A Global Economy Version of QUEST: Simulation Properties

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Abstract

This paper presents the structure and simulation properties of a core version of QUEST, an open-economy New Keynesian DSGE model developed and maintained by the European Commission. The multi-region model version with tradable goods, non-tradable goods and housing includes the euro area (EA), the non-EA EU plus the UK, the United States, Japan, Emerging Asia, and the rest of the world. The paper presents simulation results for a series of goods, factor, financial market, and policy shocks to illustrate how the structure of the model and its theoretical underpinnings shape the transmission of shocks to real and financial variables of the domestic economy and international spillover. In particular, the paper shows impulse responses for monetary policy, consumption, risk premia, productivity, credit, government spending, unconventional monetary policy and tariff shocks, and characterises their impact on real GDP, domestic demand components, trade, external balances, wages, employment, price levels, relative prices, interest rates, and public finances. While the scenarios are illustrative, they reflect important elements of the Global recession and the EA crisis (global risk shocks, private sector demand shocks and deleveraging) and of policy responses (fiscal policy, unconventional monetary policy) and challenges (protectionism) in recent years. In view of the macroeconomic conditions during this period, the paper shows simulations for an environment in which the zero lower bound on monetary policy is binding in addition to simulations under standard monetary policy.

CONTENTS

1. INTRODUCTION

This paper documents the structure and simulation properties of a core version of the European Commission's QUEST model. The simulations that we present in the paper illustrate how the structure of the model and its theoretical underpinnings shape the transmission of various standard and less-standard real and financial shocks to real and financial variables.

In particular, the paper presents and describes impulse responses for monetary policy, consumption, risk premia, productivity, credit, government spending, and unconventional monetary policy shocks. It characterises the impact of these shocks on GDP, domestic demand components, trade, external balances, wages, employment, price levels, relative prices, interest rates, and public finances. While the scenarios are illustrative, they reflect important elements of the Global recession and the EA crisis (global risk shocks, private sector demand shocks and deleveraging) and of policy responses (fiscal policy, unconventional monetary policy) and challenges (protectionism) in recent years.

The paper uses a multi-region version of QUEST with tradable goods, non-tradable goods and housing. The regions are the Euro Area (EA), the non-EA EU plus the UK (NEA), the United States (US), Japan (JA), Emerging Asia (EMA), and the rest of the world (RoW). The presentation of impulse responses concentrates on the EA as domestic economy (US for tariff shock). The general properties of the impulse responses also apply to the other regional blocks of the model, with some differences related, e.g., to the strength of financial constraints, the degree of economic openness, and the size of economic sectors and government.

The paper also discusses the transmission of shocks to foreign regions, i.e. international spillover through trade and financial channels. In view of macroeconomic conditions in recent years, the paper compares simulations in an environment with standard monetary policy to an environment, where the zero lower bound (ZLB) on monetary policy is binding.

Section 2 describes the structure of QUEST and the parametrisation adopted in this paper. Section 3 presents the impulse responses for a series of demand and supply shocks and explains their transmission to domestic and foreign macroeconomic variables. Section 4 summarises the paper and concludes.

2. MODEL DESCRIPTION

QUEST is the global macroeconomic model developed and used for macroeconomic policy analysis and research by the Directorate-General Economic and Financial Affairs (ECFIN) of the European Commission. It is a structural macroeconomic model in the New-Keynesian tradition with microeconomic foundations that are derived from utility and profit maximisation in the presence of goods, labour and financial market frictions.

The first paper describing QUEST in its modern incarnation has been published by Ratto et al. (2009) as an estimated dynamic stochastic general equilibrium (DSGE) model for the euro area. The model has been referred to as QUEST III, with a generational suffix that later got gradually into disuse. Previous generations of the model consisted of estimated macroeconometric equations (QUEST I) and macroeconometric equations with stronger theoretical foundation (QUEST II). Following Ratto et al. (2009), variants of QUEST III (to which we refer simply as QUEST in the rest of the paper) have also been estimated for more complex structures, some, e.g., including housing and a banking sector, and for different country configurations. These estimated models have been used to present shock

transmission and shock decompositions in order to, e.g., assess the main drivers of growth and intra-EA imbalances.[1]

There are different calibrated and estimated versions of the QUEST model, each used for specific purposes. In our work, we use model configurations that differ, e.g., with respect to the regional set-up, the structure of the production sector (one-sector or multi-sector), and the strength of financial frictions. The aim is to adapt the model to the specific context and need of the application.[2] Versions of the model have been used extensively for the analysis of fiscal policy (e.g., Coenen et al. 2012, in 't Veld 2013, in 't Veld 2017, in 't Veld et al. 2013, Roeger and in 't Veld 2009) and macroeconomic adjustment and rebalancing (e.g., Burgert and Roeger 2014, Vogel 2012, Vogel 2017a, Vogel 2017b). The analysis of structural ("growth") policies has particularly build on a model version with endogenous technological progress (e.g., Roeger et al. 2008, Roeger et al. 2019, Varga and in 't Veld 2009, Varga and in 't Veld 2014, Varga et al. 2014). [3]

The simulations displayed in this paper use a calibrated multi-country structure with tradable and non-tradable goods sectors, housing and collateral constraints, which can be considered to be the workhorse model used in DG ECFIN to assess policy questions and produce macroeconomic scenario analyses that are published in ECFIN series. The calibration of the model is based on national accounts data, input-output tables and international trade matrices for the long-term properties and sectoral and international linkages, and on estimated model versions for the parameters governing transitional dynamics.

Graph 2.1. **Basic structure of QUEST model regions**
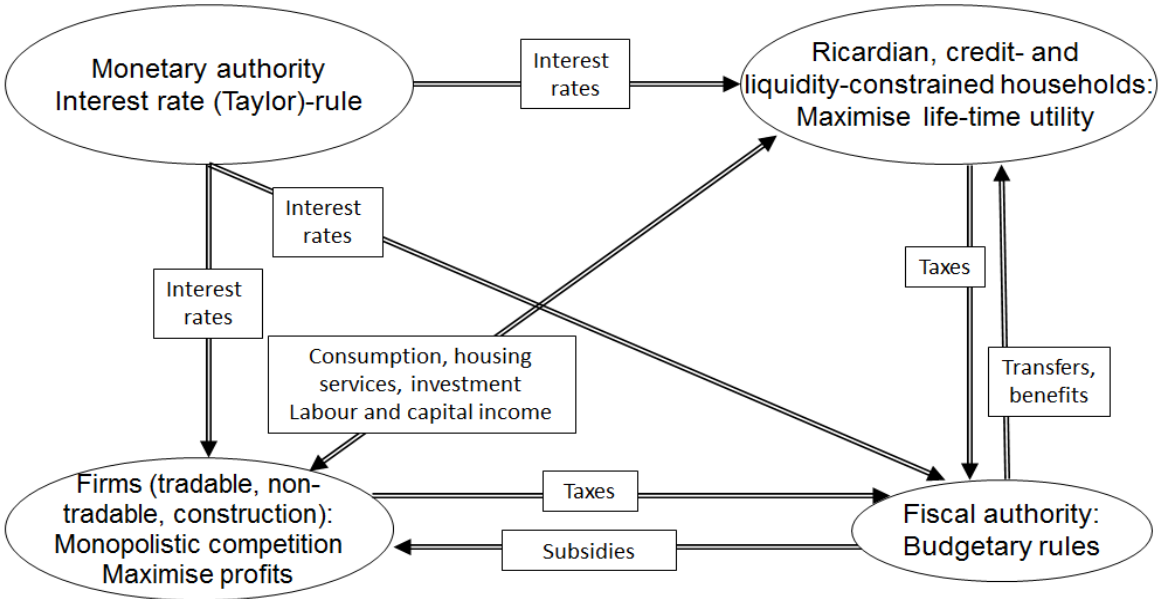
Source: Commission services.

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[1] Related publications are Kollmann et al. (2013) for the euro area, Kollmann et al. (2015) for Germany, in 't Veld et al. (2015) for Spain, and in 't Veld et al. (2011) for the U.S.

