EUROPEAN CENTRAL BANK

EUROSYSTEM

Working Paper Series

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International medium-term business cycles

No 2536 / April 2021

Abstract

Foreign driven medium-term oscillations that originate from fluctuations in technological frontier countries gained widespread attention among policymakers. To study this phenomenon in the context of domestic and other foreign drivers of the euro area business cycle, we develop a medium-scale, two-economy dynamic stochastic general equilibrium model with endogenous growth and estimate it with Bayesian methods for the United States and the euro area for the period from 1984:Q1 to 2017:Q4. The framework suggests that foreign shocks can be a substantial source of medium-term oscillations that contribute to pro-cyclicality of real GDP across countries. Notably, US shocks to liquidity preference and trade demand explain more than a third of the euro area downturn during the Great Recession.

JEL Classification: E2, E5, F1, F4, O4.

Keywords: Two-economy DSGE, endogenous growth, R&D, resilience, Bayesian estimation.

Non-technical summary

More than a decade after the Great Recession, the macroeconomic situation in the euro area is characterised by a protracted slowdown in productivity and growth that is increasingly raising policy concern.[1] International medium-term business cycles emerging from fluctuations at the technological frontier are increasingly considered to be a key driver of this post-recession weakness. At the same time, the macroeconomic environment was shaped by other developments such as a capital misallocation prior to the financial crisis, a sluggish accumulation of intangibles, an expansive monetary policy stance, as well as more persistent financial shocks.

To provide a comprehensive model-based characterisation of euro area macroeconomic developments that is able to explain the slowdown in growth and matters of international resilience, we develop and estimate a two-economy medium-scale new Keynesian model that features the following ingredients: First, the model incorporates capital to represent the sluggishness as well as problems of misallocation and under-investment. Second, the model allows for endogenous R&D and technology adoption decisions along the lines of Anzoategui et al. (2019) to reflect the importance of tangible assets, its slow moving properties and the importance of stable demand conditions for long term growth. Finally, the model should take into account the openness of the euro area economy allowing for trade in consumption and investment goods and imperfect financial markets as in Benigno (2009). The two-economy environment provides additional findings as follows:

(i) As compared to conventional frameworks, the endogenous growth framework displays increased spillovers and suggests increased co-movement of real GDP across countries as a result of certain foreign shocks. Particularly, shocks to US liquidity preference can have a similarly directed contracting effect in the euro area. Shocks to US R&D efficiency substantially affect euro area macroeconomic dynamics in the medium term, while shocks to US monetary policy have an immediate impact on euro area productivity. In contrast, the US economy behaves more resilient in response to EA shocks.

(ii) A model-based decomposition unveils that the euro area business cycle is substantially

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affected by US financial and net trade shocks, triggering international medium-term cycles. We find US shocks to liquidity preference contributing substantially during the crisis in 2001 and explaining more than one third of the downturn in the Great Recession.

1 Introduction

More than a decade after the Great Recession, the macroeconomic situation in the euro area is characterised by a protracted slowdown in productivity and growth that is increasingly raising policy concern.[1] International medium-term business cycles emerging from fluctuations at the technological frontier are increasingly considered to be a key driver of this post-recession weakness. At the same time, the macroeconomic environment was shaped by other developments such as a capital misallocation prior to the financial crisis, a sluggish accumulation of intangibles, an expansive monetary policy stance, as well as more persistent financial shocks.

To disentangle domestic and foreign drivers of the euro area business cycle, we develop and estimate a two-economy medium-scale new Keynesian model of the euro area and the United States in the style of Benigno (2009), that features trade in goods as well as incomplete financial markets. We extend it to include physical capital and make use of recent advances in endogenous growth theory along the lines of Anzoategui et al. (2019). Including a costly R&D and technology adoption mechanism allows to retrieve the dynamics of slow-moving intangibles and their dependence on stable demand conditions. This strand of literature builds on the model of Romer (1990) with an expanding variety of goods and tries to link business cycle theory as described in new Keynesian models with growth. In such models, GDP is history-dependent as shocks can have permanent effects on GDP.[2] In addition, there is growing consensus (e.g. Benigno and Fornaro (2018), Moran and Queralto (2018), or Aghion et al. (2018)) that aggregate demand conditions are a strong driver of productivity growth. As a result of the interlinked dynamics between demand and growth, an effective aggregate demand management might yield long-term benefits by maintaining a positive feedback loop in the economy. The endogenous productivity framework chosen explains slow recoveries from larger crisis due to a contraction in demand which implies lower business R&D spending, e.g. into productivity-enhancing intangible assets, leading to less adopted technologies or varieties of goods during the recovery. Hence, the model can explain a significant fraction of the post-Great Recession fall in productivity as an endogenous

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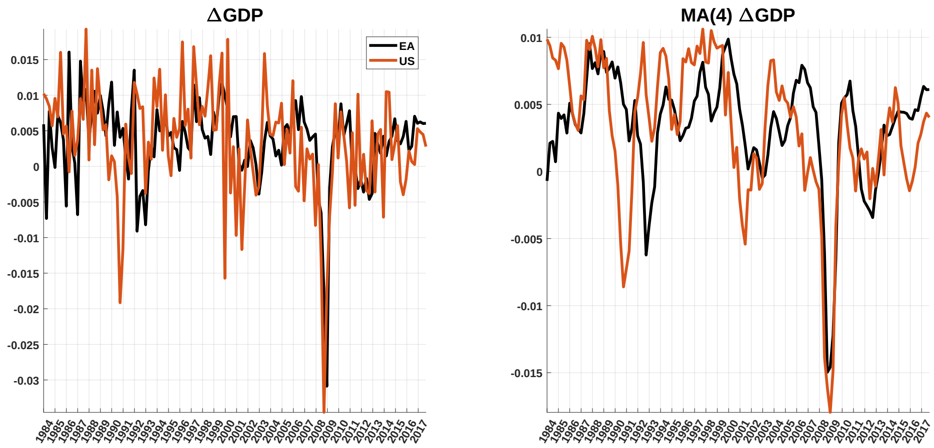
[2] Cerra et al. (2020) provide an overview on this topic.

phenomenon. As a result of this, demand factors play a substantial role as compared with conventional models where only supply factors have structural effects, and demand factors are restricted to cyclical effects. The additional R&D and technology adoption sector in these models implies that a slowdown in aggregate demand originating from financial shocks leads to a persistent slowdown in TFP due to a lower rate of adoption of new technologies and lower R&D investment. Moreover, the framework has another appealing property that explains why inflation was not substantially declining during the Great Recession. Similar to conventional models, inflation declines when aggregate demand falls. However, the endogenous decline in productivity growth lessens the reduction in marginal costs, which in turn dampens the decline in inflation.

Macroeconomic dynamics in the euro area and the United States have been shaped by pre-crisis and crisis developments. First, already prior and in response to the financial crisis, an endogenous slowdown in total factor productivity was observed in both economies. Anzoategui et al. (2019) argue for the United States that this is likely the result of a reduction in business and public R&D and other productivity-related spending. Additionally, a slowdown in demand weakened the adoption of new technologies. Second, the monetary expansion before the crisis supported investment spending and capital deepening by lowering the cost of credit and increasing the profitability of investment in future productive capacity, boosting productivity growth. During this period, the United States suffered a misallocation of mortgage-credit to households, while the euro area suffered a miscallocation of credit to non-financial corporations. Third, crisis and post-crisis dynamics have been shaped by financial shocks. The United States has experienced a single shock, while the euro area also faced a second shock in the form of the sovereign debt crisis which substantially affected consumption dynamics. These financial shocks are considered responsible for an endogenous slowdown in "embodied growth", interpreted in our model as the so-called endogenous component of TFP. This effect characterised the post-crisis period in both economies. Fourth, post-crisis developments were shaped by a slowdown in international technological diffusion. Duval et al. (2017) estimate that a 1% increase in TFP in technological frontier countries results in a spillover effect of 0.15-0.2 percentage points in the medium term for a panel of 17 advanced economies over the period 1970-2010. As a result, "embodied growth" suffered a shock not only from a fall in domestic innovation but also from a slowdown in technological frontier countries. This finding is in line with the conclusion of Giannone and Reichlin (2006), that the euro area growth rate adjusts itself to the US growth rate. Figure 1 illustrates these pro-cyclical lead/-lag dynamics of US and euro area GDP growth rates.

Figure 1 Business cycle co-movement between the United States and the euro area



Note: The chart to the left illustrates the first difference of quarterly real GDP in the euro area (black) and the United States (orange), while the chart to the right applies a 4-quarter moving average to these series illustrating even better how the EA business cycle lags the one in the US.

There is not much model-based evidence on the causes and consequences of the financial crisis for both economies. One prominent exception is Kollmann et al. (2016). The authors construct a three region model with exogenous growth and estimate it for the period between the first quarter of 1999 and the second quarter of 2016. They find that financial shocks were the key drivers of the Great Recession in 2008-09 for both economies, while the shocks were less persistent in the United States. They conclude for the euro area that a combination of adverse aggregate demand and supply shocks has been the driver of post-crisis dynamics and that mono-causal explanations of the slump might be misleading. On the other hand, there is a growing literature that utilises endogenous growth models to study the post-crisis dynamics in advanced economies. Anzoategui et al. (2019) study productivity dynamics in the United States. They find a downturn in R&D expenditures since the early 2000s to be the primary driver. The authors also show that the slowdown in productivity following the Great Recession was an endogenous response to the contraction in demand that induced the downturn. Schmöller and Spitzer (2020) apply a variation of the model to the euro area and find that there has been a slowdown in euro area productivity since the 2000s, which has been primarily driven by a slowdown in business R&D. In response to the crisis, the slowdown in adopted technologies worsened, driven by negative financial shocks linked to the double-dip recession.[3] Cozzi et al. (2017) embed Schumpeterian growth into a medium-scale dynamic stochastic general equilibrium (DSGE) model of the United States and estimate it. The authors find investment risk premia to be a key driver of the slump following the Great Recession. There are also a few studies using multi-country models that incorporate endogenous R&D. Santacreu (2015) presents a multi-country real business cycle (RBC) model with innovation and adoption of foreign technologies via trade. The model predicts that developing countries achieve 75% of their embodied growth from foreign adoption, while developed countries obtain 65% of embodied growth through domestic innovation.[4]

A simulation study that is close to ours is Varga et al. (2016). The authors develop a two-economy model of the euro area and the rest of the world (RoW) to study the slowdown in TFP growth in the euro area. The model combines the semi-endogenous growth model of Jones (2005) with R&D spillovers as described in Bottazzi and Peri (2007) and adoption as described in Anzoategui et al. (2019). The model features two types of households, liquidity and non-liquidity constrained, and a complex fiscal sector which distinguishes government consumption, investment and transfers as well as unemployment benefits. The authors run a simulation where they replicate the financial crisis, assuming a financial shock of 400 basis points to the euro area and a 300 basis points risk premium shock to the RoW. Their model can capture several observed facts from the crisis. The maximum decline in GDP is reached after 14 years, when there is a slowdown in intangibles, which is supported by a slowdown in investment. Tangible capital reacts more sluggishly due to capital adjustment cost. However, both have a significant impact on the decline in TFP growth. These developments are supported by wage rigidities fostering a slowdown in employment, which contributes 60% of the slowdown in GDP. Much of the slowdown in productivity growth

[3] Hasumi et al. (2018) performs a similar exercise for the Japanese economy to elaborate on the lost decades. In a model selection exercise, they find that the conventional model performs better than the model with endogenous growth. However, in an exercise to analyse the Asian financial crisis in 1998 and the financial crisis, the model with endogenous growth produced recessions and a period of prolonged stagnation.

[4] In a follow-up paper, Cai et al. (2017) develop a multi-country and multi-sector model of endogenous growth that is consistent with the data and in which comparative advantage and the stock of knowledge are endogenously determined by innovation and knowledge diffusion to study the effects of trade liberalisation. They find that a reduction in trade frictions induces a reallocation of innovation towards sectors that experience larger increases in comparative advantage. By contrast, comparative advantage reallocates towards sectors with stronger knowledge spillovers. The authors emphasise that dynamic gains from trade are highly dependent on knowledge diffusion across sectors and countries.

is driven by delayed adoption induced by financial shocks. Another paper close to ours is Correa-López and de Blas (2018). The authors propose a two-country model with three distinctive elements. Endogenous growth is driven by embodied technological change in new intermediate varieties for the capital goods sector, there is cross-country firm heterogeneity in the production of such intermediates and finally countries trade in varieties. Disembodied technological change in the production of the final output is the second source of growth and exogenous. In this model, the number of varieties produced domestically together with the probability of exporting determine the number of traded intermediates. In such a framework, productivity cut-offs exhibit long-term dynamics that are associated to the steady-state growth rate and short-term dynamics of adjustment after exogenous disturbances which turns out to be critical for the international transmission of shocks. In the presence of firm heterogeneity, a negative shock to TFP in the United States causes some firms to become exporters, which makes it optimal for the follower country to spend more on adoption than on R&D, leading to reduced medium-term growth. Furthermore, they find that an adverse investment-specific shock could lead to a prolonged recession in the United States, implying depressed firm productivity and GDP growth for ten years, which has consequences for trade, both in terms of quantities and varieties. Overall, they also find increased international co-movement of real variables that is closer to the data. Cova et al. (2017) employ a five-country model of endogenous growth to study the global macroeconomic effects resulting from the interaction of fiscal and monetary policy measures between the countries. In their model, a negative R&D efficiency shock to a frontier country replicates the observed slowdown in long term global growth and decrease in interest rates. They find that an increase in US public investment favours global growth in the medium and long term, while in the short term it favours domestic growth and weakens foreign growth. For the United States, accommodative monetary policy amplifies short-term effects and reduces negative spillovers. Similarly, other countries can weaken negative spillover effects by employing accommodative monetary policy and enhancing public investment.[5]

[5] Aghion and Howitt (2006) argue that non-frontier countries can gain from structural policies that favour cost-efficient adoption of existing technologies, while frontier countries would benefit most from policies to promote innovation (i.e. enhancing skills or R&D). Another paper studying R&D innovation policies is Di Comite and Kancs (2015). They study spillovers by forming a foreign knowledge stock, which is a weighted trade average of the foreign stocks of knowledge. The knowledge production function in their model requires high-skilled workers, the supply of which is endogenous however, whilst skill accumulation is not. Finally, they simulate reforms such as tax credits, tax reduction, wage subsidies and fixed cost reduction.

To provide a comprehensive model-based characterisation of euro area macroeconomic developments that is able to explain the slowdown in growth and matters of international resilience, we develop and estimate a two-economy medium-scale new Keynesian model that features the following ingredients: First, the model incorporates capital to represent the sluggishness as well as problems of misallocation and under-investment. Second, the model allows for endogenous R&D and technology adoption decisions to reflect the importance of tangible assets, its slow moving properties and the importance of stable demand conditions for long term growth. Finally, the model should take into account the openness of the euro area economy allowing for trade in consumption and investment goods. In addition, the two-economy framework provides the following additional findings:

(i) As compared to conventional frameworks, the endogenous growth framework displays increased spillovers and suggests increased co-movement of real GDP across countries as a result of certain foreign shocks. Particularly, shocks to US liquidity preference can have a similarly directed contracting effect in the euro area. Shocks to US R&D efficiency substantially affect euro area macroeconomic dynamics in the medium term, while shocks to US monetary policy have an immediate impact on euro area productivity. In contrast, the US economy behaves more resilient in response to EA shocks.

(ii) A model-based decomposition unveils that the euro area business cycle is substantially affected by US financial and net trade shocks, triggering international medium-term cycles. We find US shocks to liquidity preference contributing substantially during the crisis in 2001 and explaining more than one third of the downturn in the Great Recession.

The remainder of the paper is structured as follows. Section 2 describes the model. Section 3 presents the estimation approach and the data, as well as the dynamic transmission of shocks. Section 4 discusses the structural interpretation of business and medium-term cycle dynamics. Section 5 concludes.

2 The model

The model is a new Keynesian two-economy DSGE model with incomplete international financial markets as in Benigno (2009) that prevent households to fully hedge against country-specific income shocks. The core of the model follows Smets and Wouters (2007) while featuring costly R&D and adoption of new technologies as in Anzoategui et al. (2019). By construction, we assume that both economies follow a common balanced growth path. The most important shock driving technology adoption and business cycle dynamics is a liquidity demand shock as in Krishnamurthy and Vissing-Jorgensen (2012), which inherits the transmission properties of a financial shock. The two-economy nature allows the scope of this shock to be broadened to foreign bond holdings. Both economies are structurally symmetric. The model description follows North (N) and South (S) notation taking the perspective of the North economy. North is populated by a continuum of households of measure n, South by 1-n. We estimate this model for the euro area and the United States. After stationarising the variables, the nonlinear model equations are log-linearised around a zero-inflation steady-state by Dynare.

2.1 Endogenous productivity and the production sector

To understand how endogenous productivity enters the framework, we start by describing the firm side. Along the lines of Anzoategui et al. (2019), there are two types of firms: (i) final good producers and (ii) intermediate good producers. The former ones consist of a continuum of monopolistically competitive producers of measure one. Each final good firm i produces differentiated output $y_t^{N,i}$. A final good composite is then the following CES aggregate of the differentiated final goods:

$$y_t^N = \left(\int_0^1 (y_t^{N,i})^{\frac{1}{\mu_t^N}} \right)^{\mu_t^N}, \tag{1}$$

where $\mu_t^N > 1$ and $log(\mu_t)$ is given by an exogenous stochastic process:

$$log(\mu_t^N) = (1 - \rho_\mu^N) log(\bar{\mu}^N) + \rho_\mu^N log(\mu_{t-1}^N) + \sigma_\mu^N \epsilon_t^{N,\mu}, \tag{2}$$

where $\epsilon_t^{N,\mu}$ is i.i.d. N(0,1). Each final good firm i in country N uses $y_{mt}^{N,i}$ units of intermediate goods composite as input to produce output y_t^N. This is done via a simple linear technology:

$$y_t^{N,i} = y_{mt}^{N,i}. \tag{3}$$

We assume that each firm sets its nominal price $p_t^{N,i}$ à la Calvo making use of the Rotemberg approximation as shown in subsequent sections. Further, there exists a continuum of monopolistically competitive intermediate good producers a_t^N with each producing a differentiated product. This endogenous and predetermined variable mirrors the stock of intermediate goods adopted in production and is interpreted as the stock of adopted technologies. The intermediate good firm j produces output $y_{mt}^{N,j}$. The intermediate goods composite is the following CES aggregate of individual intermediate goods:

$$y_{mt}^{N,i} = \left(\int_0^{a_t^N} (y_{m,t}^{N,j})^{\frac{1}{\nu^N}} dj \right)^{\nu^N}, \tag{4}$$

where $\nu^N > 1$. Firm j in country N employs $k_t^{N,j}$ of capital, uses it at intensity of $u_t^{N,j}$, and employs $l_t^{N,j}$ of unskilled labour. Introducing variable utilisation is of importance, otherwise all higher frequency variation would be attributed to the Solow residual. Output of firm j is produced according to the following Cobb-Douglas technology:

$$y_{mt}^{N,j} = \theta_t^N \left(u_t^{N,j} k_t^{N,j} \right)^{\alpha^N} (l_t^{N,j})^{1-\alpha^N}, \tag{5}$$

with θ_t^N being an aggregate productivity shock whose growth rate follows a stationary AR(1) process:

$$log(\theta_t^N) = (1 - \rho_\theta^N) log(\bar{\theta}^N) + \rho_\theta^N log(\theta_{t-1}^N) + \sigma_\theta^N \epsilon_{\theta,t}^N, \tag{6}$$

with $\epsilon_{\theta,t}^N$ being i.i.d. $\sim N(0,1)$. Finally, we suppose that intermediate-goods firms set prices each period. Hence, intermediate-good prices are perfectly flexible in contrast to final good prices. Assuming symmetry in Equation 4 and 5, we can express aggregate production for the final good composite y_t^N as:

$$y_t^N = \left[a_t^{N\nu^N} \theta_t^N \right] \cdot \left(u_t^N k_t^N \right)^{\alpha^N} (l_t^N)^{1-\alpha^N}, \tag{7}$$

The first term in brackets is total factor productivity consisting of the endogenous variation a_t^N, which stems from domestic technology adoption and the exogenous variation given by θ_t^N. Endogenous productivity works through the expansion in the variety of adopted intermediate goods. Exogenous productivity is stationary, which makes endogenous productivity the driver of long term growth.

