 90 percent equal-tail uncertainty bands (grey-shaded areas) of the impulse responses of selected observed variables to a one standard deviation shock. All impulse responses are reported as percentage deviations from the non-stochastic steady state, except for the impulse responses of the inflation and the loan interest rate which are reported as annual percentage points, and the bank capital-to-asset ratio which is reported as percent value. The results are based on 40000 draws from the posterior distribution of the model's parameters.

Bank of Finland Research Discussion Papers 2016

ISSN 1456-6184, online

1/2016 Aino Silvo
The interaction of monetary and macroprudential policies in economic stabilisation
ISBN 978-952-323-088-0, online

2/2016 Rune Stenbacka – Tuomas Takalo
Switching costs and financial stability
ISBN 978-952-323-094-1, online

3/2016 Mikael Juselius – Mathias Drehmann
Leverage dynamics and the burden of debt
ISBN 978-952-323-098-9, online

4/2016 Mikael Juselius – Elod Takats
The age-structure – inflation puzzle
ISBN 978-952-323-099-6, online

5/2016 Bill B. Francis – Iftekhar Hasan – Xian Sun – Qiang Wu
CEO Political Preference and Corporate Tax Sheltering
ISBN 978-952-323-100-9, online

6/2016 Bill Francis – Iftekhar Hasan – Sureshbabu Mani – Pengfei Ye
Relative Peer Quality and Firm Performance
ISBN 978-952-323-101-6, online

7/2016 Iftekhar Hasan – Nada Kobeissi – Liuling Liu – Haizhi Wang
Corporate Social Responsibility and Firm Financial Performance:
The Mediating Role of Productivity
ISBN 978-952-323-102-3, online

8/2016 Bill B. Francis – Iftekhar Hasan – Gergana L. Kostova
When Do Peers Matter?: A Cross-Country Perspective
ISBN 978-952-323-103-0, online

9/2016 Iftekhar Hasan – Deming Wu
Credit Default Swaps and Bank Loan Sales: Evidence from Bank Syndicated Lending
ISBN 978-952-323-104-7, online

10/2016 Iftekhar Hasan – Deming Wu
How Large Banks Use CDS to Manage Risks: Bank-Firm-Level Evidence
ISBN 978-952-323-105-4, online

11/2016 Bonnie Buchanan – Xuying (Cathy) Cao – Eva Liljeblom – Susan Weihrich
Uncertainty and Firm Dividend Policy – A Natural Experiment
ISBN 978-952-323-106-1, online

12/2016 Markus Haavio – Antti Ripatti – Tuomas Takalo
Saving Wall Street or Main Street
ISBN 978-952-323-107-8, online

13/2016 Iftekhar Hasan – Kose Johnc – Padma Kadiyalad
Debt Structure When Bankruptcy Law Offers Incentives to Restructure
ISBN 978-952-323-109-2, online

14/2016 Fabio Verona
Time-frequency characterization of the U.S. financial cycle
ISBN 978-952-323-110-8, online

15/2016 Sami Oinonen – Maritta Paloviita
How informative are aggregated inflation expectations?
Evidence from the ECB Survey of Professional Forecasters
ISBN 978-952-323-111-5, online

16/2016 Juha Kilponen – Seppo Orjasniemi – Antti Ripatti – Fabio Verona
The Aino 2.0 model
ISBN 978-952-323-112-2, online

http://www.suomenpankki.fi/en • email: Research@bof.fi
ISBN 978-952-323-112-2, ISSN 1456-6184, online