[2] An overview of QUEST-based work and related publications can be found on https://ec.europa.eu/info/business-economy-euro/economic-and-fiscal-policy-coordination/economic-research/macroeconomic-models_en.

[3] For the analysis of structural reforms (notably "growth policies"), we use an extended version of QUEST that captures both investment in tangibles and intangibles (R&D) and disaggregates employment into three skill categories. In this extended model variant, technological change is semi-endogenous, adopting the Jones (1995) knowledge production function. For more details on that specific model variant, see Roeger et al. (2008), Varga and in 't Veld (2009), Varga and in 't Veld (2014), Varga et al. (2014), and Roeger et al. (2019).

The model underlying the discussion in this paper is of this type and includes six geographical regions (EA, non-EA EU, US, Japan, Emerging Asia, and the RoW). Graph 2.1 sketches the basic structure of the regional blocks.

On the production side, each regional block includes tradable and nontradable goods and a housing sector. On the household side, each block features three types of households: liquidity-constrained households (l), credit-constrained (c) households, and unconstrained Ricardian households (r). All households consume and supply labour. In addition, Ricardian households invest into domestic productive capital, domestic government bonds and an internationally tradable bond, own the firms, obtain the firms' profits, own land and invest into housing construction. Credit-constrained households distinguish themselves from Ricardian households in that they face a collateral constraint on their borrowing. There is no cross-border mobility of labour. The government levies taxes and spends its revenue on consumption, public investment, unemployment benefits, transfers, and debt service. Each region has an independent monetary policy set by a central bank that follows a standard Taylor rule; depending on the macroeconomic context, we account for the possibility that monetary policy might be constrained temporarily at the ZLB. The rest of this section describes the firm, household and government sectors, the international linkages, and the calibration of the model in more detail.

2.1. PRODUCTION

Each region is home to a tradable sector, a non-tradable sector, and a housing sector.

2.1.1. Tradable and non-tradable production

The model consists of a continuum of firms j operating in the tradable (T) and non-tradable (NT) sectors. Individual firms in T and NT are indexed by the superscript j. Each firm produces a variety of the T or NT good that is an imperfect substitute for varieties produced by other firms. Sectoral output O_t^J with $J \in \{T, NT\}$ is a CES aggregate of the varieties $O_t^{j,J}$:

$$(1) \qquad O_t^J \equiv \left(\int_0^1 (O_t^{j,J})^{(\sigma_J-1)/\sigma_J} dj \right)^{\sigma_J/(\sigma_J-1)}$$

where σ_J is the elasticity of substitution between varieties j in sector J. The elasticity value can differ between T and NT, implying sector-specific price mark-ups. Given the imperfect substitutability, firms are monopolistically competitive in the goods market and face a demand function for their output:

$$(2) \qquad O_t^{j,J} = (P_t^j/P_t^J)^{-\sigma_J} O_t^J$$

The firms in sector T sell consumption and investment goods and intermediate inputs to domestic and foreign private households and firms and consumption and investment goods to domestic and foreign governments. The NT sector sells consumption goods to the domestic households, consumption and investment goods to the domestic government, and intermediate inputs to domestic firms. Hence, all private investment in physical capital consists of T goods.

Output is produced with a CES technology that combines value-added (Y_t^j) and intermediate inputs (INT_t^j). It nests a Cobb-Douglas technology with capital (K_t^j), production workers ($L_t^j - LO_t^j$) and public capital (KG_t) for the production of Y_t^j:

$$(3) \qquad O_t^j = \left((1-s_{in}^j)^{\frac{1}{\sigma_{in}}}(Y_t^j)^{(\sigma_{in}-1)/\sigma_{in}} + (s_{in}^j)^{\frac{1}{\sigma_{in}}}(INT_t^j)^{(\sigma_{in}-1)/\sigma_{in}} \right)^{\sigma_{in}/(\sigma_{in}-1)}$$

(4) $\qquad Y_t^j = A_t^j (ucap_t^j K_t^j)^{1-\alpha} (e^{\varepsilon_t^{TFP,J}} (L_t^j - LO_t^j))^{\alpha} (KG_{t-4})^{\alpha_g} - FCY_t^j$

where s_{in}^j and σ_{in} are, respectively, the steady-state share of intermediates in output and the elasticity of substitution between intermediates and value-added, and A_t^j, $ucap_t^j$, LO_t^j and FCY_t^j are total factor productivity (TFP), capacity utilisation, overhead labour and fixed costs of producing.[4] Note that the stock of public capital enters with a lag of four quarters to account for adjustment lags in the use of public capital, notably public infrastructure.

The demand for intermediate inputs that follows from (3) is:

(5) $\qquad INT_t^j = s_{in}^j (p_t^{INT,j} / (\eta^j p_t^j))^{-\sigma_{in}} O_t^j$

where η^j is the price mark-up as defined below.

Firm-level employment L_t^j is a CES aggregate of the labour services supplied by individual households i:

(6) $\qquad L_t^j \equiv \left(\int_0^1 (L_t^{i,j})^{(\theta-1)/\theta} \, di \right)^{\theta/(\theta-1)}$

where θ indicates the degree of substitutability between the different types of labour i.

The objective of the firm is to maximise the present value of current and future expected real profits (Pr_t^j) relative to the sectoral price level:

(7) $\quad Pr_t^j = \frac{p_t^j}{p_t^J} O_t^j - \frac{p_t^{INT,j}}{p_t^J} INT_t^j - (1 + ssc_t^J) \frac{w_t^p}{p_t^J} L_t^j - i_t^J \frac{p_t^I}{p_t^J} K_t^j - (adj_t^{P,j} + adj_t^{L,j} + adj_t^{ucap,j})$

where ssc_t^J, w_t^p, i_t^J and p_t^I are the employer social security contributions, the private-sector real wage, the rental rate of capital, and the price of capital. The firms are owned by the Ricardian households that receive the firms' profits.

The firms face technology and regulatory constraints that restrict their capacity to adjust. These constraints are modelled as adjustment costs with the following convex functional forms:

(8a) $\qquad adj_t^{L,j} \equiv 0.5 \gamma_L w_t^p (\Delta L_t^j)^2$

(8b) $\qquad adj_t^{P,j} \equiv 0.5 \gamma_P (\pi_t^j)^2 P_{t-1}^J O_t^J$ with $\pi_t^j \equiv P_t^j / P_{t-1}^j - 1$

(8c) $\qquad adj_t^{ucap,j} \equiv \left(\gamma_{ucap,1} (ucap_t^j - 1) + \frac{\gamma_{ucap,2}}{2} (ucap_t^j - 1)^2 \right) \frac{p_t^I}{p_t^J} K_t^J$

The firms choose labour input, capital services, capacity utilisation, the price of output j, and the volume of output j given the demand function (2), the production technology (3) and (4), and the adjustment costs (8a-c). The first-order conditions (FOC) are:

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[4] Lower case letters denote ratios and rates. In particular, $p_t^j \equiv P_t^j / P_t$ is the price of good j relative to the GDP deflator, $w_t \equiv W_t / P_t$ is the real wage, $ucap_t^j$ is actual relative to steady-state (full) capital utilisation, and e_t is the nominal exchange rate defined as the price of foreign in domestic currency.

(9a) $\quad \frac{\partial \text{Pr}_t^j}{\partial L_t^j} => \frac{\partial O_t^j}{\partial L_t^j}\eta_t^j - \gamma_L w_t^p \Delta L_t^j + \gamma_L \beta E_t(\lambda_{t+1}^r/\lambda_t^r \, w_{t+1}^p \Delta L_{t+1}^j) = (1 + ssc_t^J)w_t^p$

(9b) $\quad \frac{\partial \text{Pr}_t^j}{\partial K_t^j} => \frac{\partial O_t^j}{\partial K_t^j}\eta_t^j = i_t^J p_t^I$

(9c) $\quad \frac{\partial \text{Pr}_t^j}{\partial ucap_t^j} => \frac{\partial O_t^j}{\partial ucap_t^j}\eta_t^j = p_t^I K_t^J(\gamma_{u1}^J + \gamma_{u2}(ucap_t^j - 1) + \varepsilon_{J,t}^{ucap})$

(9d) $\quad \frac{\partial \text{Pr}_t^j}{\partial p_t^j} => \eta_t^j = 1 - \frac{1}{\sigma^j} - \varepsilon_t^J - \frac{\gamma_P}{\sigma^j}(\beta^r E_t(\frac{\lambda_{t+1}^r}{\lambda_t^r}\frac{O_{t+1}^J}{O_t^J}\pi_{t+1}^j) - \pi_t^j)$

where η_t^j η_t^j is the Lagrange multiplier associated with the production technology, β^r is the discount factor of Ricardian households (see below) that are the firm owners, λ_t^r is their marginal value of wealth in terms of consumption as defined in (21) below, and ε_t^J is a sector-specific shock to the price mark-up.