2.2 Research and adoption

We continue to follow Comin and Gertler (2006) and Anzoategui et al. (2019) in the process of modeling creation and adoption of new technologies. After being innovated, technologies can be adopted from a country-specific pool of technologies. The creation as well as the adoption of technologies requires skilled labour. There is a continuum of adopters and innovators in each country.

2.3 Innovators' problem

There is a continuum of measure one of innovators that use skilled labour to create new ideas or technologies according to the following production function:

$$\varphi_t^N = \chi_t^N z_t^N l_{srt}^{N, \rho_z^N - 1}, \tag{8}$$

Each unit of skilled labour l_{srt}^N can create φ_t^N number of new technologies at $t+1$. l_{srt}^N is the aggregate amount of skilled labour that is working on R&D. z_t^N is the current amount of technologies available and reflects public learning by doing in the R&D process, which is in line with Romer (1990). l_{srt}^N is the aggregate amount of skilled labour working on R&D. $\rho_z^N < 1$ is a congestion externality, meaning that increased aggregate innovation activity decreases R&D efficiency at the level of an individual firm. This parameter can also be interpreted as the elasticity of the growth rate of technologies with respect to research and development. The functional form implies constant returns to scale at the innovator level, which simplifies aggregation, while ensuring diminishing returns at the aggregate level. χ_t^N is an exogenous disturbance to R&D technology. It can be interpreted as an efficiency shock to R&D and follows the exogenous process:

$$log(\chi_t) = (1 - \rho_\chi) log(\bar{\chi}) + \rho_\chi log(\chi_{t-1}) + \sigma_t^\chi \epsilon_t^\chi, \tag{9}$$

where $\epsilon_t^{\chi,N}$ is i.i.d. N(0,1). The decision problem of innovator p in country N is dependent on the value of technology and other conditions in country N, which shall reflect the fact that the size of the home market determines the ability for R&D.

$$\max_{l_{srt}^{p,N}} \mathbb{E}_t \, \Lambda_{t,t+1}^N J_{t+1}^N \varphi_t^N l_{srt}^{p,N} - w_{st}^N l_{srt}^{p,N} \quad s.t. \quad \varphi_t^N = \chi_t^N z_t^N l_{srt}^{N,\rho_z^N - 1}, \tag{10}$$

The optimality condition for R&D reads:

$$w_{st}^N = \mathbb{E}_t \left\{ \Lambda_{t,t+1}^N J_{t+1}^N \chi_t^N z_t^N l_{srt}^{N,\rho_z^N - 1} \right\}, \tag{11}$$

where the left hand side reflects marginal cost of an additional unit of skilled labour, in terms of the skilled wage w_{st}^N, while the right hand side is the discounted marginal benefit. Expanding with z_{t+1}^N:

$$w_{st}^N = \mathbb{E}_t \left\{ \Lambda_{t,t+1}^N J_{t+1}^{Z,N} \chi_t^N z_t^N \frac{1}{z_{t+1}^N} l_{srt}^{N,\rho_z^N - 1} \right\}, \tag{12}$$

$J_t^{Z,N}$ is the normalized value of an unadopted technology in North. $\Lambda_{t,t+1}^N$ is the household's stochastic discount factor and w_{st}^N is the real wage for a unit of skilled labour. Given the procyclicality of profits from intermediate goods, the value of an unadopted good, which is dependant on future profits, will be also procyclical. Combined with skilled wage stickiness, this leads to procyclical l_{srt}^N. The evolution of the stock of new technologies is represented:

$$z_{t+1}^N = \varphi_t^N l_{srt}^N + \phi^N z_t^N, \tag{13}$$

with the first part on the right hand side describing the creation of new technologies and the second part describing technologies that have survived the last period. l_{srt}^N describes the skilled labour employed in R&D, while ϕ^N describes the survival rate of technologies. Rearranging this equation yields the growth rate of new technologies:

$$\frac{z_{t+1}^N}{z_t^N} = \chi_t^N l_{srt}^{N,\rho_z^N} + \phi^N. \tag{14}$$

2.4 Adopters' problem

Newly created technologies z_t^N require to be adopted a_t^N, to become part of the total factor productivity component. Technology adoption or diffusion is supposed to be pro-cyclically, but is also supposed to take time as shown in Comin and Hobijn (2010). In order to avoid to keep track for every available technology, we assume a competitive group of adopters who convert unadopted into adopted technologies by using skilled labour l^N_{sat} and buying the right of an unadopted technology at the competitive price $J^{z,N}_t$. The stochastic rate of adoption from the pool of technologies, λ^N_t, which can be interpreted as the probability of succeeding in making a product usable, in North reads:

$$\lambda^N_t = \lambda(z^N_t, l^N_{sat}) = \kappa^N l^{N,\rho^N_z}_{sat}. \tag{15}$$

The adoption probability is increasing and concave in the resources devoted, which is skilled labour reserved for adoption l^N_{sat}. Skilled labour for research experiences a spillover effect from the total stock of domestic technologies z^N_t. Adoption becomes more efficient as the technological state of the economy improves, which ensures a balanced growth path. An increasing amount of new technologies requires to be adopted, while the supply of labour isn't changing. Unlike for R&D there is no efficiency shock in the adoption process. Anzoategui et al. (2019) motivate this asymmetry as there is no additional observable to identify this shock. In steady-state the average time of a technology to be adopted is $1/\lambda^N_{ss}$ on average, while out of steady state the pace of adoption can vary with skilled labour input. Once a good is adopted, the adopter sells the rights to the technology to a monopolistically competitive intermediate-goods producer that makes the new product. Producing the good and operating under monopolistically competitive pricing leads to profits of $\pi^N_{m,t}$. The price of an adopted technology V^N_t is given by the discounted value of profits from producing the good,

$$V^N_t = \pi^N_{m,t} + \phi^N \, \mathbb{E}_t \, \Lambda^N_{t,t+1} V^N_{t+1}. \tag{16}$$

The adopter of technologies maximises the value of an unadopted technology J^N_t by choosing l^N_{sat}

$$J^N_t = \max_{l^N_{sat}} \mathbb{E}_t \left\{ -w^N_{st} l^N_{sat} + \phi^N \Lambda^N_{t,t+1} \left[\lambda^N_t V^N_{t+1} + \left(1 - \lambda^N_t\right) J^N_{t+1} \right] \right\}. \tag{17}$$

The first term in the Bellman equation represents the adoption expenditures, while the second term reflects discounted benefits, which is the probability weighted sum of the values of adopted and unadopted technologies. The first order condition then reads:

$$\phi^N \mathbb{E}_t \left(\Lambda^N_{t,t+1} \frac{\partial \lambda^N_t}{\partial l^N_{sat}} \left[V^N_{t+1} - J^N_{t+1} \right] \right) = w^N_{st}, \tag{18}$$

where $\frac{\partial \lambda^N_t}{\partial l^N_{sat}} = \lambda^{\prime,N}(\cdot)\, z^N_t$. This results in the FOC,

$$z^N_t \lambda^{\prime,N}_t \phi^N \mathbb{E}_t \left\{ \Lambda^N_{t,t+1} \left[V^N_{t+1} - J^N_{t+1} \right] \right\} = w^N_{st}. \tag{19}$$

The FOC implies that marginal costs equal the marginal gain from adoption expenditures, which is the increase in the adoption probability times the discounted difference between the value of an adopted versus unadopted technology. Further, there is a pro-cyclical variation in l^N_{sat} due to procyclicality in $V^N_t - J^N_t$ given greater influence of near term profits on the value of adopted technologies relative to unadopted ones and stickiness in w^N_{st}. This implies that λ_t also varies procyclically. Since the adoption probability does not depend on adopter-specific characteristics, it can be aggregated to obtain the evolution of domestic adopted technologies:

$$a^N_t = \lambda^N_t \phi^N \left[z^N_t - a^N_t \right] + \phi^N a^N_t, \tag{20}$$

with $z^N_t - a^N_t$ being the stock of unadopted technologies.

2.5 Households

2.5.1 Intertemporal problem

In each country there is a continuum of identical households, normalised to 1, who consume and save in form of capital and riskless bonds which are zero in net supply. They rent capital to intermediate good firms and supply monopolistically competitive their labour. The household's problem differs from a standard setup in two ways: (i) it supplies skilled (l^N_{st}) and unskilled (l^N_t) labour, where the former one is either used for R&D or adoption, while the latter one is used for production. (ii) It is assumed that the household has a preference for domestic $b^N_{H,t}$ and foreign $b^N_{F,t}$ safe bonds, which are incorporated in the utility function similarly as in Krishnamurthy and Vissing-Jorgensen (2012) and Fisher (2015) as a motive for liquidity preference, ϱ^N_t. This shock is an explicit formulation of the risk shock in Smets and Wouters (2007). The liquidity demand shock transmits through the economy like a financial shock and is one of the main sources of cyclical variation. Further, the shock generates a co-movement between consumption and investment similar as from a monetary shock. Note that we also take into account the foreign safe asset in this formulation. The representative household in country N maximises the utility function:

$$\max_{\{c_t^N,\ b_{H,t}^N,\ b_{F,t}^N,\ l_t^N,\ l_{s,t}^N,\ k_{t+1}^N\}_{t=0}^{\infty}}$$

$$\mathbb{E}_t \sum_{t=0}^{\infty} \beta^t \left[log\left(c_t^N - bc_{t-1}^N\right) + \varrho_t^N (b_{H,t}^N + b_{F,t}^N) - \frac{\upsilon \left(l_t^N\right)^{1+\varphi^N} + \upsilon_s \left(l_{s,t}^N\right)^{1+\varphi^N}}{1+\varphi^N} \right], \tag{21}$$

subject to the household budget constraint,

$$\begin{aligned} p_t^N c_t^N + b_{H,t}^N + ner_t b_{F,t}^N &= w_t^N l_t^N + w_{st}^N l_{st}^N + p_t \Pi_t^N + q_{t-1}^N r_{kt}^N k_t^N - q_t^N k_{t+1}^N \\ &+ r_t^N b_{H,t-1}^N - r_t^S ner_t b_{F,t-1}^N - \frac{\phi_B^N}{2} \left(\frac{ner_t (b_{F,t}^N - \bar{b}_{F,t}^N)}{p_t^N} \right)^2 p_t^N + p_t^N T_t^N, \end{aligned} \tag{22}$$

and to the law of motion of capital,

$$k_{t+1}^N = \left[1 - \frac{\kappa_i^N}{2} \left(\frac{i_t^N}{i_{t-1}^N} - 1 \right)^2 \right] i_t^N + (1 - \delta(u_t^N)) k_t^N, \tag{23}$$

where c_t^N is consumption, b_t^N and b_t^S are the holdings of home and foreign bonds, Π_t^N are the profits from the ownership of monopolistically competitive firms, k_t^N is capital, q_t^N is the price of capital, r_{kt}^N is the rate of return, rer_t is the nominal exchange rate, and div_t^N the rental rate of capital. Due to the open economy dimension of the model, the value of consumption in any of the two countries does not have to to be equal to the value of domestic output. As common in the open economy literature, we follow Schmitt-Grohé and Uribe (2003) and introduce bond adjustment costs. Further, $r_{kt}^N \equiv (div_t^N + q_t^N) q_{t-1}^N$. $\Lambda_{t,t+1}^N \equiv \beta^N u'(c_{t+1}^N)/u'(c_t^N)$ is the households stochastic discount factor, while the liquidity shock is given by $\zeta_t^N = \varrho_t^N / u'(c_t^N)$. The shock is itself following an exogenous process,

$$log(\zeta_t^N) = (1 - \rho_\zeta^N) log(\bar{\zeta}^N) + \rho_\zeta^N log(\zeta_{t-1}^N) + \sigma_\zeta^N \epsilon_t^{N,\zeta}, \tag{24}$$

with $\epsilon_t^{N,\zeta}$ is i.i.d. $N(0,1)$. Then we can express the first order necessary conditions for the riskless home bonds:

$$1 = \mathbb{E}_t \left[\Lambda_{t,t+1}^N r_{t+1}^N\right] + \zeta_t^N. \tag{25}$$

As can be seen in Equation 25, the liquidity demand shock distorts the first order condition. An increase in ζ_t^N works like an increase in risk or the credit spread. Given the riskless rate r_{t+1}^N it induces a precautionary saving effect, as households would reduce their consumption to satisfy the condition (decrease in $\Lambda_{t,t+1}^N$). Further, the decline in $\Lambda_{t,t+1}^N$ (i) raises the required return on capital and promotes a drop in investment demand and (ii) promotes a drop in adoption and R&D. In order not to distort the decision between the bonds, the first order condition for the foreign bond is subject to the same shock:

$$u'(c_t^N)\left[1 + \kappa_B^N(b_{F,t}^N - \bar{b}_F^N)\right] = \beta^N \, \mathbb{E}_t \left[u'(c_{t+1}^N)\frac{r_{t+1}^S}{\pi_t^S}\frac{rer_t}{rer_{t+1}}\right] + \zeta_t^N. \tag{26}$$

Equation describes how a liquidity demand shock affects foreign bond holdings. Given the foreign riskless rate and the exchange rate, domestic households would decrease their consumption to hold more foreign bonds. Combining the Euler equation as described in Equation 25 with the first order necessary condition for capital provided by Equation 27,

$$1 = \mathbb{E}_t \left[\Lambda_{t,t+1}^N r_{k,t+1}^N\right], \tag{27}$$

we obtain:

$$\mathbb{E}_t \left[\Lambda_{t,t+1}^N (r_{k,t+1}^N - r_{t+1}^N)\right] = \zeta_t^N. \tag{28}$$

The equation shows that an increase in the liquidity preference shock ζ_t^N has an effect on $r_{k,t+1}$ and $\Lambda_{t,t+1}$ that is qualitatively similar to that arising from an increase in $r_{k,t+1}$. Furthermore, the shock increases the spread $r_{k,t+1}^N - r_{t+1}^N$ letting the shock work like a financial shock.

Using final output households produce competitively new capital goods, which are then rent to firms. i_t^N defines new capital produced in country N, which is created from final output at the relative price p_t^N and which is growing in steady state with γ_y. Following

Christiano et al. (2005) flow adjustment costs of investment are assumed. In particular, the adjustment cost function $f(i_t^N/(1+\gamma_y)i_{t-1}^N)$ is increasing and concave, with $f(1) = f'(1) = 0$ and $f''(1) > 0$. Further, there is a shock to investment efficiency given by p_{kt}^N

$$log(p_{kt}^N) = (1 - \rho_{pk}^N)log(\bar{pk}^N) + \rho_{pk_t}^N log(p_{kt-1}^N) + \sigma_t^{p_k} \epsilon_t^{p_k,N}. \tag{29}$$

Depreciation of capital is dependent on utilisation,

$$\delta(u_t^N) = \delta^N - \frac{d_1^N}{1+\omega_K^N} + d_1^N \frac{u_t^{N,1+\omega_K^N}}{1+\omega_K^N}. \tag{30}$$

The first order condition with respect to i_t^N relates the ratio of the market value of capital to the replacement price to investment ("Tobin's Q") as follows:

$$p_{k,t}^N = q_t^N \left[\left(1 - \frac{\phi_K^2}{2} \left(\frac{i_t^N}{i_{t-1}^N} \right)^2 \right) - \frac{i_t^N}{i_{t-1}^N} \phi_K^N \left(\frac{i_t^N}{i_{t-1}^N} - 1 \right) \right] + \beta E_t q_{t+1}^N \left(\frac{i_{t+1}^N}{i_t^N} - 1 \right) \frac{(i_{t+1}^N)^2}{(i_t^N)^2}. \tag{31}$$

q_t^N is the present discounted value of the rental rate on capital. The first order condition of i_t^N tells that if investment is large relative to steady state then q_t^N will be greater than 1.

2.5.2 Intratemporal problem

The Euler equation derived in the intertemporal problem determines how much each household wants to consume each period. In the intratemporal optimisation the households decide upon the consumption bundle between domestically and foreign produced final goods. This is done by minimising consumption expenses given relative prices of goods in the market:

$$\min_{c_{H,t}^N, c_{F,t}^N} p_t^N c_t^N = p_{H,t}^N c_{H,t}^N + p_{F,t}^N c_{F,t}^N, \tag{32}$$

subject to a consumption composite c_t^N, which is sub-utility index with constant elasticity of substitution between composites of imported and domestically produced goods, resulting from a two-stage Dixit-Stiglitz aggregator:

$$c_t^N \equiv \left[(1-\lambda^N)^{\frac{1}{\eta}} \left(c_{H,t}^N \right)^{\frac{\eta-1}{\eta}} + \left(\lambda^N \right)^{\frac{1}{\eta}} \left(c_{F,t}^N \right)^{\frac{\eta-1}{\eta}} \right]^{\frac{\eta}{\eta-1}}, \tag{33}$$

with $\eta > 0$ being the elasticity of substitution between goods of N and S, and $(1-\lambda^N) \in [0,1]$ being the home bias in consumption.[6] This cost minimisation of overall consumption takes the prices of the consumption bundles in N and S, $p^N_{H,t}$ and $p^S_{F,t}$, as given. The resulting aggregated consumer price index p_t, which depends on prices of domestic and foreign goods weighted by their shares in consumption:

$$p^N_t \equiv \left[(1-\lambda^N)(p^N_{H,t})^{1-\eta} + \lambda^N (p^S_{F,t})^{1-\eta}\right]^{\frac{1}{1-\eta}}. \tag{34}$$

The CES consumption bundle implies the following demand functions for c^N_H and c^N_F:

$$c^N_{H,t} = \left[\frac{p^N_{H,t}}{p^N_t}\right]^{-\eta} (1-\lambda^N)c^N_t \quad \text{and} \quad c^N_{F,t} = \left[\frac{p^S_{F,t}}{p^N_t}\right]^{-\eta} \lambda^N c^N_t. \tag{35}$$

With the latter one constituting the import relationship for the economy. The magnitude of imports depends on the elasticity of substitution between foreign and domestic goods η, the degree of openness λ^N and the relative price level for imported goods to the aggregate price level. Imports also depend on the absolute level of consumption, c^N_t. Similarly, the CES investment bundle implies the following demand functions for i^N_H and i^N_F,

$$i^N_{H,t} = \left[\frac{p^N_{H,t}}{p^N_t}\right]^{-\eta} (1-\lambda^N)i^N_t \quad \text{and} \quad i^N_{F,t} = \left[\frac{p^S_{F,t}}{p^N_t}\right]^{-\eta} \lambda^N i^N_t. \tag{36}$$

The good weight of South in the North bundle λ^N is defined to be

$$\lambda^N = \omega^N \frac{(1-n)}{\left(n + (1-n)\frac{gdp^S_t}{gdp^N_t}\right)} \frac{gdp^S_t}{gdp^N_t}, \tag{37}$$

where n is the relative population in North, ω^N being the trade openness parameter and $\frac{gdp^S_t}{gdp^N_t}$ being the relative size of the economy in South in nominal terms.

2.6 Intermediate good firms: factor demands

The intermediate good producer j in country N chooses capital, $k^{j,N}_t$, utilisation $u^{j,N}_t$, and labour $l^{j,N}_t$ to minimize costs given the relative price of the intermediate goods composite p^N_{mt}, the real wage w^N_t, the price of capital q^N_t, the rental rate div^N_t, and the desired mark-up

[6] We use λ^N for facilitating the notation in this subsection. Please note that this lambda is unrelated to the one of the adoption rate.

ι^N. The capital utilisation is endogenised following Greenwood et al. (1988). In particular, the depreciation rate $\delta(u_t^{j,N})$ is an increasing and convex function of capital utilisation $u_t^{j,N}$. The firm's cost minimization problems for $k_t^{j,N}$, $u_t^{j,N}$, and $l_t^{j,N}$ are given by:

$$\alpha^N \frac{p_{mt}^N y_{mt}^{j,N}}{k_t^{j,N}} = \iota^N [div_t^N + \delta(u_t^{j,N}) q_t^N], \tag{38}$$

$$\alpha^N \frac{p_{mt}^N y_{mt}^{j,N}}{u_t^{j,N}} = \iota^N \delta'(u_t^{j,N}) q_t^N k_t^{j,N}, \tag{39}$$

$$(1-\alpha^N) \frac{p_{mt}^N y_{mt}^{j,N}}{l_t^{j,N}} = \iota^N w_t^N. \tag{40}$$

ι^N is allowed to be smaller than the optimal unconstrained markup ν^N. As argued by Aghion and Howitt (1998), this is motivated by the threat of entry of competitors.

2.7 Labour unions

Households supply differentiated labour types, which are then sold by labour unions to perfectly competitive labour packers who assemble them in a composite of skilled and unskilled labour, and sell the homogeneous labour to intermediate firms. Each representative union is related to an household $j \in [0;1]$. As the model is implemented in non-linear form, we choose Rotemberg (1982) pricing and make use of the first order equivalence to Calvo (1983). In particular, the model uses the Schmitt-Grohé and Uribe (2005) (SGU) setup as described in Born and Pfeifer (2020). A labour union supplies distinct labour services. The problem of household j is to choose w_t^j to maximise:

$$V_{w,t}^N = \mathbb{E}_t \sum_{k=0}^{\infty} \beta^{N,k} u\left(c_{t+k}^{N,j}, l_{t+k}^{N,j}\right), \tag{41}$$

taking into account the demand for its labour variety:

$$l_{t+k}^{N,j} = \left(\frac{w_{t+k}^{N,j}}{w_{t+k}^N}\right)^{-\epsilon_w^N} l_{t+k}^{N,d}, \tag{42}$$

and subject to the budget constraint:

$$p_t^N c_t^N = \int_0^1 w_t^{N,j} l_t^{N,j} dj - \frac{\kappa_w^N}{2} \left(\frac{1}{\Gamma_{t-1,t}^{N,ind}} \frac{w_t^{N,j}}{w_{t-1}^{N,j}} - 1\right)^2 dj \; \Xi_t^N + X_t^N. \tag{43}$$

The second last term represents the Rotemberg costs of adjusting the wage, with ϕ_w being the wage adjustment cost parameter. The costs are proportional to the nominal adjustment cost base Ξ_t and arise when wage changes differ from the indexed inflation rate $\Gamma_{t-1,t}^{N,ind}$. X_t^N captures all other additive terms that are not related to the current optimisation problem. We can rewrite the optimisation problem of the household using the following lagrangian

$$\mathcal{L} = \sum_{k=0}^{\infty} \beta^{N,k}\, \mathbb{E}_t \left[u\left(c_{t+k}^N,\ l_{t+k}^N\right) - \lambda_{t+k}^N \left\{ p_{t+k}^N c_{t+k}^N - l_{t+k}^{N,d} \int\limits_{t+k}^{d} \int_0^1 w_{t+k}^{N,j} \left(\frac{w_{t+k}^{N,j}}{w_{t+k}^N} \right)^{\epsilon_w^N} dj \right.\right.$$
$$\left.\left. + \frac{\kappa_w^N}{2} \int\limits_0^1 \left(\frac{1}{\gamma_{t,t+k}^{N,j}} \frac{w_{t+k}^{N,j}}{w_{t+k-1}^{N,j}} - 1 \right)^2 dj\ \Xi_{t+k}^N - X_{t+k}^N \right\} \right]. \quad (44)$$

Rearranging the corresponding first order condition for the optimal wage, and making use of the relations $MRS^N = \frac{\kappa_L^N l^{N,\varphi}}{\lambda_t^N}$ and $\frac{\Xi_t^N}{p_t^N} = y_t^N$ results in the non-linear new Keynesian wage Phillips curve (NKWPC):

$$0 = \epsilon_w^N \frac{\frac{\kappa_L^N l^{N,\varphi}}{\lambda_t^N}}{w_t^N} + \left[(1-\epsilon_w^N) - \kappa_w^N \left(\frac{w_t^N}{w_{t-1}^N} \frac{1}{\Gamma_{t-1,t}^{N,ind}} - 1 \right) \frac{\pi_t^N}{l_t^N} \frac{1}{\Gamma_{t-1}^{N,ind}} \frac{y_t^N}{w_{t-1}^N} \right]$$
$$- \mathbb{E}_t\, \beta^N \frac{\lambda_{t+1}^N}{\lambda_t^N} \pi_{t,t+1}^N \frac{1}{l_t^N} \frac{1}{\frac{w_t^N}{p_t^N}} \left[\kappa_w^N \left(\frac{w_{t+1}^N}{w_t^N} \frac{1}{\Gamma_{t-1,t}^{N,ind}} - 1 \right) y_{t+1}^N \right]. \quad (45)$$

Mapping the Calvo wage duration parameter into the Rotemberg adjustment cost parameter:

$$\kappa_w^N = \frac{(\epsilon_w^N - 1)N^N}{(1-\theta_w^N)(1-\beta^N\theta_w^N)} \theta_w^N, \quad (46)$$

with $N^N = \frac{l^N w^N}{\Xi^N}$ being the steady state share of the wage bill in the adjustment cost base. We can calibrate the unskilled labour disutility parameter using the steady state values of the variables i.e. $l_t^N = 1$ or $\pi_t^N = 1$,

$$\psi^N = -\frac{\bar{\lambda}_t^N \bar{w}^N (1-\epsilon_w^N)}{\epsilon_w^N}. \quad (47)$$

Unskilled labour is subject to a wage mark-up shock,

$$log(\mu_{wt}^N) = (1-\rho_{\bar{\mu}_w}^N) log(\mu_w^N) + \rho_{\mu_w}^N log(\mu_{wt-1}^N) + \sigma_t^{\mu_w} \epsilon_t^{\mu_w,N}. \quad (48)$$

The problem for skilled labour is defined analogously. Hence, unskilled wage and hours of unskilled workers have to be replaced by their skilled equivalents. Details are delegated to Appendix C.1.2.

2.8 Price setting

We follow Ascari and Rossi (2012) to solve for the Rotemberg (1982) new Keynesian price Phillips curve (NKPPC), making use of the first order equivalence to Calvo (1983). Firms set the prices in their own currency (PCP). The profit maximisation problem of firm i in country N, expressed in terms of the domestic price index, is given by,

$$\max_{\{p^N_{H,t}(i),\ l^N_t(i),\ k^N_t(i),\ y^N_t(i)\}_{t=0}^{\infty}} \mathbb{E}_t \left\{ \sum_{t=0}^{\infty} \beta^{N,t} \frac{\lambda^N_{t+1}}{\lambda^N_t} \left[\frac{p^N_{H,t}(i)}{p^N_t} y^N_t(i) - w^N_t l^N_t(i) - r^{k,N}_t k^N_t(i) \right.\right.$$
$$\left.\left. - \frac{\kappa^N_P}{2} \left(\frac{p^N_{H,t}(i)}{p^N_{H,t-1}(i)} - \bar{\pi}^N \right)^2 \frac{p^N_{H,t}}{p^N_t} y^N_t \right] \right\}$$

$$s.t. \quad \begin{cases} y^N_t(i) & = y^N_t \left(\frac{p^N_{H,t}(i)}{p^N_{H,t}} \right)^{1-\epsilon^N_p} \\ y^N_t(i) & = a^{T,N}_t (k^N_t(i))^{\alpha^N} (l^N_t(i))^{1-\alpha^N}. \end{cases} \tag{49}$$

The langragian multiplier mc^N_t can be interpreted as the real marginal cost of producing an additional unit of output. The first order condition with respect to $p^N_{H,t}(i)$ is given by

$$(1-\epsilon^N_p) \left(\frac{p^N_{H,t}(i)}{p^N_t} \right)^{-\epsilon^N_p} \frac{y^N_t}{p^N_{H,t}} - \frac{\kappa^N_P}{p^N_{H,t-1}(i)} \left(\frac{p^N_{H,t}(i)}{p^N_{H,t-1}(i)} - \bar{\pi}^N \right) y^N_t + \epsilon^N_p mc^N_t(i) \frac{y^N_t}{p^N_{H,t}} \left(\frac{p^N_{H,t}(i)}{p^N_{H,t}} \right)^{-\epsilon^N_p - 1}$$
$$+ \beta^N \mathbb{E}_t \left[\frac{\lambda^N_{t+1}}{\lambda^N_t} \kappa^N_P \frac{p^N_{H,t+1}}{p^N_t} \left(\frac{p^N_{H,t+1}(i)}{p^N_{H,t}(i)} - \bar{\pi}^N \right)^2 y^N_{t+1} \right] = 0 \tag{50}$$

. Rearranging the pricing condition and making use of $\pi^N_{H,t} = \frac{p^N_{H,t+1}}{p^N_{H,t}}$ yields the non-linear new Keynesian Phillips curve for prices,

$$\pi^N_{H,t}\mu^N_t(\pi^N_{H,t}\mu^N_t - \bar{\pi}^N) = \beta^N \, \mathbb{E}_t \left[\frac{\lambda^N_{t+1}}{\lambda^N_t} \pi^N_{H,t+1}(\pi^N_{H,t+1} - \bar{\pi}^N) \frac{p^N_{H,t+1}}{p^N_{H,t}} \frac{y^N_{t+1}}{y^N_t} \right] + \frac{\epsilon^N_p}{\kappa^N_P} \left(\frac{mc^N_t}{p^N_{H,t}} - \frac{\epsilon^N_p - 1}{\epsilon^N_p} \right). \quad (51)$$

Assuming that each period a fraction of firms $(1 - \xi^N_p)$ with $\xi^N_p \in [0,1]$ is able to reset their prices optimally, while the other fraction ξ^N_p can not. This implies an average Calvo duration of a price of $\theta^N_p = \frac{1}{1-\xi^N_p}$. In a further step, the Calvo duration parameter is translated into Rotemberg adjustment cost, which is done by equating the slopes of the linearised Calvo and Rotemberg price NKPCs,

$$\kappa^N_P = \frac{(\epsilon^N_p - 1)\theta^N_p}{(1-\theta^N_p)(1-\beta^N\theta^N_p)}. \quad (52)$$

Further, inflation is subject to a price mark-up shock,

$$log(\mu^N_t) = (1-\rho^N_\mu)log(\bar{\mu}^N) + \rho^N_\mu log(\mu^N_{t-1}) + \sigma^N_{\mu,t}\epsilon^N_{\mu,t}. \quad (53)$$

In order to consider backward-looking behavior, we introduce a respective term,

$$\pi^\star_{H,t} = \rho^{\pi^\star}_k \bar{\pi} + (1-\rho^{\pi^\star}_k)(\pi^Y_{H,t-1}) \quad (54)$$

. The price Phillips curve then becomes

$$\begin{aligned} \pi^N_{H,t}\mu^N_t(\pi^N_{H,t}\mu^N_t - \bar{\pi}^N) = \\ \beta^N \, \mathbb{E}_t \left[\frac{\lambda^N_{t+1}}{\lambda^N_t} \pi^N_{H,t+1} \left[sfp_H(\pi^N_{H,t+1} - \bar{\pi}^N) + (1-sfp_H)(\pi^\star_{H,t+1} - \bar{\pi} \right] \right) \frac{p^N_{H,t+1}}{p^N_{H,t}} \frac{y^N_{t+1}}{y^N_t} \right] \\ + \frac{\epsilon^N_p}{\kappa^N_P} \left(\frac{mc^N_t}{p^N_{H,t}} - \frac{\epsilon^N_p - 1}{\epsilon^N_p} \right), \end{aligned} \quad (55)$$

with sfp_H being the share of forward-looking price setters. A more detailed derivation is delegated to Appendix C.1.1.

2.9 Authorities

The nominal interest rate $r_{n,t+1}^{N}$ in country N is set according to the following Taylor rule

$$r_{n,t+1}^{N} = r_t^{m,N} \left(\left(\frac{\pi_t^N}{\pi_0^N} \right)^{\phi_\pi^N} \left(\frac{l_t^N}{l^{ss,N}} \right)^{\phi_y^N} r_n^N \right)^{1-\rho_R^N} \left(r_{nt}^N - 1 \right)^{\rho_R^N}, \tag{56}$$

with r_n^N being the steady-state nominal rate, π_0^N the target rate of inflation, ρ_R^N the persistence parameter of monetary policy, l_t^N total employment and $l^{ss,N}$ steady state employment. The feedback coefficients on inflation and on the labour gap are given by ϕ_π^N and ϕ_y^N. We follow Anzoategui et al. (2019) in using the employment gap as opposed to an output gap to measure capacity utilisation. Berger et al. (2019) have shown that measures of employment are the strongest predictors of changes in the Fed Funds rate. The employment gap also delivers a more reasonable response of the nominal rate to real activity compared to one with an output gap. The nominal interest rate is subject to a monetary shock $r_t^{m,N}$, which is as follows

$$log(r_t^{m,N}) = (1 - \rho_{rm}^N) log(\bar{r}^{m,N}) + \rho_{rm}^N log(r_{t-1}^{m,N}) + \epsilon_t^{r^m,N}. \tag{57}$$

The Fisher relation links the nominal with the real rate

$$r_{n,t}^N = r_t^N \, \mathbb{E}_t \, \pi_{t+1}^N. \tag{58}$$

Government consumption G_t^N is financed by lump sum taxes and follows an AR(1) process that captures the variation of the provided series

$$log(g_t^N) = (1 - \rho_g^N) log(\bar{g}^N) + \rho_g^N log(g_{t-1}^N) + \epsilon_t^{g,N}. \tag{59}$$

2.10 Terms of trade, capital flows and the current account

The exchange rate pass through is complete. The nominal exchange rate is defined,

$$rer_t = ner_t \frac{p_t^\star}{p_t}. \tag{60}$$

The terms of trade are defined to be the ratio between the price of imports and the price of exports

$$T_t = \frac{p_{F,t}}{p_{H,t}}. \tag{61}$$

The trade balance reads

$$\begin{aligned} tb_t^N = b_{H,t}^N - \frac{r_t^N b_{H,t-1}^N}{\pi_t^N} + rer_t^N b_{F,t}^N - rer_t \frac{r_t^S}{\pi_t^S} b_{F,t-1}^N \\ - \frac{1-n}{n} \frac{\kappa_B^S}{2} \left(b_{H,t}^S - \bar{b}_H^S\right)^2 + \frac{\kappa_B^N}{2} \left(b_{F,t} - \bar{b}_F\right)^2, \end{aligned} \tag{62}$$

which reflects net asset holdings corrected for bond adjustment costs. Capital inflows into North are net investments in Home assets by North residents and vice versa,

$$in_t^N = -(b_{H,t}^N - b_{H,t-1}^N). \tag{63}$$

Similarly, capital outflows from North are net investment in Foreign assets by North residents,

$$out_t^N = rer(b_{F,t}^N - b_{F,t-1}^N). \tag{64}$$

The financial account is given by the difference between capital inflows and outflows,

$$fa_t^N = in_t^N - out_t^N. \tag{65}$$

The current account evolves,

$$ca_t^N = (b_{H,t}^N - b_{H,t-1}^N) + rer_t(b_{F,t}^N - b_{F,t-1}^N). \tag{66}$$

By construction the financial and the current account add up to zero. The net foreign asset position expressed in terms of domestic GDP is

$$nfa_t^N = \frac{b_{H,t}^N + rer_t b_{F,t}^N}{gdp_t^N}. \tag{67}$$

2.11 Closing the economy

In a closed economy the goods market clearing requires for all t that domestic output equals domestic demand

$$y_t^N = c_t^N + p_{kt}^N \left[1 + f\left(\frac{i_t^N}{i_{t-1}^N}\right)\right] i_t^N + g_t^N, \tag{68}$$

with $f\left(\frac{i_t^N}{i_{t-1}^N}\right) = \frac{\phi_K^N}{2}\left(\frac{i_t^N}{i_{t-1}^N} - 1\right)^2$. Analogously, in an open economy this assumption is relaxed due to trade and international bonds. In addition, we introduce an export demand shock. Goods market clearing for North becomes,

$$\begin{aligned} ny_t^N = n & \left[(1-\lambda^N)(p_{H,t}^N)^{-\eta}\left(c_{H,t}^N + p_{kt}^N\left[1 + f\left(\frac{i_t^N}{i_{t-1}^N}\right)\right] i_{H,t}^N\right) + g_t^N + \frac{\kappa_P}{2}\left(\frac{p_{H,t}}{p_{H,t-1}} - \bar{\pi}^p\right)^2 y_t^N \right. \\ & \left. + \frac{\kappa_w}{2}\left(\frac{w_t^N}{w_{t-1}^N} - \bar{\pi}^w\right)^2 y_t^N + \frac{\kappa_{ws}}{2}\left(\frac{ws_t^N}{ws_{t-1}^N} - \bar{\pi}^{ws}\right)^2 y_t^N\right] \\ & + (1-n)\lambda^S \left(p_{H,t}^S\right)^{-\eta}(c_{H,t}^S + i_{H,t}^S). \end{aligned} \tag{69}$$

Equivalently, goods markets for country S clear

$$\begin{aligned} (1-n)y_t^S = (1-n) & \left[g_t^S + (1-\lambda^S)(p_{H,t}^S)^{-\eta}(c_t^S + p_{kt}^S\left[1 - f\left(\frac{i_t^S}{i_{t-1}^S}\right)\right] i_t^S) \right. \\ & \left. + \frac{\kappa_P}{2}\left(\frac{p_{F,t}}{p_{F,t-1}} - \bar{\pi}^p\right)^2 y_t^S + \frac{\kappa_w}{2}\left(\frac{w_t^S}{w_{t-1}^S} - \bar{\pi}^w\right)^2 y_t^S + \frac{\kappa_w}{2}\left(\frac{ws_t^N}{ws_{t-1}^N} - \bar{\pi}^{ws}\right)^2 y_t^S\right] \\ & + n\lambda^N \left(p_{F,t}^S\right)^{-\eta}(c_t^N + i_t^N). \end{aligned} \tag{70}$$

Markets for domestic and foreign bonds have to clear

$$nb_{H,t}^N + (1-n)b_{H,t}^S = 0, \tag{71}$$

$$nb_{F,t}^N + (1-n)b_{F,t}^S = 0. \tag{72}$$

Skilled labour market clearing reads

$$l_{st}^N = \left[1 - \frac{a_t^N}{z_t^N}\right] l_{sat}^N + l_{srt}^N, \tag{73}$$

the first term denotes the skilled labour spent in the adoption of locally invented technologies and the last term denotes skilled labour spent in R&D.