Equation (9a) implies that optimising firms equate the marginal product of labour net of adjustment costs to wage costs. The equations (9b-c) jointly determine the optimal capital stock and capacity utilisation by equating the marginal value product of capital to the rental price and the marginal product of capital services to the marginal cost of increasing capacity. Equation (9d) defines the price mark-up factor as function of the elasticity of substitution and price adjustment costs. QUEST follows the empirical literature and allows for backward-looking elements in price setting by assuming that the fraction *1-sfp* of firms indexes prices to past inflation, which leads to the specification:

(9d') $\quad \eta_t^j = \frac{\sigma^j - 1}{\sigma^j} - \varepsilon_t^J - \frac{\gamma_P}{\sigma^j}(\beta E_t\left(\frac{\lambda_{t+1}^r}{\lambda_t^r}\frac{O_{t+1}^J}{O_t^J}(sfp^J E_t\pi_{t+1}^j + (1 - sfp^J)\pi_{t-1}^j)\right) - \pi_t^j)$ with $0 \leq sfp \leq 1$.

for the inverse of the price mark-ups in the T and NT sectors. Given the symmetry of objectives and constraints across firms *j* in sector *J*, the superscript *j* for individual firms can be dropped to obtain aggregate sectoral equations for T and NT. The price setting decision establishes a link between output and prices in the economy. For constant technology, factor demand and/or capacity utilisation increase (decline) with increasing (declining) demand for output, which leads to an increase (decline) in factor and production costs and, hence, an increase (decline) in the price level of domestic output.

2.1.2. Residential construction

Firms in the residential construction sector use new land (I_t^L) sold by (Ricardian) households and non-tradable goods ($I_t^{inp,H}$) to produce new houses, using a CES technology:

(10) $\quad I_t^H = \left(s_L^{\frac{1}{\sigma_L}} I_t^{L \frac{\sigma_L-1}{\sigma_L}} + (1 - s_L)^{\frac{1}{\sigma_L}} I_t^{inp,H \frac{\sigma_L-1}{\sigma_L}}\right)^{\frac{\sigma_L}{\sigma_L-1}}$

that gives the following demand functions for construction services and land:

(11) $\quad I_t^{inp,H} = (1 - s_L)(p_t^{NT}/p_t^H)^{-\sigma_L}I_t^H$

(12) $\quad I_t^L = s_L(p_t^L/p_t^H)^{-\sigma_L}I_t^H$

The demand for land (12) reduces the stock of available building land, which grows at the exogenous rate g^L:

(13) $Land_t = (1 + g^L)Land_{t-1} - I_t^L$

The price of land follows:

(14) $\frac{p_t^L}{p_t^H} = \beta^r \frac{1+g_t^L}{1+\varepsilon_t^{rL}} E_t(\frac{\lambda_{t+1}^r}{\lambda_t^r} \frac{p_{t+1}^L}{p_{t+1}^H})$,

where $\varepsilon_t^{rL} = -rp^L(p_t^L/p_t^{NT} Land_t - \overline{Land}) + u_t^{rL}$ is a risk premium on land with the exogenous component u_t^{rL}.

Firms in the residential construction sector are monopolistically competitive and face price adjustment costs, so that the inverse of the mark-up is given by:

(15) $\eta_t^H = 1 + \gamma_{P,H}(\beta^r E_t(\lambda_{t+1}^r/\lambda_t^r)(sfp E_t \pi_{t+1}^H + (1 - sfp)\pi_{t-1}^H) - \pi_t^H)$ with $0 \leq sfp \leq 1$,

where $\eta_t^H \equiv p_t^H/(s_L(p_t^L)^{1-\sigma_L} + (1 - s_L)(p_t^{NT})^{1-\sigma_L})^{1/(1-\sigma_L)}$ is the ratio of the house price over construction costs.

The housing stock net of depreciation is given by:

(16) $H_t = I_t^H + (1 - \delta^H)H_{t-1}$

New and existing houses are perfect substitutes. Hence, households can make capital gains or suffer capital losses depending on house price fluctuations.

2.2.   HOUSEHOLDS

The household sector consists of a continuum of households $h \in [0,1]$. There are three groups of households: (1) A share of households $s^l \leq 1$ is liquidity-constrained and indexed by l. These households do not trade on asset markets. Instead, they consume their entire disposable wage and transfer income in each period of time. (2) A fraction s^r of all households are Ricardian with full access to financial markets and indexed by r. (3) A fraction s^c of households are credit-constrained and indexed by c.

The period utility function is identical for Ricardian and credit-constrained households. Period utility is separable in consumption (C_t^h), leisure ($1 - npart - L_t^i$) and housing services (H_t^h), where *npart* is the share of labour force non-participants. We also allow for habit persistence in consumption (h^c). Period utility is hence determined as:

(17) $U(C_t^h, 1 - L_t^h, H_t^h) = \frac{1-h}{1-\sigma_c}(C_t^h - h^c \bar{C}_{t-1}^h)^{1-\sigma_c} + \omega \frac{(1-npart-L_t^i)^{1-\kappa}}{1-\kappa} + \omega^{house} \frac{(H_t^h)^{1-\sigma_{house}}}{1-\sigma_{house}}$

where $\sigma_c > 0$, $\kappa > 0$ and $\sigma_{house} > 0$. Liquidity-constrained households have no housing wealth and only derive utility from consumption and leisure. Equation (17) for liquidity-constrained households is adjusted accordingly. Households supply differentiated types of labour services i, which we assume to be distributed equally over the three household types. Unions bundle the differentiated labour services perovided by the three types of households and maximise a joint utility function for each type of labour i. Nominal rigidity in wage setting is introduced by assuming that the households face adjustment costs for changing wages that are borne by the households.

2.2.1. Ricardian households

Ricardian households have full access to financial markets. They hold domestic government bonds (B_t^G) and bonds issued by other domestic and foreign households $(B_t^r, B_t^{F,r})$, real capitals (K_t^J) of the tradable and non-tradable sectors, the stock of land $(Land_t)$ which is still available for building new houses, and cash balances (M_t^r).

The household receives income from labour (net of adjustment costs on wages), financial assets, rental income from lending capital to firms, selling land to the residential construction sector, and profit income from firms (tradable, non-tradable and construction sector) that are owned by the household. The unemployed $(1 - npart - L_t)$ receive benefits $ben_t = benrr W_t$, where $benrr$ is the exogenous benefit replacement rate, and $W_t = \sum_{n=p,g}(L_t^n/L_t)W_t^n$ is the average wage level in the economy. In addition, there is income from general transfers, TR_t. We assume that all domestic firms are owned by domestic Ricardian households. Income from labour is taxed at rate t_t^w. We allow for taxes on the house stock, t_t^H, and on corporate profits, t_t^k. Finally, households pay lump-sum taxes, T_t^{LS}.

We assume that income from financial wealth is subject to different types of risk. Domestic bonds yield risk-free nominal return equal to i_t. Foreign bonds are subject to risk premia linked to net foreign indebtedness plus an idiosyncratic component. An equity premium on real capital arises because of uncertainty about the future value of real assets. These risk premia are denoted by ε_t^{rB}, $\varepsilon_t^{rK,J}$, ε_t^{rH} and ε_t^{rL} for bonds, physical capital, housing capital, and land, respectively. In the model they are captured as exogenous preference shifters to the willingness of households to keep the given assets. The Lagrangian of this maximisation problem is given by:

$$
(18) \quad
\begin{aligned}
Max \quad V_0^r = E_0 \sum_{t=0}^{\infty} (\beta^r)^t &\left(\begin{array}{c} U(C_t^r, 1 - L_t^i, H_t^r) \\ -\bar{\lambda}_t^r(\varepsilon_t^{rBF}B_t^{F,r} + \varepsilon_t^{rB}B_t^c + \varepsilon_t^{rL}p_t^L Land_t \\ + \sum_{J=T,NT} \varepsilon_t^{rK,J}p_t^I K_t^J + \varepsilon_t^{rH}p_t^H H_t) \end{array} \right) \\
- E_0 \sum_{t=0}^{\infty} \lambda_t^r(\beta^r)^t &\left(\begin{array}{c} (1 + t_t^c)p_t^C C_t^r + \sum_{J=T,NT} p_t^I I_t^J \\ +(1 + t_t^c)p_t^H I_t^{H,r} + (B_t^G + B_t^r) \\ + rer_t B_t^{F,r} + T_t^{LS,r} \\ -(1 + r_{t-1})(B_{t-1}^G + B_{t-1}^r) - (1 + r_{t-1}^F)rer_t B_{t-1}^{F,r} \\ -(1 - t_t^W)w_t^{p,i}L_t^{p,i} - (1 - t_t^W)w_t^{g,i}L_t^{g,i} \\ -ben_t^{real}(1 - npart - L_t^{p,i} - L_t^{g,i}) - TR_t^{real} \\ -p_t^L I_t^{Land} - (1 - t_t^k)\sum_{J=T,NT}(i_t^J p_t^I K_t^J + p_t^J Pr_t^J) \\ -t_t^k \sum_{J=T,NT} \delta^{K,J}p_t^I K_{t-1}^J - p_t^H Pr_t^H \\ +t_t^H p_t^H H_t^r + \sum_{J=T,NT}(adj_t^{K,J} + adj_t^{I,J}) \\ +adj_t^{H,r} + adj_t^{I^H,r} + adj_t^{wp,r} + adj_t^{wg,r} \end{array} \right) \\
- E_0 \sum_{t=0}^{\infty} \lambda_t^r (\beta^r &\sum_{J=T,NT} \xi_t^J (K_{t+1}^J - I_t^J - (1 - \delta^{K,J})K_t^J) \\
- E_0 \sum_{t=0}^{\infty} \lambda_t^r \zeta_t^r (\beta^r &(H_t^r - I_t^{H,r} - (1 - \delta^H)H_{t-1}^r) \\
- E_0 \sum_{t=0}^{\infty} \lambda_t^r \xi_t^{Land} (\beta^r &(Land_t + I_t^L - Land_{t-1})
\end{aligned}
$$

where the adjustment costs have the functional forms:

(19a) $adj_t^{K,J} \equiv 0.5\gamma_{K,J}(I_t^J/K_{t-1}^J - \delta^{K,J})^2 p_t^I \bar{K}_{t-1}^J$

(19b) $adj_t^{I,J} \equiv 0.5\gamma_{I,J}p_t^I(\Delta I_t^J)^2$

(19c) $adj_t^{H,r} \equiv 0.5\gamma_H(I_t^{H,r}/H_{t-1}^r - \delta^H)^2 p_t^H \bar{H}_{t-1}^r$

(19d) $adj_t^{I^H,r} \equiv 0.5\gamma_{I^H}p_t^H(\Delta I_t^{H,r})^2$

(19e) $adj_t^{wp,r} \equiv 0.5\gamma_W(\pi_t^{wp,i})^2\bar{L}_t^{p,r}$

(19e) $adj_t^{wg,r} \equiv 0.5\gamma_W(\pi_t^{wg,i})^2\bar{L}_t^{g,r}$

and where p_t^C, p_t^I, p_t^H and p_t^L are the price deflators for consumption, investment, houses and land price relative to the GDP deflator.

The FOCs of the optimisation problem provide the intertemporal consumption rule, where the ratio of the marginal utility of consumption in periods t and $t+1$ is equated to the real interest rate adjusted for the rate of time preference:

(20) $E_t(\lambda_t^r/\lambda_{t+1}^r) = \beta(1 + r_t)$

(21) $\lambda_t^r = \frac{(1-h^c)^{\sigma_c}}{(1+t_t^c)p_t^C(C_t^r - h^c C_{t-1}^r)^{\sigma_c}}$,

with the real interest rate $r_t = i_t - E_t\pi_{t+1}$, i.e. the nominal rate minus the expected per-cent change in the GDP deflator.

The FOC for investment provides an investment rule linking capital formation to the shadow price of capital:

(22) $\gamma_{K,J}\left(\frac{I_t^J}{K_{t-1}^J} - \delta^{K,J}\right) + \gamma_{I,J}\Delta I_t^J - \gamma_{I,J}\beta E_t\left(\frac{\lambda_{t+1}^r}{\lambda_t^r}\frac{p_{t+1}^I}{p_t^I}\Delta I_{t+1}^J\right) = q_t^J - 1$

and $q_t^J \equiv \frac{\xi_t^J}{p_t^I}$ corresponds to the present discounted value of rental income from physical capital, which follows from the FOC w.r.t. the stock of capital:

(23) $q_t^J = i_i^J + \beta E_t\left(\frac{\lambda_{t+1}^r}{\lambda_t^r}\frac{p_{t+1}^I}{p_t^I}\left[t_{t+1}^k\delta^{K,J} - \gamma_K(\frac{I_{t+1}^J}{K_t^J} - \delta^{K,J})\frac{I_{t+1}^J}{K_t^J} + (1 - \delta^{K,J})q_{t+1}^J\right]\right)$

The FOC for investment in foreign bonds together with equation (20) and the approximation $\ln(1 + x) \approx x$ for small values of x gives the UIP condition:

(24) $i_t = i_t^F + E_t\frac{\Delta e_{t+1}}{e_t} + \varepsilon_t^{rBF}$

that determines the nominal exchange rate vis-à-vis the RoW. There are no capital controls that would insulate domestic from international capital markets and separate domestic monetary from exchange rate policy.

Equation (24) contains an endogenous external risk premium $\varepsilon_t^{rBF} = -\alpha \left(\frac{e_t B_t^{F,r}}{4Y_t} - \frac{B^{F,tar}}{4\bar{Y}} \right) + u_t^{rBF}$ that depends on the net foreign asset (NFA) position $(B_t^{F,r})$ of the domestic economy relative to the target value plus an exogenous term u_t^{rBF}. An increase (decline) in the NFA position of the domestic economy increases (reduces) the risk on foreign relative to domestic bonds. The endogenous NFA risk premium rules out explosive NFA dynamics and closes the external side of the model as shown by Schmitt-Grohé and Uribe (2003). In particular, a deterioration of the domestic NFA position increases domestic financing costs and dampens interest-sensitive domestic consumption and investment demand.