3 Data and estimation approach

3.1 Estimation

We log-linearise the stationarised model equations. The model parameters are estimated using a Bayesian approach via Markov chain Monte Carlo (MCMC) simulation (see An and Schorfheide (2007), Smets and Wouters (2007) or Justiniano et al. (2010)). For finding the mode, we apply a sequence of solvers[7] while after each the mode is updated. By evaluating the likelihood from the Kalman filter with a prior density, we obtain the posterior density. We generate two chains with 300.000 draws from the posterior distribution of the parameters using the Metropolis-Hastings algorithm. We discard the first 10% as burn-in iterations.

3.2 Calibrated parameters

Table 1 describes the calibrated parameters. As it is common, we calibrate the steady-state ratio of government expenditures to output to match the data. Furthermore, we make use of the first-order equivalence of Rotemberg and Calvo pricing. Therefore, we map the price duration into the adjustment cost parameter as described in Equation 46 for wages and in Equation 52 for prices. The international parameters are calibrated symmetrically assuming a similar population and size of both economies. We follow Anzoategui et al. (2019) to calibrate the R&D parameters. We assume a quarterly growth rate of the world economy of 0.4%.

3.3 Observable variables

We use quarterly data for the euro area and the United States over the sample from the first quarter of 1984 to the fourth quarter of 2017. The dataset includes 18 time series as shown in Table A.1. These variables comprise the policy rate that is extended for the shadow rate as calculated by Wu and Xia (2016) to take into account monetary policy in the zero lower bound period, the log difference of GDP, consumption, investment, government consumption, and real wages, business R&D expenditures and the GDP deflator, as well

[7] In particular, we apply the Sims, the fminsearch, the fmincon, and then the Monte Carlo solver.

Table 1 CALIBRATED PARAMETERS

Parameter	Description	EA	US
Open economy			
ψ	Ratio of US to euro area GDP		1.000
n	Share population	0.500	0.500
ω	Trade openness	0.300	0.300
η	Substituteability of domestic and foreign goods	1.500	1.500
κ_B	Bond adjustment cost parameter	0.010	0.010
Technology			
ρ_z	R&D elasticity	0.4500	0.5000
λ_ρ	Adoption elasticity	0.9250	0.9250
$1-\phi$	Obsolesence rate	0.08/4	0.08/4
ϕ_S	Frisch elasticity skilled labour	1.5000	1.5000
ν	Intermediate goods elasticity of substitution	1.3500	1.3500
$\bar{\lambda}$	Steady state adoption lag	0.0500	0.0500
General			
g_y	SS Growth rate of the economy	0.4000	0.4000
φ	Frisch elasticity unskilled labour	2.0000	1.8000
β	Discount factor	0.9920	0.9920
Steady-state			
$\frac{G}{Y}$	Steady state government consumption / output	0.2000	0.1600
μ	Steady state final goods mark-up	1.1000	1.1000
ι	Steady state intermediate goods mark-up	1.1800	1.1800
$\bar{\zeta}$	Steady state liquidity demand	0.0125	0.0125
D	External gross debt	0.2000	0.2000

as the demeaned log-level of hours worked. In another step, we harmonise the data in a model-consistent way. As business R&D expenditures are an annual series, we interpolate those to obtain a series with a quarterly frequency. Moreover, we extrapolate the series of the United States for one observation. In addition, we harmonise the volatility of this series between countries. All series are illustrated in the Appendix in Figure A.1. The associated measurement equations can be found in Appendix A.2.

3.4 Parameter estimates and variance decomposition

Table 2 presents the prior and posterior distributions for the estimated parameters. The estimation finds the consumption habits parameter (h) to be 0.366 for the euro area, and 0.197 for the United States. Investment adjustment costs (ddac) are higher in the euro area, than in the US and the pricing parameters for wages and prices are within the range found in the literature with wages in the US appearing more flexible. Finally, the capital depreciation rate (δ) appears higher in the US than in the euro area.

Table 3 displays the estimated standard deviations and persistency parameters. Both, euro area and US exogenous TFP shocks are found to be very persistent, at 0.969 and 0.926 respectively. Liquidity demand shocks are found similarly persistent in the euro area at 0.982, as compared to the US with 0.951. The size of the shock is estimated to be smaller in the euro area than in the United States. Due to the harmonisation, R&D productivity shocks are found to be broadly similar in the two countries both in their persistence and

Table 2 Parameter estimates (prior and posterior distributions).

	Prior Distribution			Posterior Distribution					
					EA			US	
	Distr.	Mean	St. Dev.	Mode	Mean	St. Dev.	Mode	Mean	St. Dev.
ρ^R	Beta	0.7000	0.1500	0.5656	0.5669	0.0122	0.6589	0.6659	0.0059
ϕ_m	Gamma	1.7000	0.2500	0.7166	0.7171	0.0165	1.0037	1.0195	0.0477
ϕ_y	Gamma	0.3000	0.1000	0.1019	0.0825	0.0077	0.1256	0.1218	0.0029
ϕ	Gamma	2.0000	0.7500	1.9641	2.0280	0.0384	0.2259	0.1700	0.1058
$ddac$	Gamma	4.0000	1.0000	4.4737	4.5371	0.0499	2.7740	2.7445	0.1291
δ	Beta	0.4000	0.1000	0.0176	0.0176	0.0001	0.0241	0.0242	0.0001
α	Beta	0.2000	0.0500	0.1921	0.1929	0.0007	0.1876	0.1876	0.0009
$calvo_w$	Beta	0.5000	0.1000	0.9288	0.9287	0.0084	0.6542	0.6524	0.0075
$calvo_p$	Beta	0.7500	0.1000	0.8851	0.8907	0.0116	0.9235	0.9243	0.0043
h	Beta	0.4000	0.1000	0.3664	0.3819	0.0082	0.1976	0.1943	0.0092

Note: The posterior distributions are obtained using the Metropolis-Hastings algorithm. Col. (1) lists model parameters. Cols. (2)-(4) indicate the prior distribution function. Identical priors are assumed across countries. Cols. (5)-(7) show the mean, the mode and the standard deviation of the posterior distribution for the EA, while Cols. (8)-(10) show the respective ones for the US.

and in their size.

Table 3 Shocks processes estimates (prior and posterior distributions).

	Prior Distribution			Posterior Distribution					
					EA			US	
	Distr.	Mean	St. Dev.	Mode	Mean	St. Dev.	Mode	Mean	St. Dev.
ρ_θ	Beta	0.5000	0.2000	0.9690	0.9826	0.0042	0.9257	0.9429	0.0084
ρ_g	Beta	0.5000	0.2000	0.9894	0.9930	0.0044	0.9904	0.9931	0.0068
ρ_{mp}	Beta	0.5000	0.2000	0.5012	0.4797	0.0082	0.2461	0.2327	0.0090
ρ_b	Beta	0.5000	0.2000	0.9822	0.9957	0.0055	0.9508	0.9479	0.0068
ρ_μ	Beta	0.5000	0.2000	0.8030	0.7857	0.0101	0.5710	0.5878	0.0090
ρ_{pk}	Beta	0.5000	0.2000	0.8008	0.8176	0.0108	0.9544	0.9585	0.0169
$\rho_{\mu w}$	Beta	0.5000	0.2000	0.8541	0.8412	0.0148	0.2883	0.2973	0.0181
ρ_χ	Beta	0.5000	0.2000	0.9857	0.9909	0.0029	0.9831	0.9823	0.0054
ρ_e	Beta	0.5000	0.2000	0.8832	0.8767	0.0097	0.7547	0.7891	0.0219
σ_θ	Inv.Gamma	0.1000	2.0000	0.5787	0.6000	0.0308	1.3536	1.3969	0.0543
σ_g	Inv.Gamma	0.1000	2.0000	0.1310	0.1243	0.0088	0.2518	0.2363	0.0144
σ_{mp}	Inv.Gamma	0.1000	2.0000	1.0644	1.0478	0.0294	0.9988	0.9842	0.0515
σ_b	Inv.Gamma	0.1000	2.0000	0.1908	0.1203	0.0276	0.4360	0.4066	0.0295
σ_μ	Inv.Gamma	0.1000	2.0000	4.1957	4.2957	0.0956	2.4079	2.5126	0.0958
σ_{pk}	Inv.Gamma	0.1000	2.0000	0.2407	0.2642	0.0127	0.2451	0.2490	0.0134
$\sigma_{\mu w}$	Inv.Gamma	0.1000	2.0000	0.0838	0.0841	0.0052	0.6463	0.6504	0.0638
σ_χ	Inv.Gamma	0.1000	2.0000	1.3491	1.3849	0.0610	1.3525	1.2656	0.1566
σ_e	Inv.Gamma	0.1000	2.0000	1.5374	1.3691	0.0489	1.0031	0.9927	0.0883

Note: The posterior distributions are obtained using the Metropolis-Hastings algorithm. Col. (1) lists shock parameters. Cols. (2)-(4) indicate the prior distribution function. Identical priors are assumed across countries. Cols. (5)-(7) show the mean, the mode and the standard deviation of the posterior distribution for the EA, while Cols. (8)-(10) show the respective ones for the US.

3.5 Dynamic transmission of shocks

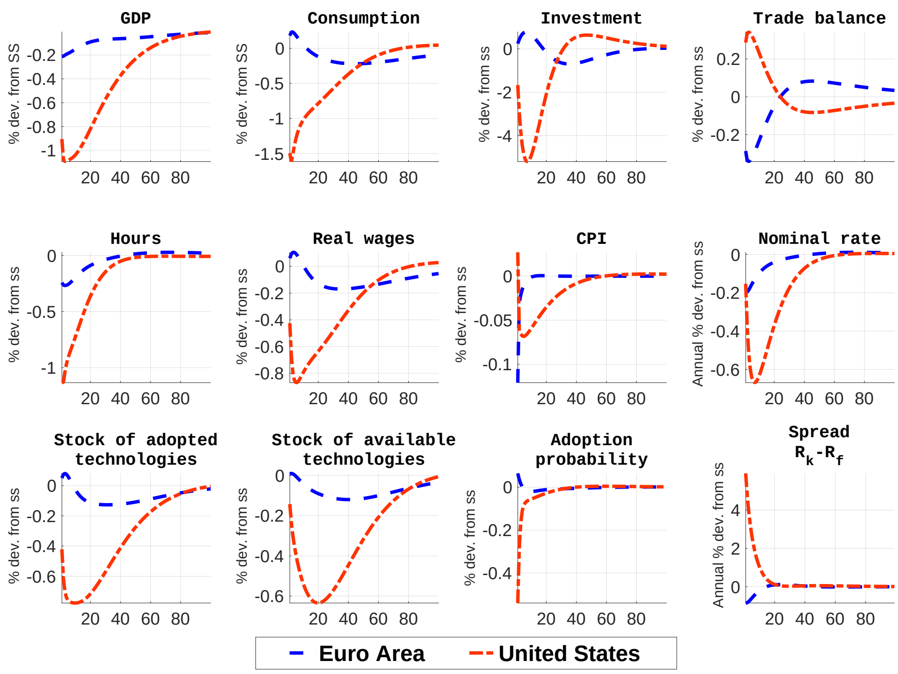
This section describes the dynamic responses of the main variables to liquidity preference, R&D and monetary policy shocks. Additional results are provided in Appendix B.1.

3.5.1 Non-resilience to foreign liquidity preference shocks

Figure 2 illustrates the estimated impulse response functions for the US and the euro area economies to a one standard deviation shock to US liquidity preference. This shock is the most prominent shock in the model as it acts like a financial shock and is responsible for a large part of the observed business cycle fluctuations. An increase in preference to hold safe assets leads to an increase in the spread between the rates on capital and the safe asset, which reduces investment. This reduction in investment leads to a slowdown in aggregate demand, which then leads to reduced R&D and technology adoption, implying a slowdown in TFP and output.

As regards the domestic shock transmission, a one standard deviation shock to liquidity demand displays broadly similar mechanics as seen in the one country model of Anzoategui et al. (2019). An increase in demand for the liquid asset implies that households reduce their consumption and their investment in capital assets. This results in an upward pres-

Figure 2 Shock to liquidity preference in the US



Note: Real variables are presented as percentage deviation. The dynamic responses of EA and US variables are represented by blue dashed and red dash-dotted lines.

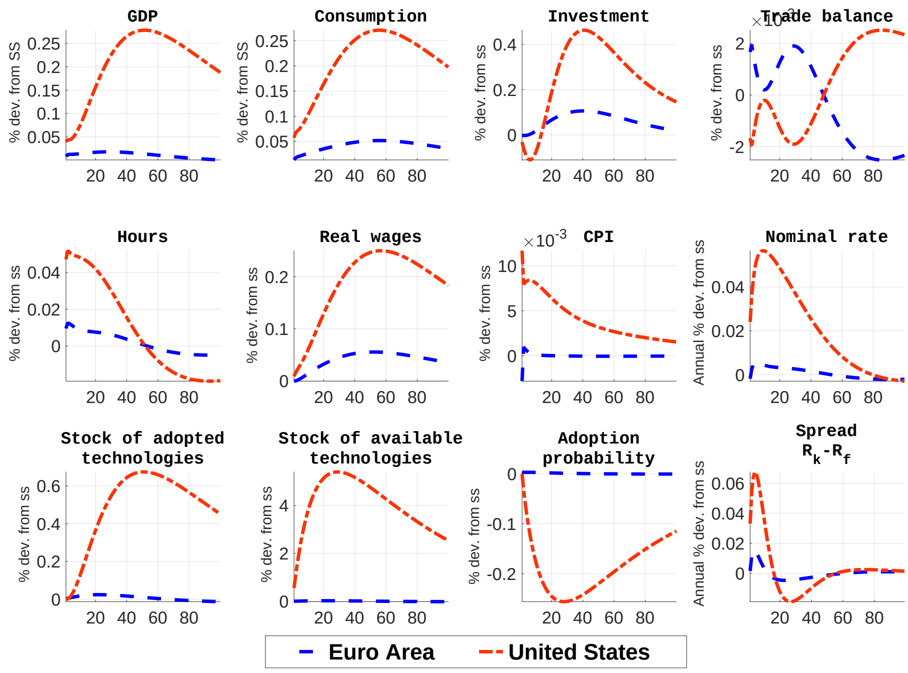
sure on the required return on capital, leading to a fall in capital investment demand and productivity-enhancing investments such as R&D and adoption expenditures. In addition, there is a downward pressure on the required return on the safe asset real rate, which bolsters the fall in consumption. Note that the introduction of incomplete financial markets prevents households from hedging fully against their income risk. The drop in consumption and investment implies a fall in output, which reduces the profits of adoption firms. This results in a decline in productivity-enhancing investments decreasing productivity. In comparison to conventional models, the drop in inflation in response to a contractionary demand shock is muted in this framework as the decline in productivity lessens the decline in marginal costs making the effect on inflation negligible and providing an explanation for the muted response of inflation to the Great Recession.

At the same time, the model finds a negative impact of US liquidity preference shocks on euro area economic activity. An immediate reduction in GDP via exports leads to the emergence of foreign-driven medium-term oscillations after two to five years, along with reduced technology adoption and reductions in consumption, investment, imports and wages. While a shock to euro area liquidity preference, as illustrated in the Appendix in Figure B.1, does not show a negative effect on US output, it replicates similar dynamics as found in Varga et al. (2016). In response to the financial shock, GDP reaches a trough after 50 quarters. Moreover, the shock explains a significant contribution of both tangible and intangible capital to the growth slowdown, while it leaves the US economy largely unaffected. The increased co-movement in real GDP across countries by this shock, which works via a reduction in hours, helps to capture medium-term oscillations across countries. This is of high relevance as trade itself can only induce a small co-movement between the two countries' macroeconomic aggregates (see Bayoumi et al., 2016). In a conventional two-economy framework assuming uncorrelated shocks, a loss in one country is usually associated with a gain in the other country.

3.5.2 R&D shocks at the technological frontier

In line with Bottazzi and Peri (2007), our model predicts that the technological non-frontier country (euro area) benefits from a shock to R&D in the frontier country (the United States). Equation 8 states that a shock to R&D behaves like a productivity shock to the production of new technologies. The increase in available technologies leads immediately to a higher GDP which triggers a self-loop that increases the stock of adopted technologies, boosts GDP and real wages even more. Figure 3 illustrates the estimated impulse responses of a shock to US R&D. In response to the shock in the US, the euro area experiences an economic expansion, that is triggered by higher US imports, which in turn leads to an increase in the stock of adopted technologies and GDP after five, and in investment after seven years. A direct foreign technology adoption channel is likely to amplify the impact in euro area

Figure 3 Shock to US R&D



Note: Real variables are presented as percentage deviation. The dynamic responses of EA and US variables are represented by blue dashed and red dash-dotted lines.

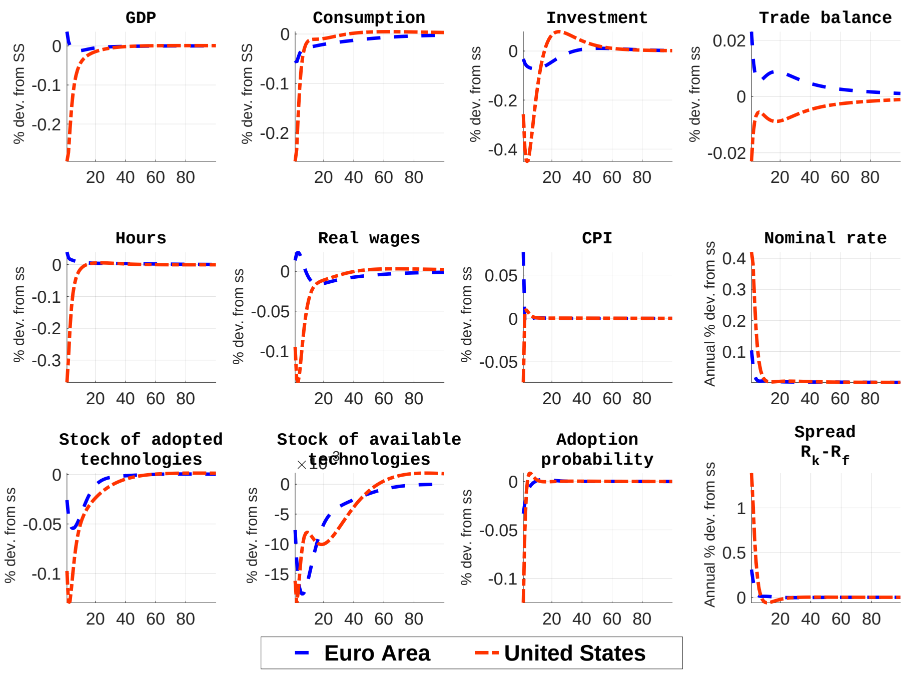
macroeconomic dynamics.