The FOC with respect to the housing stock determines the evolution of the shadow price of houses, $q_t^{H,r} \equiv \frac{\zeta_t^r}{(1+t_t^c)p_t^H}$:

$$(25) \qquad q_t^{H,r} = \frac{U_t^{H,r}}{U_t^{C,r}} \frac{p_t^C}{p_t^H} - \frac{t_t^H + \varepsilon_t^{rH}}{1+t_t^c} + \beta E_t \frac{\lambda_{t+1}^r}{\lambda_t^r} \frac{p_{t+1}^H}{p_t^H} \left(\frac{\gamma_H}{1+t_t^c} (\frac{I_{t+1}^{H,r}}{H_t^r} - \delta^H) \frac{I_{t+1}^{H,r}}{H_t^r} + (1-\delta^H) \frac{1+t_{t+1}^c}{1+t_t^c} q_{t+1}^{H,r} \right)$$

Finally, the FOC with respect to housing investment links the shadow price of houses to the formation of housing capital:

$$(26) \qquad q_t^{H,r} = 1 + \frac{\gamma_H + u_t^H}{1+t_t^c} \left(\frac{I_t^{H,r}}{H_{t-1}^r} - \delta^h \right) + \frac{\gamma_{IH}}{1+t_t^c} \Delta I_t^{H,r} - \frac{\gamma_{IH}}{1+t_t^c} \beta^r E_t \left(\frac{\lambda_{t+1}^r}{\lambda_t^r} \frac{p_{t+1}^H}{p_t^H} \Delta I_{t+1}^{H,r} \right)$$

2.2.2. Credit-constrained households

Credit-constrained households have been introduced as financial friction into QUEST by Roeger and in 't Veld (2009) in addition to liquidity-constrained consumers, present already in Ratto et al. (2009). Credit-constrained households were introduced to capture important transmission channels of the global financial crisis of 2007-8 to the real economy, namely higher risk premia and a tightening of credit conditions in conjunction with a sharp fall in house prices. The modelling follows the literature on the financial accelerator mechanism and Iacoviello (2005) in particular.[5]

Credit-constrained households differ from Ricardian households in two respects. First, they have a higher rate of time preference $(\beta^c < \beta^r)$ and second, they face a collateral constraint on their borrowing. They borrow $B_t^c \equiv -B_t^r$ exclusively from domestic Ricardian households. Ricardian households have the possibility to refinance themselves via the international capital market.

It is assumed that only a share $1 - \rho^B$ of the past debt of credit-constrained households is reimbursed in a given period. The Lagrangian of the maximisation problem for credit-constrained households is given by:

---

[5] Different kinds of financial frictions in the DSGE literature, notably frictions inside financial institutions versus frictions on the side of borrowers, are discussed in Christiano et al. (2018).

$$Max \quad V_0^c = E_0 \sum_{t=0}^{\infty} (\beta^c)^t \left(U(C_t^c, 1 - L_t^i, H_t^c) - \bar{\lambda}_t^c (\varepsilon_t^{cH} p_t^H H_t^c - \varepsilon_t^{cB} B_t^c) \right)$$

$$(27) \quad -E_0 \sum_{t=0}^{\infty} \lambda_t^c (\beta^c)^t \begin{pmatrix} (1 + t_t^c) p_t^C C_t^c + (1 + t_t^c) p_t^H I_t^{H,c} + (1 + r_{t-1}) B_{t-1}^c - B_t^c \\ -(1 - t_t^W) w_t^{p,i} L_t^{p,i} - (1 - t_t^W) w_t^{g,i} L_t^{g,i} \\ -ben_t^{real} (1 - npart - L_t^{p,i} - L_t^{g,i}) - TR_t^{real} + T_t^{LS,c} + t_t^H p_t^H H_t^c \\ +adj_t^{H,c} + adj_t^{I^H,c} + adj_t^{wp,c} + adj_t^{wg,c} \end{pmatrix}$$

$$-E_0 \sum_{t=0}^{\infty} \lambda_t^c \zeta_t^c \left(\beta^c (H_t^c - I_t^{H,c} - (1 - \delta^H) H_{t-1}^c) \right)$$

$$-E_0 \sum_{t=0}^{\infty} \lambda_t^c \psi_t \left(\beta^c (B_t^c - \rho^B B_{t-1}^c - (1 - \rho^B)(1 - \chi) p_t^H H_t^c) \right)$$

Housing investment adjustment and wage adjustment costs for the credit-constrained households are analogous to those for Ricardian households defined in equations (19c) and (19e).

The FOC with respect to the debt stock is given by:

$$(28) \quad \lambda_t^c (1 + \varepsilon_t^{cB} - \psi_t) = \beta E_t (\lambda_{t+1}^c (1 + r_t - \rho^B \psi_{t+1}))$$

Combining this expression with the FOC with respect to consumption:

$$(29) \quad \lambda_t^c = \frac{(1 - h^c)^{\sigma_c}}{(1 + t_t^c) p_t^C (C_t^c - h^c C_{t-1}^c)^{\sigma_c}}$$

yields the consumption Euler equation for credit-constrained households up to a first order approximation:

$$(30) \quad \beta^c E_t \frac{(1 + t_t^c) p_t^C U_{t+1}^{C,c}}{(1 + t_{t+1}^c) p_{t+1}^C U_t^{C,c}} = \frac{1 + \varepsilon_t^{rB} - \psi_t}{(1 + r_t) - \rho^B E_t \psi_{t+1}}$$

The consumption Euler equation for credit-constrained households distinguishes itself from the Euler equation of unconstrained Ricardian households by the presence of ψ_t, the utility value the additional debt has in relaxing the credit constraint. The presence of the constraint on the accumulation of debt also leads to an asymmetry in investment decisions into housing between credit-constrained and unconstrained households. Intuitively, the term ψ_t acts like a spread on the interest rate for credit-constrained households, which fluctuates positively with the tightness of the constraint.

The FOC with respect to the housing stock reads:

$$(31) \quad q_t^{H,c} = \frac{U_t^{H,c}}{U_t^{C,c}} \frac{p_t^C}{p_t^H} - \frac{t_t^H + \varepsilon_t^{cH}}{1 + t_t^c} + \beta E_t \frac{p_{t+1}^H}{p_t^H} \frac{\lambda_{t+1}^c}{\lambda_t^c} \left(\frac{\gamma_H}{1 + t_t^c} (\frac{I_{t+1}^{H,c}}{H_t^c} - \delta^H) \frac{I_{t+1}^{H,c}}{H_t^c} + (1 - \delta^H) \frac{1 + t_{t+1}^c}{1 + t_t^c} q_{t+1}^{H,c} \right)$$
$$+ \frac{(1 - \rho^B)(1 - \chi)}{1 + t_t^c} \psi_t$$

where the shadow value of housing is given by $q_t^{H,c} \equiv \frac{\zeta_t^c}{(1 + t_t^c) p_t^H}$.

The FOC with respect to housing investment can be expressed as:

$$(32) \quad q_t^{H,c} = 1 + \frac{\gamma_H + u_t^H}{1 + t_t^c} \left(\frac{I_t^{H,c}}{H_{t-1}^c} - \delta^h \right) + \frac{\gamma_{IH}}{1 + t_t^c} \Delta I_t^{H,c} - \frac{\gamma_{IH}}{1 + t_t^c} \beta^c E_t \left(\frac{\lambda_{t+1}^c}{\lambda_t^c} \frac{p_{t+1}^H}{p_t^H} \Delta I_{t+1}^{H,c} \right)$$

2.2.3. Liquidity-constrained households

Liquidity-constrained households do not optimise the intertemporal consumption path, but simply consume their entire disposable income at each date. Real consumption of household l is thus determined by the net wage, benefit and transfer income minus the lump-sum tax:

(33) $\quad (1 + t_t^c) P_t^C C_t^l = (1 - t_t^w)(W_t^p L_t^{p,i} + W_t^g L_t^{g,i}) + TR_t + ben_t(1 - npart - L_t^{p,i} - L_t^{g,i}) - T_t^{LS}$

The labour supply behaviour of liquidity-constrained households is determined by the utility function (17) which also applies to Ricardian and credit-constrained households. Labour supply and wage setting is described next.

2.2.4. Wage setting

Household members are employed in the private sector ($L_t^{i,p}$) and the government sector ($L_t^{i,g}$), with preferences given by the CES function:

(34) $\quad L_t = \left(s_P^{\frac{1}{\sigma_P}} L_t^{i,p\,\frac{\sigma_P-1}{\sigma_P}} + s_G^{\frac{1}{\sigma_P}} L_t^{i,g\,\frac{\sigma_P-1}{\sigma_P}} \right)^{\frac{\sigma_P}{\sigma_P-1}}$

with $s_G = 1 - s_P$, and where private-sector employment is the sum of employment in the production of tradable and non-tradable goods, i.e. $L_t^{i,p} = \sum_{J=T,NT} L_t^{i,J}$.