In the medium-to-long run, the euro area expansion has second-round effects on the US economy. In the model, this is less pronounced than in traditional empirical setups. However, as displayed in the Appendix in Figure B.3, a shock to EA R&D productivity does not trigger such a strong response in the US economy. This is complementary to the findings of Cova et al. (2017). In their model, a negative shock to R&D in the major advanced countries partially replicates the observed slowdown in long-term global growth and the decrease in interest rates.

3.5.3 Monetary and fiscal policy spillovers

Regarding monetary policy, the model finds a strong impact of US monetary policy on euro area technology adoption. This gives rise to medium-term oscillations in euro area GDP and its components, as indicated in Figure 4. Again, the US economy behaves more resilient to euro area monetary policy shocks. As illustrated in Figure B.6, the model suggests that an increase in US government spending, crowds out investment and consumption in the euro area, while in the medium-run GDP increases. This affects R&D and technology adoption.

Figure 4 Shock to US monetary policy



Note: Real variables are presented as percentage deviation. The dynamic responses of EA and US variables are represented by blue dashed and red dash-dotted lines.

4 Structural interpretation of business and medium-term cycle dynamics

This section highlights the historical decomposition, the contributions of different shocks to year-on-year representations of historical time series and model-implied variables, for the period between 1984 and 2017 for the two economies. The decomposition for quarter-on-quarter observable variables is given in Appendix B.2. In each figure, the black line depicts the time-series and the vertical bars show the contributions of the different shocks to movements in the data. Vertical bars above the horizontal line contribute positively, while the ones below contribute negatively.

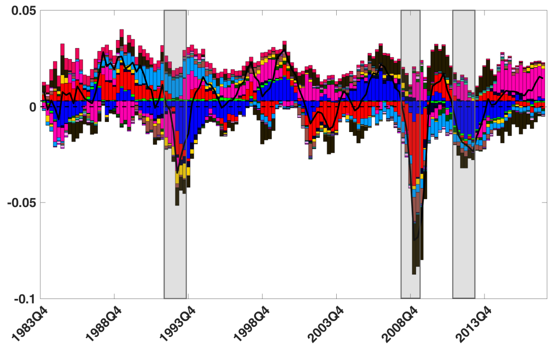
4.1 GDP and its components

Figure 5 illustrates the historical decomposition for year-on-year real GDP growth. In both economies, the most prominent shock that drives GDP fluctuations is the liquidity preference shock. Macroeconomic dynamics implied by this shock are more pronounced in the United States. In addition, euro area dynamics are largely influenced by the US liquidity preference shock dynamics. In particular, this is the case during all US recessionary phases since 1984. Even without explicit modeling of foreign technology adoption, the model interprets the downturn during the Great Recession to be strongly affected by shocks to US liquidity preference. Next to a lack of US demand, the Great Recession in the euro area appears to be largely explained by exogenous TFP, still leaving a substantial fraction of the loss not well explained by the mechanisms incorporated in the model. While US monetary policy appears strongly anti-cyclical over the entire period, euro area monetary policy only seems to be until the end of the sovereign debt crisis. During the post-crisis period, monetary policy became an essential driver of real GDP growth, counteracting weak growth. In addition, wage developments and foreign liquidity preference contribute positively.

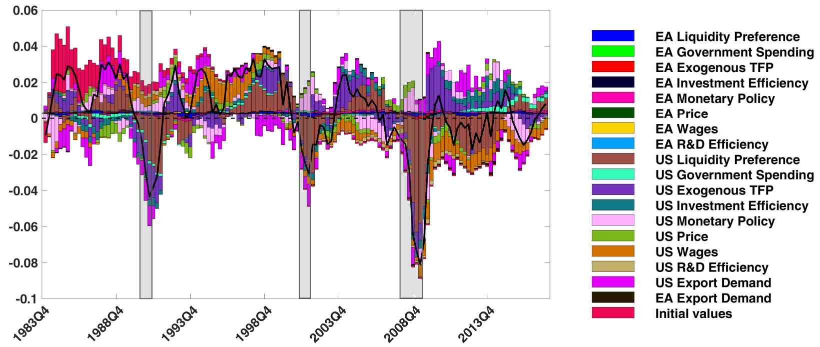
Consumption dynamics are shown in Figure 6. In both economies, consumption is strongly driven by shocks to domestic liquidity preference. Moreover, in the United States government spending is found to be an important anti-cyclical driver after the Great Recession. In the post-crisis period in the euro area, this role was played by monetary policy helping to keep up consumption.

Shock contributions explaining fluctuations in investment and employment are shown in Figures 7 and 8. After recessions investment behaves more sluggishly than utilisation in returning to steady-state. The model identifies the price of investment, monetary policy, the wage mark-up and liquidity preference shocks as strong drivers of business cycle fluctuations. In both economies, also employment is largely driven by the domestic liquidity preference shock. Additionally, in the euro area foreign liquidity preference and trade demand shocks are a strong source of cyclical variation of employment. This is not the case for the United States. In addition, in both countries monetary policy has a strong anti-cyclical impact on hours worked, while in the post-crisis period in the euro area it was also strongly supporting employment.

Figure 5 Real GDP, year-on-year



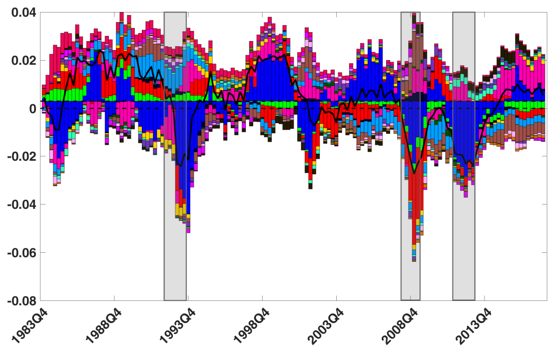
(a) Euro area



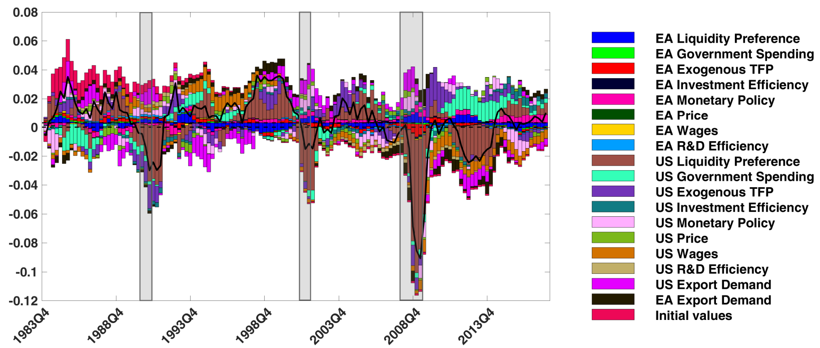
(b) United States

Note: The graphs show the historical decomposition of real GDP in yoy growth rates for the euro area (left) and the United States (right). Shaded areas indicate recession periods as classified by CEPR for the euro area and NBER for the United States.

Figure 6 Real consumption, year-on-year



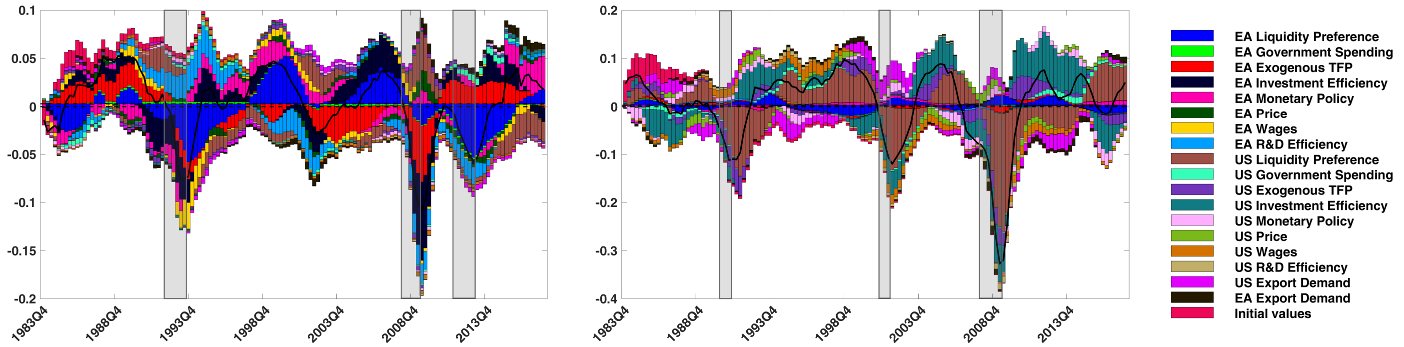
(a) Euro area



(b) United States

Note: The graphs show the historical decomposition of real consumption in yoy growth rates for the euro area (left) and the United States (right). Shaded areas indicate recession periods as classified by CEPR for the euro area and NBER for the United States.

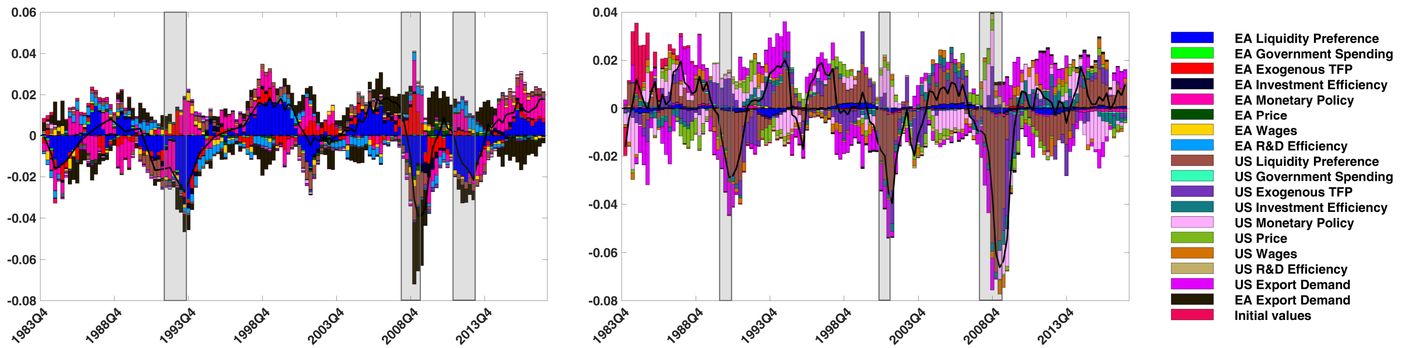
Figure 7 Real investment, year-on-year



(a) Euro area **(b)** United States

Note: The graphs show the historical decomposition of real investment in yoy growth rates for the euro area (left) and the United States (right). Shaded areas indicate recession periods as classified by CEPR for the euro area and NBER for the United States.

Figure 8 Employment, year-on-year



(a) Euro area **(b)** United States

Note: The graphs show the historical decomposition of employment in yoy growth rates for the euro area (left) and the United States (right). Shaded areas indicate recession periods as classified by CEPR for the euro area and NBER for the United States.

4.2 Decomposing the sources of labour productivity growth

As higher labour productivity growth is a key factor in raising living standards, anaemic labour productivity growth in the euro area has become an increasing concern of policy-makers.[8] The two-economy model allows to shed light on labour productivity developments and its components:

$$LP_t = \frac{y_t}{l_t} = \theta_t \ (a_t)^{\nu-1} \left(\frac{u_t k_t}{l_t}\right)^{\alpha} \tag{74}$$

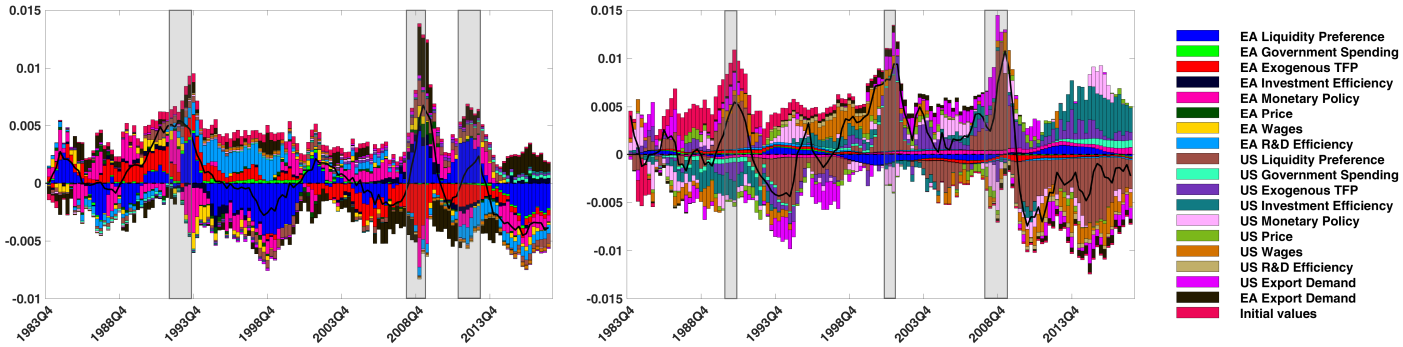
(i) exogenous TFP as measured by θ_t (ii) a_t measuring adopted technologies (endogenous TFP) and (iii) capital deepening $\left(\frac{u_t k_t}{l_t}\right)^{\alpha}$, which is a ratio of utilised-capital to labour. The third component is the most important and discussed driver of labour productivity growth, the capital-labour ratio.[9] Figure 9 presents the historical decomposition of capital deepening for both economies. During economic downturns, the reduction in hours worked with capital remaining constant leads to an increase in capital deepening or capital per hour worked. This phenomenon is present in all recession periods in both economies. During the recovery phase, capital deepening declines again as investment is still low but more hours are worked. In our model, liquidity preference, monetary policy and investment shocks are the key drivers of capital deepening in the euro area and the United States. In addition, monetary policy shocks contribute pro-cyclically, while financial shocks behave anti-cyclically as they are usually associated with a reduction in hours worked. Moreover, euro area capital deepening faces strong contributions from US liquidity preference and trade demand shocks. These foreign shocks contributed positively during the global financial crisis and negatively in the mid-1990s and since 2016.

Figure 10 shows the historical decomposition of labour productivity for the euro area and the United States. For both economies, exogenous TFP is a strong driver of labour productivity. At the same time, liquidity preference and R&D productivity shocks play a substantial role. While R&D shocks contribute positively, liquidity preference shocks have a tendency to contribute negatively to labour productivity. In the euro area, the slowdown in labour productivity in the post-crisis period has been kept up by monetary policy shocks. While capital deepening in the euro area is strongly driven by cyclical foreign shocks, labour productivity itself in this model is only little affected by foreign shocks.

[8] See ECB Economic Bulletin, Issue 3 / 2017 "The slowdown in euro area productivity in a global context."

[9] See Owyang, Michael "How capital deepening affects labor productivity.", 19 April 2018.

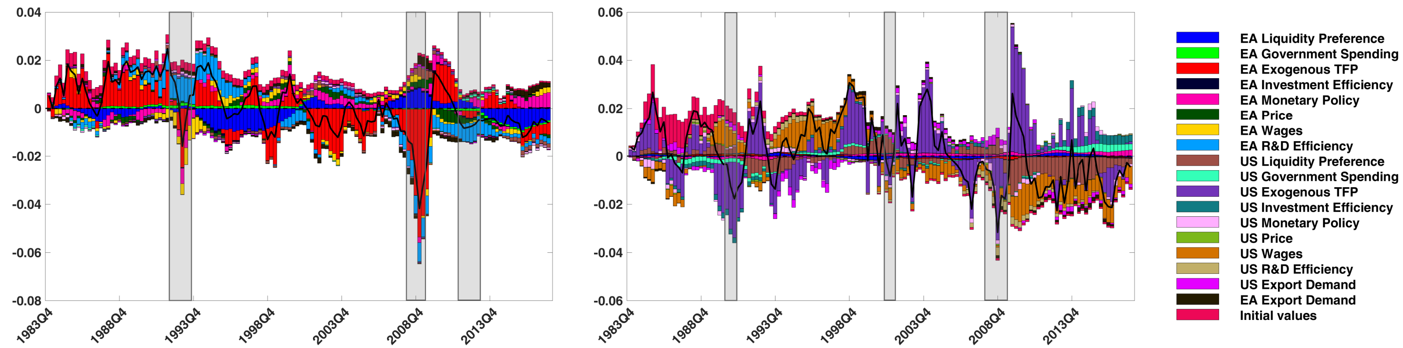
Figure 9 Capital deepening, year-on-year



(a) Euro area **(b)** United States

Note: The graphs show the historical decomposition of capital deepening in yoy growth rates for the euro area (left) and the United States (right). Shaded areas indicate recession periods as classified by CEPR for the euro area and NBER for the United States.

Figure 10 Labour productivity, year-on-year



(a) Euro area **(b)** United States

Note: The graphs show the historical decomposition of labour productivity growth in yoy growth rates for the euro area (left) and the United States (right). Shaded areas indicate recession periods as classified by CEPR for the euro area and NBER for the United States.

5 Conclusions

The role of foreign driven medium-term cycles in the euro area post-crisis slowdown in productivity and growth gained relevance in policy discussions. In an attempt to disentangle the domestic and foreign drivers held responsible for euro area business cycle and productivity dynamics, we develop and estimate a two-economy medium-scale new Keynesian model of the euro area and the United States in the style of Benigno (2009) that features trade in goods as well as incomplete financial markets. We extend it for physical capital and make use of recent advances in endogenous growth theory (see Anzoategui et al., 2019) by including a costly R&D and technology adoption mechanism to reflect the critical role played by intangible assets.

Our two-economy framework provides additional findings as follows. As compared to conventional frameworks, the endogenous growth framework presented displays increased spillovers and co-movement of real GDP across countries as a result of foreign shocks. Particularly, shocks to US liquidity preference can have a similarly directed contracting effect in euro area GDP and even more in endogenous productivity. Shocks to US R&D efficiency substantially affect euro area macroeconomic dynamics in the medium term, while shocks to US monetary policy have an immediate impact on euro area productivity. In contrast, the US economy behaves more resilient in response to EA shocks. A model-based decomposition unveils that the euro area business cycle is substantially affected by US financial and net trade shocks, triggering international medium-term cycles. In addition, we find US shocks to liquidity preference contributing substantially during the crisis in 2001, and explaining more than one third of the downturn in the Great Recession.

To the best of our knowledge, this model is a first attempt to model and estimate a two-economy medium-size DSGE model with endogenous growth for the euro area and the United States. While the existing model already allows to draw some policy conclusions, the model setup could profit from a number of extensions. First, the role of different factor endowments could be reviewed as technology might be dependent on the availability of skilled labour and capital.[10] Second, an application to the role of explicit adoption and

[10] Comin and Hobijn (2004) investigate to what extent different factor endowments, in particular physical capital, human capital and trade-induced technological development are the sources of innovation and adoption. The authors argue that factor endowments can affect the speed of adoption for three reasons. First, in the case of complementarity of technology and the factor of production, the marginal value of the new

diffusion of foreign technology could be explored. Linking endogenous TFP components across countries is likely to increase the co-movement of the economies. Third, an extension to a multi-economy model that includes the RoW or a version of the euro area that includes the biggest 5 countries could be of interest. Finally, a more explicit exploration of fiscal and monetary policy spillovers within this estimated framework could prove insightful.