Aggregate labour input in the private and the government sectors $n \in \{p, g\}$ is a CES aggregate of differentiated labour services i supplied by the individual households:

(35) $\quad L_t^n = \left(\int_0^1 L_t^{i,n\,\frac{\theta-1}{\theta}} di \right)^{\frac{\theta}{\theta-1}},$

with θ being the elasticity of substitution between labour varieties i, which provides the demand function for differentiated labour services, $L_t^{i,n} = \left(W_t^{i,n}/W_t^n \right)^{-\theta} L_t^n$.

A trade union maximises a joint utility function for each type of labour i in the private sector and the government sector. It is assumed that types of labour are distributed equally over Ricardian, credit-constrained and liquidity-constrained households with their respective population weights.

The trade union sets wages in the private sector and the public sector by maximising a weighted average of the utility functions of these households. The sectoral wage rules with symmetry in the behaviour between types of labour i are:

(36) $\quad \left(\frac{\omega(1-npart-L_t)^{-\kappa}}{(s_n\frac{L_t}{L_t^n})^{1/\sigma_P}\lambda_t^{av}} \right)^{1-wrlag} \left(\frac{\frac{W_{t-1}^n}{P_{t-1}^C}}{(1-t_t^W)\frac{\theta-1}{\theta}-benrr} \right)^{wrlag} = \frac{\frac{\theta-1}{\theta}(1-t_t^W)W_t^n-ben_t}{P_t^C}$

$\quad + \frac{\gamma^{w,n}}{\theta}(1+\pi_t^{w,n})\pi_t^{w,n} - \beta E_t \left(\frac{\lambda_{t+1}^{av}}{\lambda_t^{av}}\frac{\gamma^{w,n}}{\theta}(1+\pi_{t+1}^{w,n})\frac{L_{t+1}^n}{L_t^n}(sfw\pi_{t+1}^{w,n}+(1-sfw)\pi_{t-1}^{w,n}) \right)$

where $\lambda_t^{av} \equiv s^r\lambda_t^r + s^c\lambda_t^c + s^l\lambda_t^l$, $benrr$ is the benefit replacement rate, and ben_t are benefits. The wage rule (36) allows for (ad hoc) real wage rigidity ($wrlag$) in the spirit of Blanchard and Galí (2007). In the presence of wage stickiness, the fraction *1-sfw* of workers ($0 \leq sfw \leq 1$) forms expectations of future wage growth on the basis of wage inflation in the previous period.

2.2.5. Aggregation

The aggregate value of any household-specific variable X_t^h in per-capita terms is given by $X_t \equiv \int_0^1 X_t^h \, dh = s^r X_t^r + s^c X_t^c + s^l X_t^l$, since the households within each group are identical with respect to their consumption and labour supply decisions. Aggregate consumption is, hence, given by:

(37a) $C_t = s^r C_t^r + s^c C_t^c + s^l C_t^l$

and aggregate employment by:

(37b) $L_t = s^r L_t^r + s^c L_t^c + s^l L_t^l$ with $L_t^r = L_t^c = L_t^l$.

The liquidity-constrained households do not own financial assets, which implies $B_t^l = B_t^{l,F} = K_t^l = 0$. Credit-constrained households only engage in debt contracts with Ricardian households, so that we have:

(38) $B_t^c = \frac{s^r}{s^c} B_t^r$.

Since liquidity-constrained households do not engage in housing investment, credit-constrained and Ricardian households' housing investment aggregate to total housing investment in per-capita terms as:

(39) $I_t^H = s^r I_t^{H,r} + s^c I_t^{H,c}$

The average real wage level in the economy can be computed as follows:

(40) $w_t = (w_t^p L_t^p + w_t^g L_t^g)/L_t$,

and the economy-wide unemployment rate defined as:

(41) $u_t \equiv 1 - npart - L_t^p - L_t^g$.

2.3.   FISCAL AND MONETARY POLICY

Government purchases (G_t), government investment (IG_t) and nominal transfers (TR_t) correspond to constant shares of nominal GDP $(\overline{gs}, \overline{igs}, \text{and } \overline{trs})$ plus respective shock terms:

(42a) $G_t = \frac{\overline{gs} P_t Y_t}{P_t^C} + \varepsilon_t^g$

(42b) $IG_t = \frac{\overline{igs} P_t Y_t}{P_t^C} + +\varepsilon_t^{ig}$

(42c) $TR_t = \overline{trs} P_t Y_t + \varepsilon_t^{tr}$

The public capital stock KG_t, which enters the production function (4), develops according to:

(43) $KG_t = IG_t + (1 - \delta^g)KG_{t-1}$

The nominal benefits paid to the unemployed part of the labour force correspond to the exogenous replacement rate $(\overline{benr})$ times the nominal wage:

(44) $ben_t = \overline{benr} \, W_t$

The government receives consumption, labour, corporate and lump-sum tax revenue, and employer social security contributions. Real government debt (B_t) evolves according to:

$$
\begin{aligned}
B_t^G = & (1 + i_{t-1}^g - \pi_t)B_{t-1}^G + p_t^C(G_t + IG_t) + w_t^g L_t^g + ben_t^{real}(1 - npart_t - L_t^p - L_t^g) \\
& + TR_t^{real} - \sum_J t_t^k(p_t^J O_t^J - p_t^{INT,J} INT_t^J - (1 + ssc_t^J)w_t L_t^J - i_t^J p_t^I K_t^J) \\
& - \sum_J (t_t^w + ssc_t^J)w_t^p L_t^J - t_t^w w_t^g L_t^g - t_t^C p_t^C C_t - t_t^C p_t^H I_t^H - t_t^H p_t^H H_t - trev_t - T_t^{LS}
\end{aligned}
$$
(45)

where we use $i_t^g = \rho_{ig}i_{t-1}^g + (1 - \rho_{ig})(i_t + \varepsilon_t^{rg})$ to account for a gradual pass through of policy rates into effective government financing costs. The gradual pass through of policy rates into financing costs is associated with the maturity structure of government debt. ε_t^{rg} is an exogenous risk premium on the newly issued government debt. The variable $trev_t \equiv \sum_f t_t^f/(1 + t_t^f)p_t^{M,f} M_t^f$ is the government revenue in real terms from import tariffs as introduced in subsection 2.4 below.

The government balance relative to GDP is given by:

$$
\begin{aligned}
GBY_t = & (\sum_J t_t^k(p_t^J O_t^J - p_t^{INT,J} INT_t^J - (1 + ssc_t^J)w_t L_t^J - i_t^J p_t^I K_t^J) + \sum_J (t_t^w + ssc_t^J)w_t^p L_t^J \\
& + t_t^w w_t^g L_t^g + t_t^C p_t^C C_t + t_t^C p_t^H I_t^H + t_t^H p_t^H H_t + trev_t + T_t^{LS} - (i_{t-1}^g - \pi_t)B_{t-1}^G - p_t^C(G_t + IG_t) \\
& - w_t^g L_t^g - TR_t^{real} - ben_t^{real}(1 - npart_t - L_t^p - L_t^g))/Y_t
\end{aligned}
$$
(46)

The lump-sum tax is used to stabilise the debt-to-GDP ratio:

(47) $\quad \Delta T_t^{LS} = \tau^B(B_t^G/(4Y_t) - \overline{btar}) + \tau^{def}\Delta B_t^{real}$

with $\overline{btar}$ being the target level of government debt-to-GDP. The consumption, corporate income and personal income tax rates and the rate of employer social security contributions are exogenous.

Value added in government sector equals the wage sum $w_t^g L_t^g$, so that total GDP is:

(48) $\quad Y_t = \sum_{J=T,NT} (p_t^J O_t^J - p_t^{INT,J} INT_t^J) + w_t^g L_t^g$

Monetary policy follows a Taylor rule that allows for a smoothing of the interest rate response to inflation and the output gap:

(49) $\quad i_t = \rho_i i_{t-1} + (1 - \rho_i)(\bar{r} + \pi^{tar} + \tau_\pi(\pi_{t,yoy}^C/4 - \pi^{tar}) + \tau_y ygap_t) + \varepsilon_t^M$

The central bank has an inflation target π^{tar}, adjusts its policy rate relative to the steady-state value $\bar{r}$ when actual CPI inflation deviates from the target, where $\pi_{t,yoy}^C \equiv P_t^C/P_{t-4}^C - 1$ is year-on-year CPI inflation, or output deviates from its potential level, i.e. a non-zero output gap (*ygap*). The output gap is not calculated as the difference between actual and efficient output, but derived from a production function framework, which is the standard practice of output gap calculation for fiscal surveillance and monetary policy. More precisely, the output gap is defined as deviation of factor utilisation from its long-run trend:

(50) $\quad ygap_t = \alpha\ln(\frac{L_t}{L_t^{SS}}) + (1 - \alpha)\ln(\sum_J \frac{Y_t^J}{Y_t}\frac{ucap_t^J}{ucap_t^{SS,J}})$

The variables L_t^{SS} and $ucap_t^{SS}$ are moving averages of employment and capacity utilisation rates:

(51a) $\quad L_t^{SS} = \rho^L L_{t-1}^{SS} + (1 - \rho^L) L_t$

(51b) $\quad ucap_t^{SS,J} = \rho^{ucap} ucap_{t-1}^{SS,J} + (1 - \rho^{ucap}) ucap_t^J$

that adjust slowly to actual values of employment and capacity utilisation.

2.4. TRADE AND FINANCIAL LINKAGES

This sub-section describes the key relationships for the response of the trade balance, the current account and the net foreign asset (NFA) position to relative prices and demand. Previous sub-sections have determined aggregate domestic consumption, investment and government expenditure, but not the allocation of demand for private sector output (a) across T versus NT output and (b) domestically produced versus imported T goods.

In order to facilitate aggregation, private households and the government are assumed to have identical preferences across goods used for private and government consumption and public investment. Let Z=C+G+IG be the demand by private households and the government, and let their preferences for T and NT goods be given by the CES functions:

(52) $\quad Z_t = \left((1 - s^T)^{1/\sigma_{tnt}} (Z_t^{NT})^{(\sigma_{tnt}-1)/\sigma_{tnt}} + (s^T)^{1/\sigma_{tnt}} (Z_t^T)^{(\sigma_{tnt}-1)/\sigma_{tnt}} \right)^{\sigma_{tnt}/(\sigma_{tnt}-1)}$

where Z_t^{NT} is an index of domestic demand across NT varieties, and Z_t^T is a bundle of domestically produced ($Z_t^{T,D}$) and imported ($Z_t^{T,M}$) T goods:

(53) $\quad Z_t^T = \left((1 - s_m)^{1/\sigma_x} (Z_t^{T,D})^{(\sigma_x-1)/\sigma_x} + s_m^{1/\sigma_x} (M_t^Z (1 - \Gamma_t^{M,Z}))^{(\sigma_x-1)/\sigma_x} \right)^{\sigma_x/(\sigma_x-1)}$

The elasticity of substitution between the bundles of NT versus T goods is σ_{tnt}. The elasticity of substitution between the bundles of domestically produced versus imported T goods is σ_x. The steady-state shares of T goods in Z_t and imports in Z_t^T are s^T and s_m, respectively. Following the approach in Christoffel et al. (2008), the term $\Gamma_t^{M,Z} \equiv \frac{\gamma^M}{2} \left(\frac{M_t^Z / M_{t-1}^Z}{Z_t^T / Z_{t-1}^T} - 1 \right)^2$ captures import adjustment costs that enter the resource constraint of the economy.

All private investment in physical capital in the $J \in \{T, NT\}$ sectors consists of T goods:[6]

(54) $\quad I_t^J = \left((1 - s_m)^{1/\sigma_x} (I_t^{J,T,D})^{(\sigma_x-1)/\sigma_x} + s_m^{1/\sigma_x} (M_t^{I,J} (1 - \Gamma_t^{M,I,J}))^{(\sigma_x-1)/\sigma_x} \right)^{\sigma_x/(\sigma_x-1)}$,

with the adjustment costs $\Gamma_t^{M,I,J} \equiv \frac{\gamma^M}{2} \left(\frac{M_t^{I,J} / M_{t-1}^{I,J}}{I_t^J / I_{t-1}^J} - 1 \right)^2$.

The CES aggregate (52) combining T and NT goods gives the following demand functions:

(55a) $\quad Z_t^T = s^T (P_t^T / P_t^C)^{-\sigma_{tnt}} (C_t + G_t + IG_t)$

(55b) $\quad Z_t^{NT} = (1 - s^T)(P_t^{NT} / P_t^C)^{-\sigma_{tnt}} (C_t + G_t + IG_t)$

The intermediate inputs in sector $J \in \{T, NT\}$ are also composites of T and NT analogously to equations (52) and (53), with T being domestically produced or imported:

---

[6] The assumption of all investment goods being composed of tradable investment is a simplification, but accounts for the observation that the content in tradable goods and imports is substantially higher for private investment compared to consumption goods, including less demand for non-tradable services in the distribution (e.g. Bems 2009, Burstein et al. 2004). Note also that tradable goods production also uses non-tradable intermediate goods, so that non-tradable goods and prices enter indirectly also the production of investment goods.

(56) $\quad INT_t^J = \left((1 - s_{\text{int}}^J)^{1/\sigma_{tnt}}(INT_t^{NT,J})^{(\sigma_{tnt}-1)/\sigma_{tnt}} + (s_{\text{int}}^J)^{1/\sigma_{tnt}}(INT_t^{T,J})^{(\sigma_{tnt}-1)/\sigma_{tnt}}\right)^{\frac{\sigma_{tnt}}{\sigma_{tnt}-1}}$

(57) $\quad INT_t^{T,J} = \left((1 - s_m)^{1/\sigma_x}(INT_t^{T,D,J})^{(\sigma_x-1)/\sigma_x} + s_m^{1/\sigma_x}(M_t^{INT,J}(1 - \Gamma_t^{M,INT,J}))^{(\sigma_x-1)/\sigma_x}\right)^{\frac{\sigma_x}{\sigma_x-1}},$

with the adjustment costs $\Gamma_t^{M,INT,J} \equiv \frac{\gamma^M}{2}\left(\frac{M_t^{INT,J}/M_{t-1}^{INT,J}}{INT_t^{T,J}/INT_{t-1}^{T,J}} - 1\right)^2.$

This gives demand functions for T and NT intermediates analogously to (55):

(58a) $\quad INT_t^{T,J} = s_{\text{int}}^J(P_t^T/P_t^{INT,J})^{-\sigma_{tnt}}INT_t^J$

(58b) $\quad INT_t^{NT,J} = (1 - s_{\text{int}}^J)(P_t^{NT}/P_t^{INT,J})^{-\sigma_{tnt}}INT_t^J$

The price index for the bundle of tradable goods for each demand category H_t^T is:

(59) $\quad P_t^{T,H} = \left((1 - s_m)(P_t^{T,D})^{1-\sigma_x} + s_m(P_t^M(1 - \Gamma_t^{M,H}))^{1-\sigma_x}\right)^{1/(1-\sigma_x)}$

Import demand by demand components is:

(60) $\quad M_t^H = s_m\left(\frac{1}{\Gamma_t^{M,H\prime}}\frac{P_t^M}{P_t^{T,H}}\right)^{-\sigma}\frac{H_t^T}{1-\Gamma_t^{M,H}},$

where $\Gamma_t^{M,H\prime} \equiv \partial((1 - \Gamma_t^{M,H})M_t^H)/\partial M_t^H$. Total imports are the sum of imports by component:

(61) $\quad M_t = \sum_H M_t^H.$

Total imports are a CES bundle of bilateral imports from foreign regions f:

(62) $\quad M_t = \left(\sum_f (s^f)^{\frac{1}{\sigma_1}}\left(M_t^f(1 - \Gamma_t^f)\right)^{\frac{\sigma_1-1}{\sigma_1}}\right)^{\frac{\sigma_1}{\sigma_1-1}},$

where σ_1 is the elasticity of substitution between imports of different origins, s^f is the steady-state share of region f in the domestic economy's imports, and $\Gamma_t^f \equiv \frac{\gamma^f}{2}\left(\frac{M_t^f/M_{t-1}^f}{M_t/M_{t-1}} - 1\right)^2$ are bilateral import adjustment costs. The demand for goods from region f is given by:

(63) $\quad M_t^f = s^f\left(\frac{1}{\Gamma_t^{f\prime}}\frac{P_t^{M,f}}{P_t^M}\right)^{-\sigma_1}\frac{M_t}{1-\Gamma_t^f}$

where $\Gamma_t^{f\prime} \equiv \partial((1 - \Gamma_t^f)M_t^f)/\partial M_t^f$.