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technology increases in the level of the factor. Second, if they are substitutes, firms will have an incentive to invest in factor-saving technologies. Finally, adoption might only be successful with the appropriate or optimal endowments of factors. In their international setup, the authors model a trickle-down diffusion, which means that most innovations across technologies happen in economically advanced countries, and that those gradually diffuse to other countries. However, in reality the leading country is not only the better innovator, but also the better adopter.

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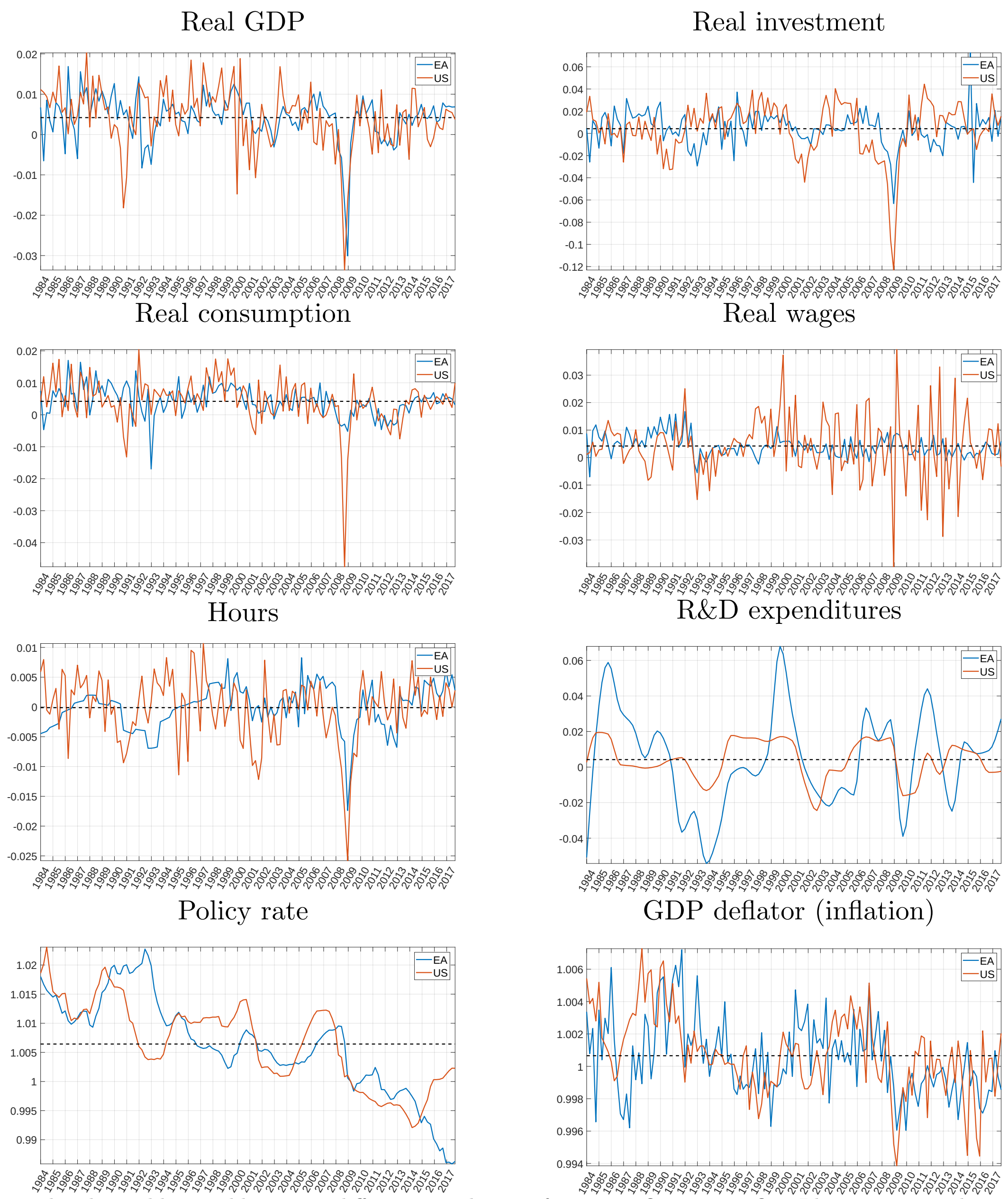
Appendix

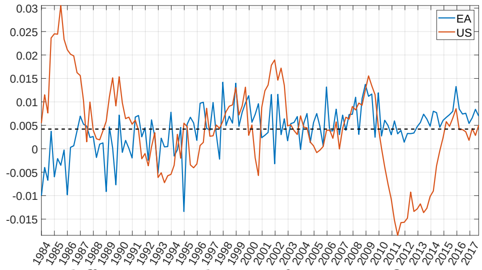
A Data

Figure A.1 Observable variables



Note: The observable variables are in differences and range from 1984:Q1 to 2017:Q4. Blue represents the EA and orange the US. If necessary the nominal series are deflated using the respective GDP deflator and divided by the population size to have the series in per capita terms. More details can be found in Table A.1. As there are no official series for this time range for the euro area, we construct own synthetic data following Smets and Wouters (2003). The black dashed line illustrates the mean of the series.

Real government expenditures



Note: The observable variables are in differences and range from 1984:Q1 to 2017:Q4. Blue represents the EA and orange the US. If necessary the nominal series are deflated using the respective GDP deflator and divided by the population size to have the series in per capita terms. More details can be found in Table A.1. As there are no official series for this time range for the euro area, we construct own synthetic data following Smets and Wouters (2003). The black dashed line illustrates the mean of the series.

A.1 Data Series

Table A.1 Data sources observable variables.

Country	Variable	Definition	Series	Source
	$Y_t^{obs,US}$	qoq change real GDP per capita	GDPC1	FED FRED
	$C_t^{obs,US}$	qoq change real consumption per capita	PCEC	FED FRED
	$I_t^{obs,US}$	qoq change real investment per capita	FPI	FED FRED
	$G_t^{obs,US}$	qoq change real general government consumption and investment per capita	GCEC1	FED FRED
US	$W_t^{obs,US}$	qoq change real wage	COMPNFB	FED FRED
	$L_t^{obs,US}$	Demeaned Log-level of hours worked	AWHNONAG	FED FRED
	$\Pi_t^{obs,US}$	GDP deflator (inflation)	GDPDEF	FED FRED
	$r_{n,t}^{obs,US}$	1/4× min(FEDFUNDS / Wu-Xia)		FED FRED / Wu-Xia
	$R\&D_t^{obs,US}$	qoq change real R&D expenditures per capita	rd_e_gerdtot/A.BES.MIO_NAC.US	EUROSTAT-GERD-BES
	$Y_t^{obs,EA}$	qoq change real GDP per capita		own calculations
	$C_t^{obs,EA}$	qoq change real consumption per capita		own calculations
	$I_t^{obs,EA}$	qoq change real investment per capita		own calculations
	$G_t^{obs,EA}$	qoq change real general government final consumption per capita		AWM Update 18
EA	$W_t^{obs,EA}$	qoq change real wage		own calculations
	$L_t^{obs,EA}$	Demeaned log-level of hours worked		own calculations
	$\Pi_t^{obs,EA}$	GDP deflator (inflation)		own calculations
	$r_{n,t}^{obs,EA}$	1/4× min(3m-interbank rate / Wu-Xia shadow rate)		own calculations
	$R\&D_t^{obs,EA}$	qoq change real R&D expenditures per capita	rd_e_gerdtot/A.BES.MIO_EUR. for EA-17	EUROSTAT-GERD-BES

Note: As there are no official series for this time range for the euro area, we construct own synthetic data following Smets and Wouters (2003). For the construction of the observables we follow Anzoategui et al. (2019). We deviate from this procedure by using shadow rates instead of ZLB, and by interpolating the annual R&D expenditure series instead of relying on the Kalman filter. In another step, we harmonise the series within and between countries as regards the underlying growth rate. Moreover, we harmonise the volatility of the R&D expenditure series.

A.2 Measurement: Linking observables with endogenous variables

The links between the model variables and the data is given by:

1. Real GDP:

$$y_t^{obs,US} = Log\left((1+gy)\frac{y_t^{US}}{y_{t-1}^{US}}\right), \qquad y_t^{obs,EA} = Log\left((1+gy)\frac{y_t^{EA}}{y_{t-1}^{EA}}\right). \tag{A.1}$$

2. Real private consumption:

$$c_t^{obs,US} = Log\left((1+gy)\frac{c_t^{US}}{c_{t-1}^{US}}\right), \qquad c_t^{obs,EA} = Log\left((1+gy)\frac{c_t^{EA}}{c_{t-1}^{EA}}\right). \tag{A.2}$$

3. Real private investment:

$$i_t^{obs,US} = Log\left((1+gy)\frac{i_t^{US}}{i_{t-1}^{US}}\right), \qquad i_t^{obs,EA} = Log\left((1+gy)\frac{i_t^{EA}}{i_{t-1}^{EA}}\right). \tag{A.3}$$

4. Real wage:

$$w_t^{obs,US} = Log\left((1+gy)\frac{w_t^{US}}{w_{t-1}^{US}}\right), \qquad w_t^{obs,EA} = Log\left((1+gy)\frac{w_t^{EA}}{w_{t-1}^{EA}}\right). \tag{A.4}$$

5. labour supply:

$$l_t^{obs,US} = Log\left(\frac{l_t^{US}}{l_{t-1}^{US}}\right), \qquad l_t^{obs,EA} = Log\left(\frac{l_t^{EA}}{l_{t-1}^{EA}}\right). \tag{A.5}$$

6. Nominal interest rate:

$$r_{n,t}^{obs,US} = r_{n,t}^{US}, \tag{A.6}$$

$$r_{n,t}^{obs,EA} = r_{n,t}^{EA}. \tag{A.7}$$

7. Price inflation rate:

$$\pi_t^{obs,US} = \pi_t^{US}, \qquad \pi_t^{obs,EA} = \pi_t^{EA}. \tag{A.8}$$

8. R&D business expenditures

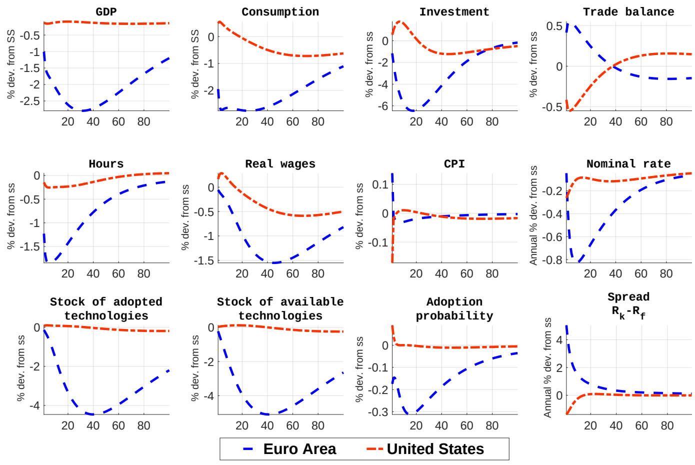
$$R\&D_t^{obs,US} = Log\left((1+ga)\frac{\text{R\&D expenditures}_t^{US}}{\text{R\&D expenditures}_{t-1}^{US}}\right), \tag{A.9}$$

$$R\&D_t^{obs,EA} = Log\left((1+ga)\frac{\text{R\&D expenditures}_t^{EA}}{\text{R\&D expenditures}_{t-1}^{EA}}\right). \tag{A.10}$$

B Additional Results

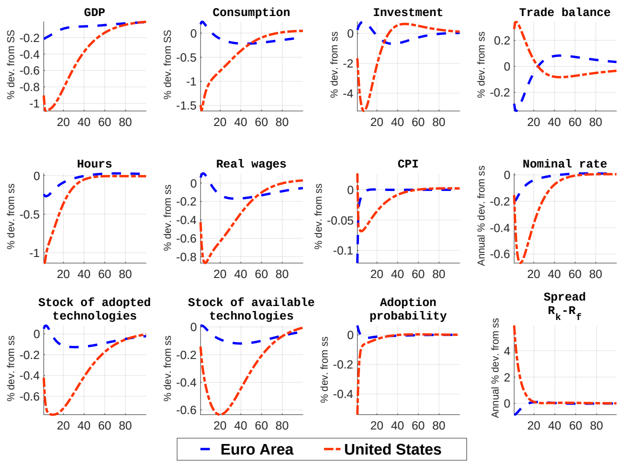
B.1 Impulse response functions

Figure B.1 Shock to EA liquidity preference



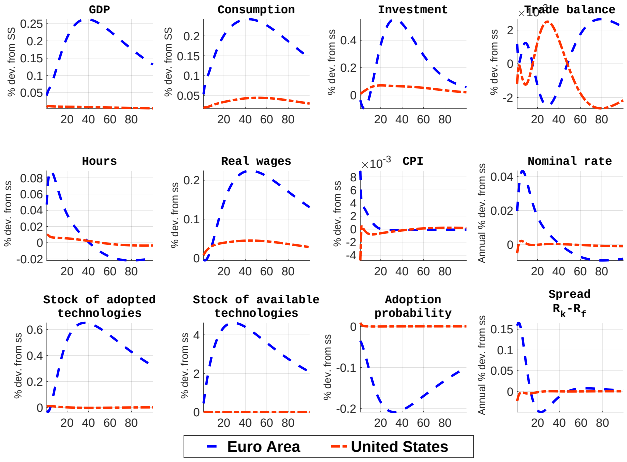
Note: Real variables are presented as percentage deviation. The dynamic responses of EA and US variables are represented by dashed and dash-dotted lines.

Figure B.2 Shock to US liquidity preference



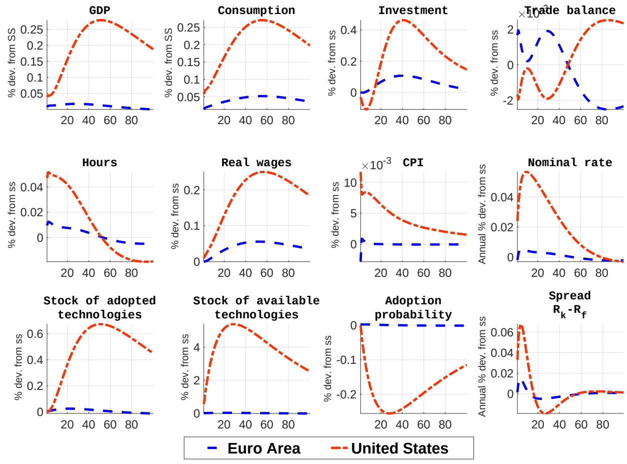
Note: Real variables are presented as percentage deviation. The dynamic responses of EA and US variables are represented by dashed and dash-dotted lines.

Figure B.3 Shock to EA R&D expenditures



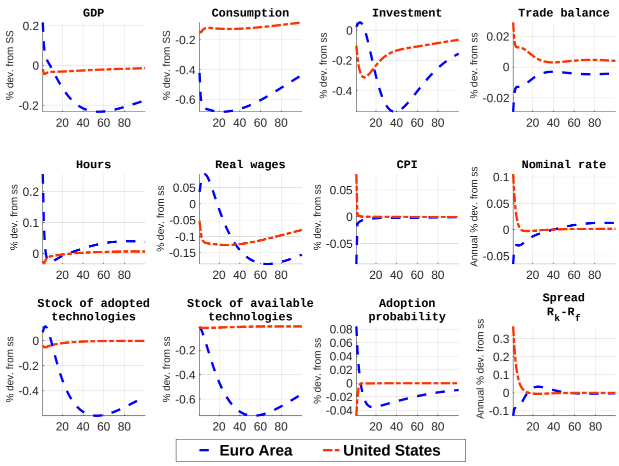
Note: Real variables are presented as percentage deviation. The dynamic responses of EA and US variables are represented by dashed and dash-dotted lines.

Figure B.4 Shock to US R&D expenditures



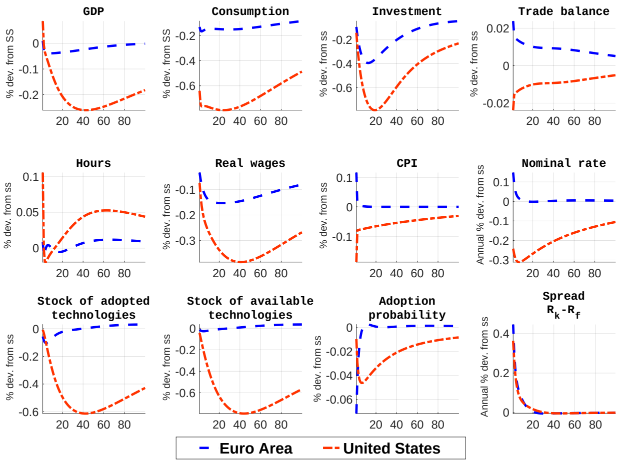
Note: Real variables are presented as percentage deviation. The dynamic responses of EA and US variables are represented by dashed and dash-dotted lines.

Figure B.5 Shock to EA govenment expenditures



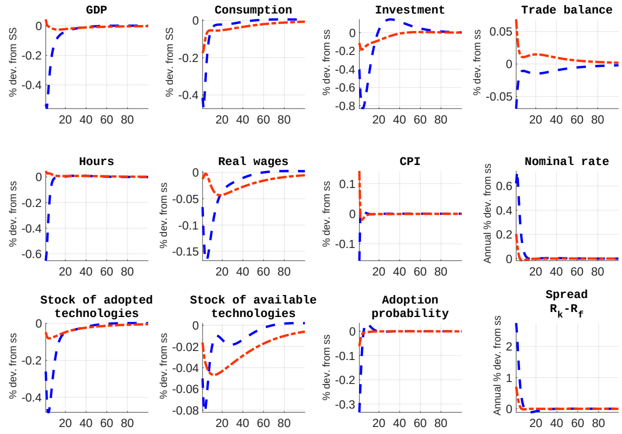
Note: Real variables are presented as percentage deviation. The dynamic responses of EA and US variables are represented by dashed and dash-dotted lines.

Figure B.6 Shock to US government expenditures



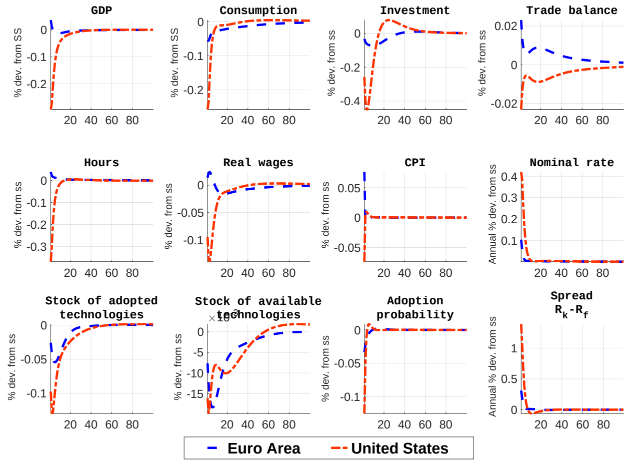
Note: Real variables are presented as percentage deviation. The dynamic responses of EA and US variables are represented by dashed and dash-dotted lines.

Figure B.7 Shock to EA monetary policy



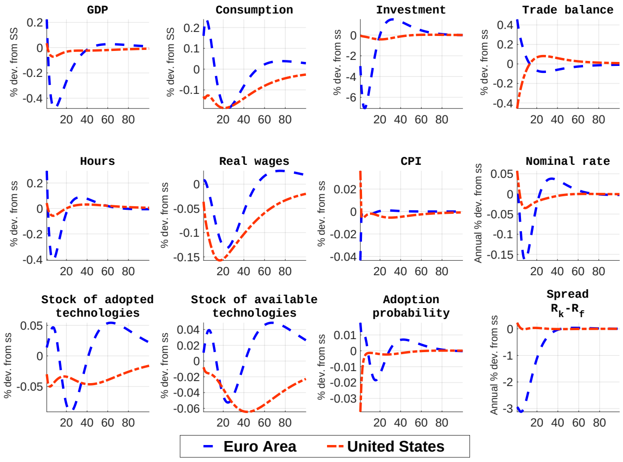
Note: Real variables are presented as percentage deviation. The dynamic responses of EA and US variables are represented by dashed and dash-dotted lines.

Figure B.8 Shock to US monetary policy



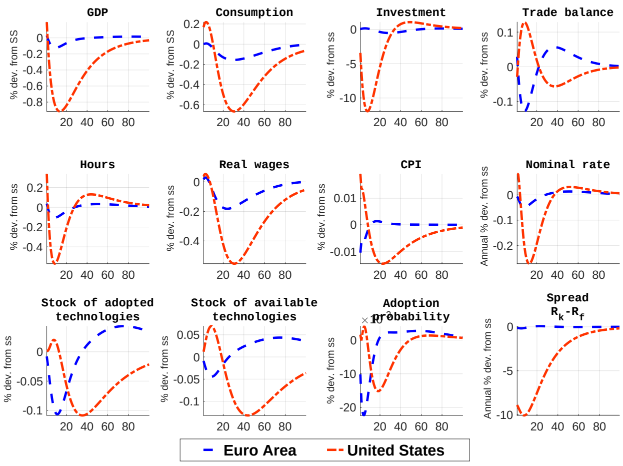
Note: Real variables are presented as percentage deviation. The dynamic responses of EA and US variables are represented by dashed and dash-dotted lines.

Figure B.9 Shock to EA investment



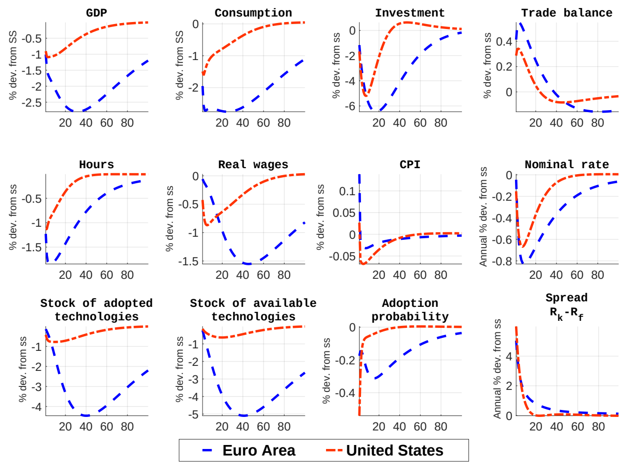
Note: Real variables are presented as percentage deviation. The dynamic responses of EA and US variables are represented by dashed and dash-dotted lines.

Figure B.10 Shock to US investment



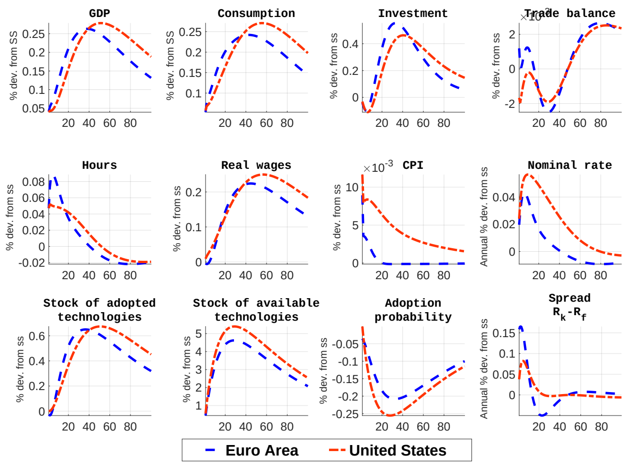
Note: Real variables are presented as percentage deviation. The dynamic responses of EA and US variables are represented by dashed and dash-dotted lines.

Figure B.11 Shock to own liquidity preference



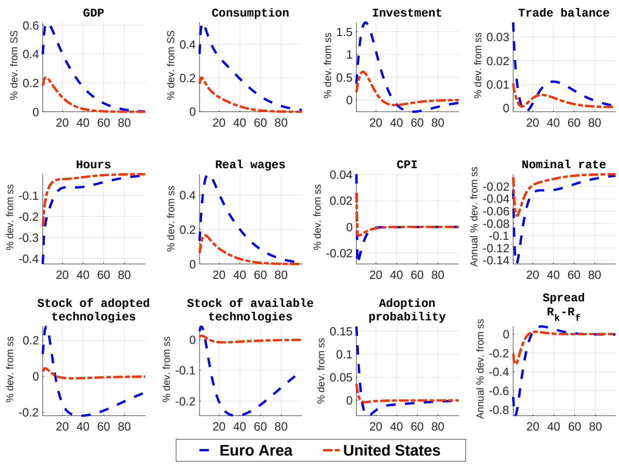
Note: Real variables are presented as percentage deviation. The dynamic responses of EA and US variables are represented by dashed and dash-dotted lines.

Figure B.12 Shock to own R&D expenditures



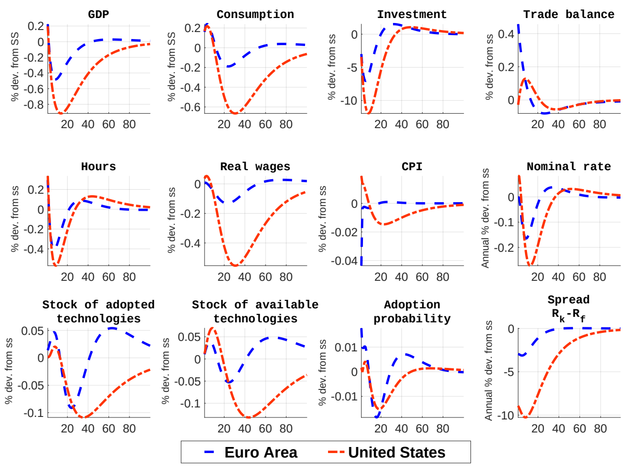
Note: Real variables are presented as percentage deviation. The dynamic responses of EA and US variables are represented by dashed and dash-dotted lines.

Figure B.13 Shock to own TFP



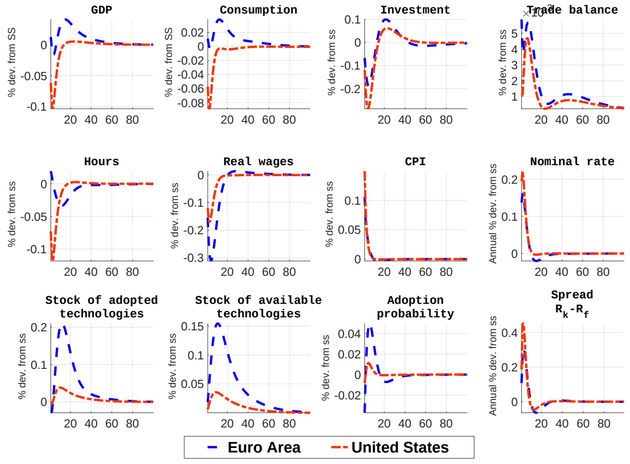
Note: Real variables are presented as percentage deviation. The dynamic responses of EA and US variables are represented by dashed and dash-dotted lines.

Figure B.14 Shock to own price of capital



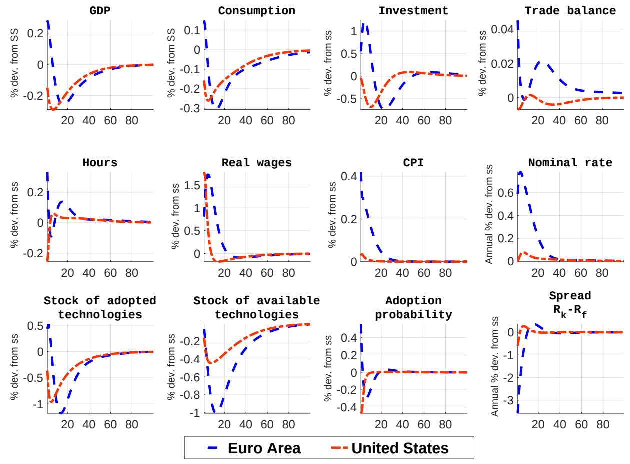
Note: Real variables are presented as percentage deviation. The dynamic responses of EA and US variables are represented by dashed and dash-dotted lines.

Figure B.15 Shock to own price mark-up



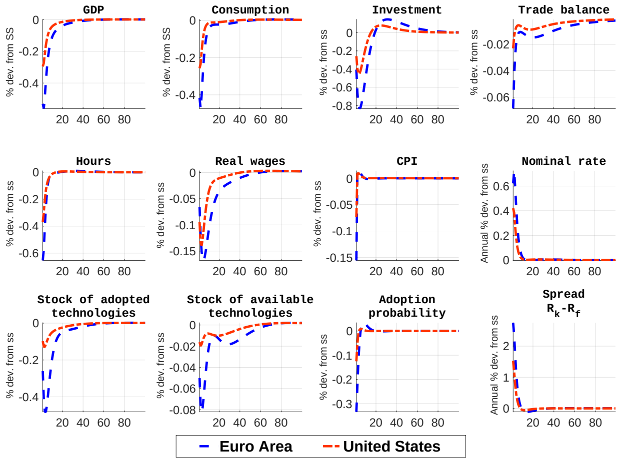
Note: Real variables are presented as percentage deviation. The dynamic responses of EA and US variables are represented by dashed and dash-dotted lines.

Figure B.16 Shock to own wage mark-up



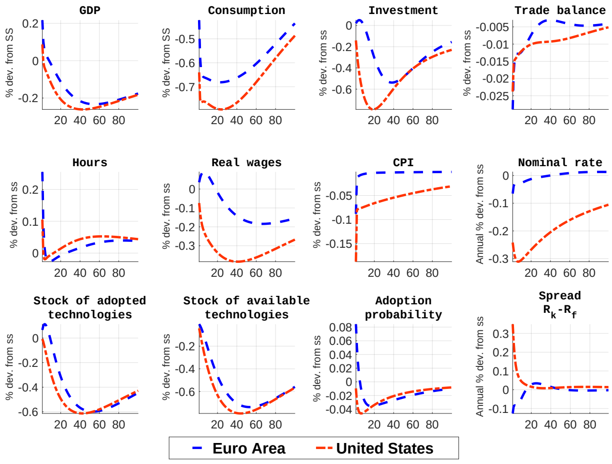
Note: Real variables are presented as percentage deviation. The dynamic responses of EA and US variables are represented by dashed and dash-dotted lines.

Figure B.17 Shock to own monetary policy



Note: Real variables are presented as percentage deviation. The dynamic responses of EA and US variables are represented by dashed and dash-dotted lines.

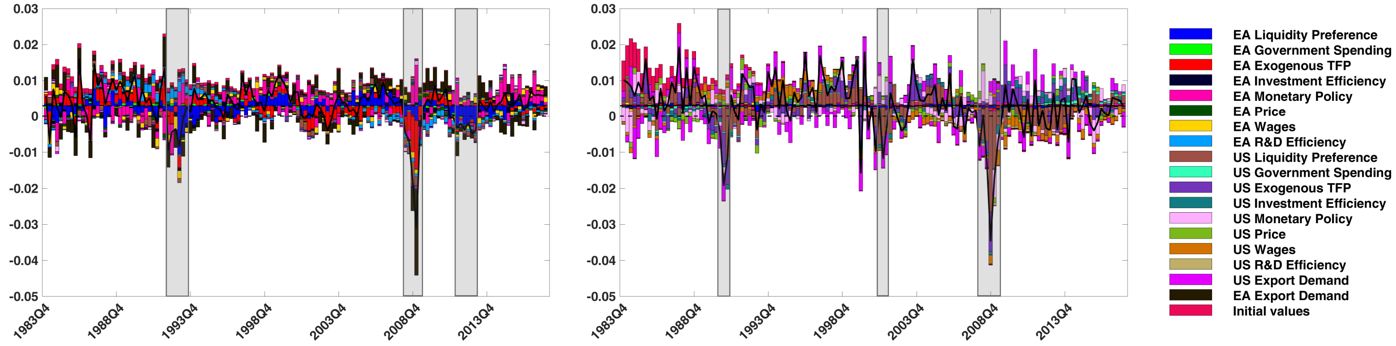
Figure B.18 Shock to own government spending



Note: Real variables are presented as percentage deviation. The dynamic responses of EA and US variables are represented by dashed and dash-dotted lines.

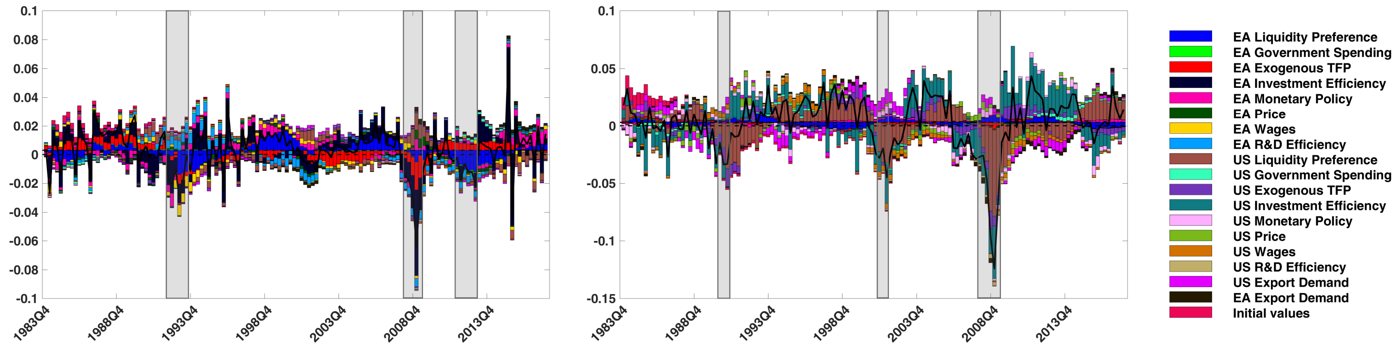
B.2 Historical decomposition of model-detrended observables

Figure B.19 Real GDP (observable)



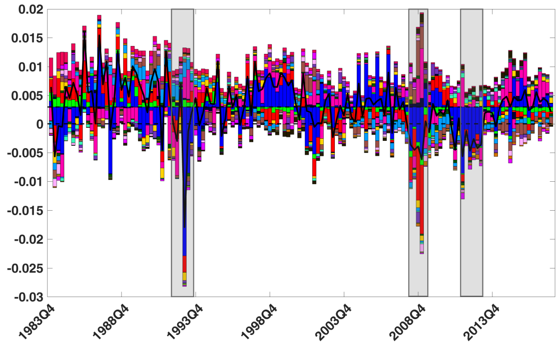
(a) Euro area **(b)** United States

Figure B.20 Real investment (observable)

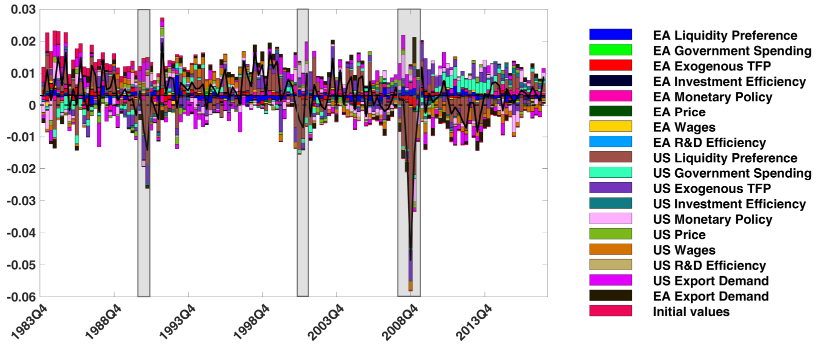


(a) Euro area **(b)** United States

Figure B.21 Real consumption (observable)

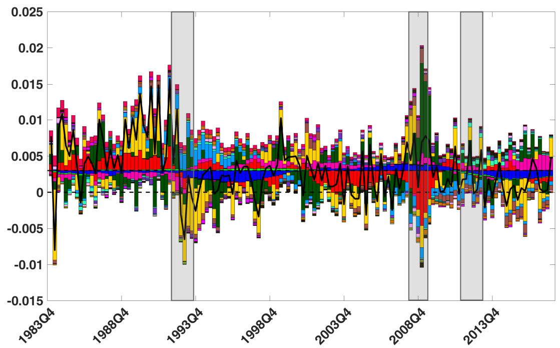


(a) Euro area

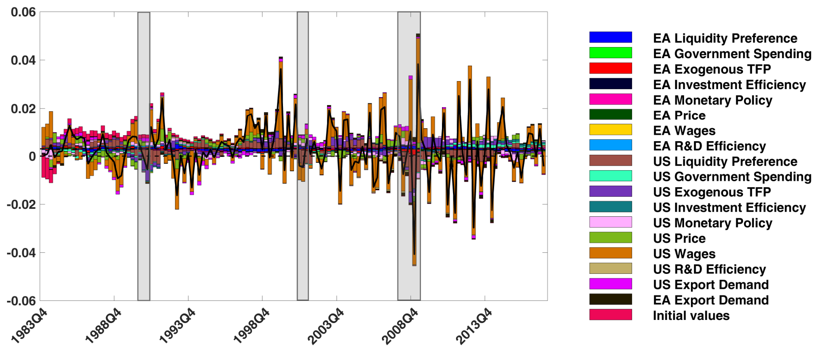


(b) United States

Figure B.22 Real wages (observable)

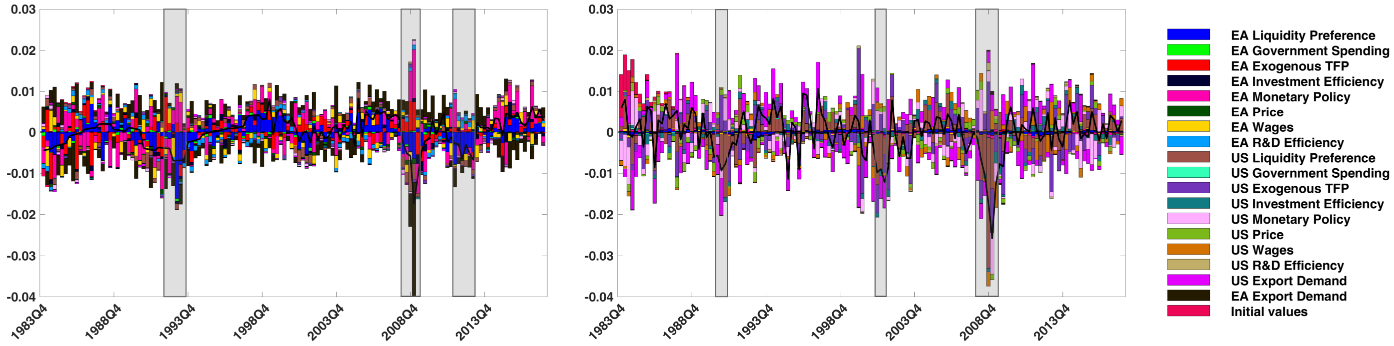


(a) Euro area



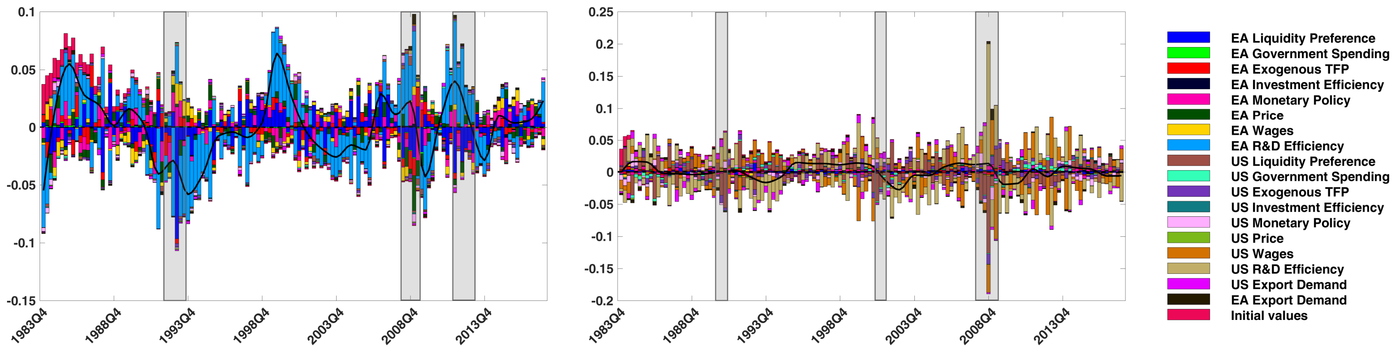
(b) United States

Figure B.23 Hours (observable)



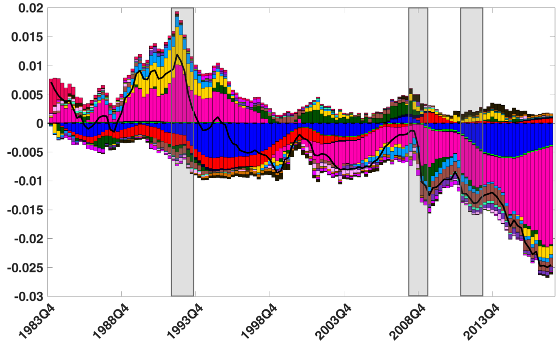
(a) Euro area **(b)** United States

Figure B.24 R&D expenditures (observable)

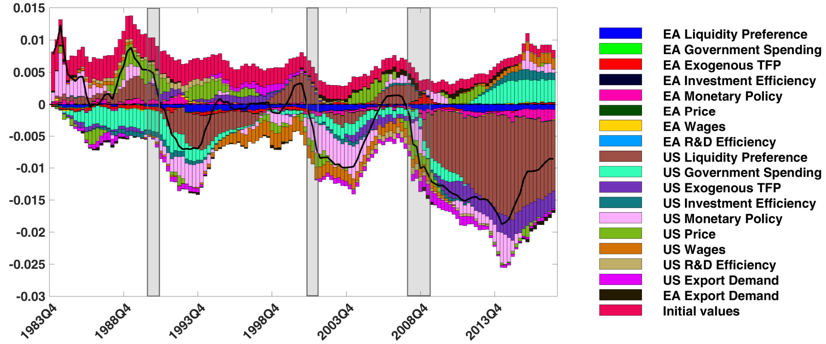


(a) Euro area **(b)** United States

Figure B.25 Policy rate (observable)

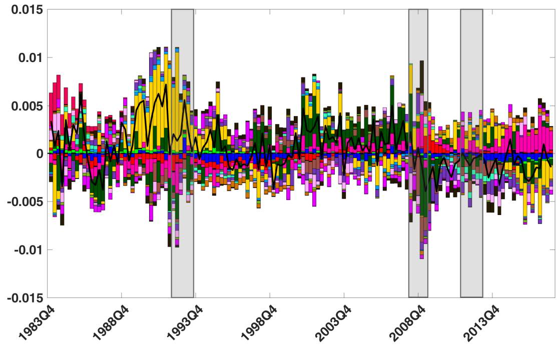


(a) Euro area



(b) United States

Figure B.26 Inflation (GDP deflator, observable)

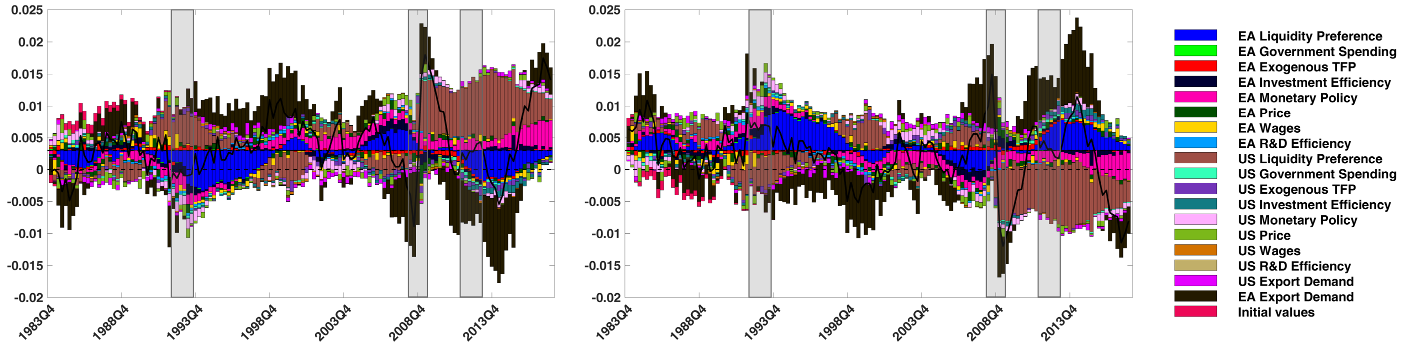


(a) Euro area

(b) United States

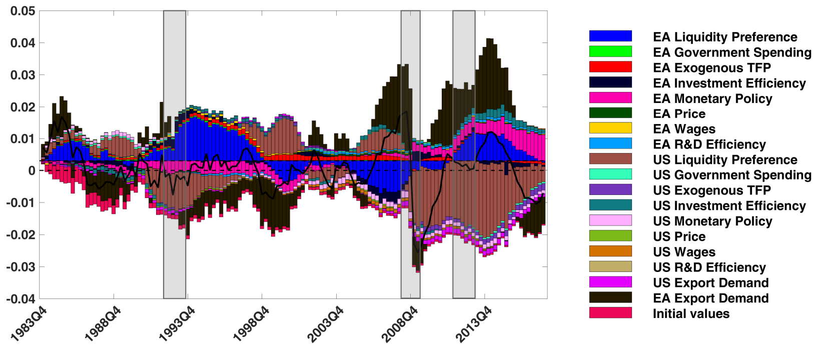
B.3 Historical decomposition additional latent variables

Figure B.27 Capital flows, Euro area



(a) Capital inflows **(b)** Capital outflows

Figure B.28 Trade balance, Euro area



C Additional derivations

C.1 Rotemberg new Keynesian Phillips curve

Due to the non-linear character of the model it is convenient to introduce price and wage rigidities á la Rotemberg (1982). For convenience we drop the country index; the functional form holds for all countries and all types of labour.

C.1.1 Prices

For solving for the Price new Keynesian Phillips curve, we follow Ascari and Rossi (2012). The profit maximisation problem of firm i, expressed in terms of the domestic price index, is given by,

$$\max_{\{p_t(i),h_t(i),k_{t-1}(i)\}_{t=0}^{\infty}} \mathbb{E}_0^t \left\{ \sum_{t=0}^{\infty} \beta^t \frac{\lambda_t}{\lambda_0} \left[\frac{p_t(i)}{p_t} y_t(i) - w_t l_t(i) - r_t^k k_{t-1}(i) - \frac{\phi_P}{2} \left(\frac{p_t(i)}{p_{t-1}(i)} - \bar{\pi} \right)^2 y_t \right] \right\} \tag{C.1}$$

$$s.t. \quad \begin{cases} y_t(i) &= y_t \left(\frac{p_t(i)}{p_t} \right)^{-\epsilon_p}. \\ y_t(i) &= a_t (k_{t-1}(i))^{\alpha} (h_t(i))^{1-\alpha}. \end{cases} \tag{C.2}$$

Equating the two constraints and inserting them into the Lagrangian reads

$$\begin{aligned} \mathcal{L} = \mathbb{E}_0^t \Bigg\{ \sum_{t=0}^{\infty} \beta^t \frac{\lambda_t}{\lambda_0} & \left[y_t \left(\frac{p_t(i)}{p_t} \right)^{1-\epsilon_p} - w_t l_t(i) - r_t^k k_{t-1}(i) - \frac{\phi_P}{2} \left(\frac{p_t(i)}{p_{t-1}(i)} - \bar{\pi} \right)^2 y_t \right] \\ & + mc_t(i) \left[a_t (k_{t-1}(i))^{\alpha} (h_t(i))^{1-\alpha} - y_t \left(\frac{p_t(i)}{p_t} \right)^{-\epsilon_p} \right] \Bigg\} \end{aligned} \tag{C.3}$$

The Lagrangian multiplier mc_t can be interpreted as the real marginal cost of producing an additional unit of output.

FOC wrt. to $p_t(i)$:

$$(1-\epsilon_p)\left(\frac{p_t(i)}{p_t}\right)^{-\epsilon}\frac{y_t}{p_t}-\frac{\phi_P}{p_{t-1}(i)}\left(\frac{p_t(i)}{p_{t-1}(i)}-\bar{\pi}\right)y_t+\epsilon_p mc_t(i)\frac{y_t}{p_t}\left(\frac{p_t(i)}{p_t}\right)^{-\epsilon_p-1}$$
$$+\beta\,\mathbb{E}_t\left[\frac{\lambda_{t+1}}{\lambda_t}\phi_P\frac{p_{t+1}}{p_t}\left(\frac{p_{t+1}(i)}{p_t(i)}-\bar{\pi}\right)^2 y_{t+1}\right]=0 \tag{C.4}$$

Rearranging the pricing condition:

$$(1-\epsilon_p)\frac{y_t}{p_t}-\frac{\phi_P}{p_{t-1}}\left(\frac{p_t}{p_{t-1}}-\bar{\pi}\right)y_t+\epsilon_p mc_t\frac{y_t}{p_t}+\beta\,\mathbb{E}_t\left[\frac{\lambda_{t+1}}{\lambda_t}\phi_P\frac{p_{t+1}}{p_t^2}\left(\frac{p_{t+1}}{p_t}-\bar{\pi}\right)\frac{y_{t+1}}{y_t}\right]=0 \tag{C.5}$$

$$\frac{p_t}{p_{t-1}}\left(\frac{p_t}{p_{t-1}}-\bar{\pi}\right)=\beta\,\mathbb{E}_t\left[\frac{\lambda_{t+1}}{\lambda_t}\frac{p_{t+1}}{p_t}\left(\frac{p_{t+1}}{p_t}-\bar{\pi}\right)\frac{y_{t+1}}{y_t}\right]+\frac{\epsilon_p}{\phi_P}\left(mc_t-\frac{\epsilon_p-1}{\epsilon_p}\right) \tag{C.6}$$

The non-linear new Keynesian Phillips curve for prices is then given by

$$\pi_t(\pi_t-\bar{\pi})=\beta\,\mathbb{E}_t\left[\frac{\lambda_{t+1}}{\lambda_t}\pi_{t+1}(\pi_{t+1}-\bar{\pi})\frac{y_{t+1}}{y_t}\right]+\frac{\epsilon_p}{\phi_P}\left(mc_t-\frac{\epsilon_p-1}{\epsilon_p}\right) \tag{C.7}$$

We map the Calvo duration parameter θ_p into the Rotemberg adjustment cost, by equating the slopes of the linearised Calvo and Rotemberg Price NKPCs:

$$\frac{(1-\theta_p)(1-\theta_p\beta)}{\theta_p}=\frac{\epsilon_p-1}{\phi_P} \tag{C.8}$$
$$\phi_P=\frac{(\epsilon_p-1)\theta_p}{(1-\theta_p)(1-\beta\theta_p)} \tag{C.9}$$

C.1.2 Wages

In order to derive the new Keynesian Wage Phillips-Curve á la Rotemberg, we follow Born and Pfeifer (2020). In particular, we make use of the SGU case, which is based on Schmitt-Grohé and Uribe (2005). Here a labour union supplies distinct labour services. Again we drop the country index. The functional form is valid for the unskilled and skilled labour case. The problem of household j is to choose w_t^j to maximise:

$$V_t = E_t \sum_{k=0}^{\infty} \beta^k u\left(c_{t+k}^j, l_{t+k}^j\right), \tag{C.10}$$

taking into account the demand for its labour variety:

$$l_{t+k}^j = \left(\frac{w_{t+k}^j}{w_{t+k}}\right)^{-\epsilon_w} l_{t+k}^d \tag{C.11}$$

and subject to the budget constraint:

$$p_t c_t = \int_0^1 w_t^j l_t^j dj - \frac{\phi_w}{2}\left(\frac{1}{\Gamma_{t-1,t}^{ind}} \frac{w_t^j}{w_{t-1}^j} - 1\right)^2 dj\ \Xi_t + X_t \tag{C.12}$$

The second last term represents the Rotemberg costs of adjusting the wage, with ϕ_w being the wage adjustment cost parameter. The costs are proportional to the nominal adjustment cost base Ξ_t and arise when wage changes differ from the indexed inflation rate $\Gamma_{t-1,t}^{ind}$. X_t captures all other additive terms that are not related to the current optimisation problem. we can rewrite the optimisation problem of the household using an lagrangian

$$\begin{aligned}\mathcal{L} = \sum_{k=0}^{\infty} \beta^k E_t \Bigg[u\left(c_{t+k}, l_{t+k}\right) - \lambda_{t+k} \Bigg\{ p_{t+k} c_{t+k} - l_{t+k}^d \int_{t+k}^{d} \int_0^1 w_{t+k}^j \left(\frac{w_{t+k}^j}{w_{t+k}}\right)^{\epsilon_w} dj \\ + \frac{\phi_w}{2} \int_0^1 \left(\frac{1}{\gamma_{t,t+k}^j} \frac{w_{t+k}^j}{w_{t+k-1}^j} - 1\right)^2 dj\ \Xi_{t+k} - X_{t+k} \Bigg\} \Bigg]\end{aligned} \tag{C.13}$$

The corresponding first order condition for the optimal wage is given by

$$
\begin{aligned}
0 =& u_{l,t}(-\epsilon_w)\int_0^1 \left(\frac{w_t^j}{w_t}\right)^{-\epsilon_w} \frac{l_t^d}{w_t^j} dj + \lambda_t \Bigg\{ (1-\epsilon_w) l_t^d \int_0^1 \left(\frac{w_t^j}{w_t}\right)^{-\epsilon_w} dj \\
& -\phi_w \int_0^1 \left(\frac{1}{\Gamma_{t-1,t}^{ind}} \frac{w_t^j}{w_{t-1}^j}\right) \frac{1}{\Gamma_{t-1,t}^{ind} w_{t-1}^j} dj \ \Xi_t \Bigg\} \\
& - \mathbb{E}_t \, \beta\lambda_{t+1} \left\{ \phi_w \int_0^1 \left(\frac{1}{\Gamma_{t,t+1}^{ind}} \frac{w_{t+1}^j}{w_t^j}\right) (-1) \frac{w_{t+j}^j}{\Gamma_{t,t+1}^{ind} (w_t^j)^2} dj \ \Xi_{t+1} \right\}
\end{aligned}
\tag{C.14}
$$

Imposing symmetry results in an equation similar to the one under the EHL setup.

$$
\begin{aligned}
0 =& u_l(c_t, l_t, \cdot)(-\epsilon_w) \frac{l_t}{w_t} + \lambda_t \left\{ (1-\epsilon_w) L_t^d - \phi_w \left(\frac{1}{\Gamma_{t-1,t}^{ind}} \frac{w_t}{w_{t-1}} - 1 \right) \frac{\Xi_t}{\Gamma_{t-1,t}^{ind} w_{t-1}} \right\} \\
& - \mathbb{E}_t \, \beta\lambda_{t+1} \left\{ \phi_w \left(\frac{1}{\Gamma_{t,t+1}^{ind}} \frac{w_{t+1}}{w_t} - 1 \right) (-1) \frac{w_{t+1}}{\Gamma_{t,t+1}^{ind} (w_t)^2} \Xi_{t+1} \right\}
\end{aligned}
\tag{C.15}
$$

Rearranging

$$
\begin{aligned}
0 =& -\psi l_t^{\phi} (-\epsilon_w) \frac{l_t}{w_t} + \lambda_t \left\{ (1-\epsilon_w) l_t^d - \phi_w \left(\frac{1}{\Pi_{t-1,t}} \frac{w_t}{w_{t-1}} - 1 \right) \frac{y_t}{\Pi_{t-1,t} w_{t-1}} \right\} \\
& - \mathbb{E}_t \, \beta\lambda_{t+1} \left\{ \phi_w \left(\frac{1}{\Pi_{t,t+1}} \frac{w_{t+1}}{w_t} - 1 \right) (-1) \frac{w_{t+1}}{\Pi_{t,t+1} (w_t)^2} y_{t+1} \right\}
\end{aligned}
\tag{C.16}
$$

In order to calibrate labour in steady state to 1, we solve for the labour disutility parameter

$$
\psi = -\frac{\bar{\lambda}(1-\epsilon_w)\bar{l}^d}{(\epsilon_w)\frac{l_t^d}{\bar{w}}\bar{l}^{\phi}} = -\frac{\bar{\lambda}(1-\epsilon_w)}{\epsilon_w \frac{1}{\bar{w}}}
\tag{C.17}
$$

Acknowledgements

This study has benefited from discussions with Diego Comin, Wouter den Haan, Stefan Hohberger, Joseba Martinez, Beatrice Pierluigi, Marco Ratto and Diego Rodriguez Palenzuela. Furthermore, we would like to thank several participants in seminars at the European Commission's Joint Research Centre in Ispra and the European Central Bank in 2019 for their valuable comments. This paper should not be reported as representing the views of the European Central Bank (ECB) or the European Commission (EC). The views expressed are those of the authors and do not necessarily reflect those of the ECB or the EC.

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PDF ISBN 978-92-899-4536-3 ISSN 1725-2806 doi:10.2866/08879 QB-AR-21-027-EN-N