Exporters sell domestically produced tradable goods in world markets. Prices are sticky in the currency of the importer, so that pass-through of nominal exchange rate movements into import prices is incomplete in the short and medium term. Furthermore, export prices in foreign currency respond to export market conditions and not solely to exchange rate movements and domestic conditions, i.e. a form of pricing-to-market (PTM). PTM requires the modelling of bilateral trade between regions. Export firms are monopolistically competitive and maximise their profits while they have to bear price adjustment costs if they adjust prices in the foreign currency. This gives rise to a mark-up on export prices. More specifically, the mark-up is determined by the (constant) substitution elasticity of export goods and by (variable) adjustment costs for export prices in foreign currency. Prices of imports from region f are then:

(64) $\quad P_t^{M,f} = (1+t_t^f)e_t^f P_t^{T*,f}\left(1 + \frac{\gamma^M}{\sigma_1-1}(\beta E_t \frac{P_{t+1}^{T,f}}{P_t^{T,f}}(sfpm\, E_t \pi_{t+1}^{M,f} + (1-sfpm)\pi_{t-1}^{M,f}) - \pi_t^{M,f})\right)$

with t_t^f as a tariff of imports from region f, e_t^f as the corresponding bilateral exchange rate, $P_t^{T*,f}$ the price of the tradable good in the foreign region f denoted in country f currency, γ^M the adjustment cost parameter in import prices, and *sfpm* the fraction of firms indexing import prices to expected future import price inflation. $\pi_t^{M,f}$ is the rate of inflation of bilateral import prices of imports from region f to the domestic region denoted in domestic region's (i.e. importer) currency.

Total exports of the domestic economy are the sum of all foreign regions' imports stemming from the domestic region, which corresponds to the exports of the domestic region to all other regions:

(65) $\quad X_t = \sum_f X_t^f$

Aggregate import prices are a CES aggregate over bilateral import prices:

(66) $\quad P_t^M = \left(\sum_f s^f (P_t^{M,f})^{1-\sigma_1}\right)^{\frac{1}{1-\sigma_1}}$

Aggregate export prices are a weighted average over bilateral import prices in export destinations, $P_t^{M*,f}$, adjusted by foreign countries' tariffs, $t_t^{*,f}$, and the bilateral exchange rate:

(67) $\quad P_t^X = \left(\sum_f \frac{P_t^{M*,f}}{(1+t_t^{*,f})e_t^f} X_t^f\right)/X_t$

The terms of trade of the economy are defines as the ratio of export over import prices:

(68) $\quad TOT_t \equiv P_t^X/P_t^M$

The trade balance of the domestic economy is net trade in value terms:

(69) $\quad TB_t \equiv \sum_f \frac{P_t^{M*,f}}{(1+t_t^{*,f})e_t^f} X_t^f - \sum_f \frac{P_t^{M,f}}{1+t_t^f} M_t^f$

Adding interest income on net foreign assets (NFA) to the trade balance gives the current account position of the domestic economy:

(70) $\quad CA_t/P_t \equiv r_{t-1}^F rer_t B_{t-1}^F + TB_t/P_t$

where r_t^F denotes real interest paid on net foreign asset denominated in the reserve currency of the world economy, which in the model is the U.S. dollar.

The law of motion for the NFA position is:

(71) $\quad rer_t B_t^F = (1 + r_{t-1}^F)rer_t B_{t-1}^F + TB_t/P_t$

The focus on the NFA position abstracts from valuation effects on gross foreign assets or liabilities that otherwise could affect the financial wealth of domestic households.

2.5. CALIBRATION

Model parameters that characterise the steady state of the model are calibrated on the basis of national accounts, fiscal and trade data. Behavioural parameters that govern the dynamic adjustment to shocks are based on earlier estimates of version of the QUEST model.[7] Table 2.1 summarises common values and Table 2.2 block-specific values. In the absence of detailed evidence for behavioural differences between the blocks represented in our model, common values of behavioural parameters are used across regions. Only where we judge it particularly necessary, or where we have firm evidence for behavioural differences, we use block-specific values. Macroeconomic aggregates that characterise the steady state, like private and public consumption and investment, trade openness, and trade linkages are calibrated on block-specific data.

The discount factor for Ricardian households, β^r, is set at 0.997 for consistency with global long-run real interest rates. The discount factor for credit-constrained households, β^c, is set marginally lower at 0.967, to reflect impatience relative to Ricardian households. The loan-to-value ratio of credit-constrained households, $1-\chi$, is set at 0.75 in all regions, calibrated to fit a mortgage debt ratio as share of GDP of around 50 percent in the baseline. To assure compatibility with the balanced growth path, the intertemporal elasticity of substitution in consumption, σ_c, is set at 1. Utility in housing services, σ_{house}, is set in the same way to 1.

Habit persistence in consumption is set to 0.85 and in line with evidence from estimated versions of QUEST. The labour supply elasticity is set at 0.2, a value that is lower than in the standard DSGE literature, where the elasticity captures the responsiveness of labour supply to wages over the business cycle. Examples include Hristov and Huelsewig (2017) who estimate an elasticity of 0.8 for the EA, Ratto et al. (2009) who find a posterior value of around 0.5 for the EA in an estimated version of QUEST, and Kollmann et al. (2016) who report values of 0.4 for the EA and 0.5 for the US. Similarly,

Table 2.1. **Model parameters – common values**

Parameter	Value	Description
β^r	0.997	Discount factor Ricardian households
β^c	0.967	Discount factor credit-constrained households
$1-\chi$	0.75	Loan-to-value ratio
σ_c	4	Intertemporal elasticity of substitution in consumption
h	0.85	Habit persistence in consumption
σ_{house}	1	Preference parameter in housing
$1/\kappa$	0.2	Labour supply elasticity
γ^L	25	Head-count adjustment costs parameter
γ^P	20	Price adjustment costs parameter
$\gamma^{ucap,1}$	0.04(T); 0.03(NT)	Linear capacity-utilisation adjustment cost
$\gamma^{ucap,2}$	0.05	Quadratic capacity-utilisation adjustment cost
γ^K	20	Capital adjustment cost
γ^I	75	Investment adjustment cost
γ^W	120	Wage adjustment cost
γ^H	40	Adjustment costs to the housing stock
γ^{I^H}	75	Housing investment adjustment costs
sfp	0.9	Share of forward looking T price setters
γ^f	0.5	Adjustment cost parameter bilateral imports
γ^M	5	Adjustment cost parameter import prices
$sfpm$	0.5	Share of forward looking import price setters
sfw	0.9	Share of forward looking wage setters
$sfph$	1	Share of forward looking NT price setters

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[7] See for example in 't Veld et al. (2015), in 't Veld et al. (2011), Kollmann et al. (2013), and Kollmann et al.(2015).

$wrlag$	0.6	Real wage inertia
$sfphouse$	1	Share of forward looking house price setters
$sfpland$	1	Share of forward looking land price setters
σ_{tnt}	0.5	Elasticity of substitution T-NT
σ_x	1.2	Elasticity of substitution in total trade
σ_1	1.2	Elasticity of substitution between import sources
σ_L	0.3	Elasticity of substitution between land and construction services
α	0.65	Cobb-Douglas labour parameter
α_g	0.12	Cobb-Douglas public capital stock parameter
σ_{in}	0.5	Elasticity of substitution between value added and intermediates
$\overline{gs}$	0.09	Government purchases (share in GDP)
$\overline{igs}$	0.04	Government investment (share in GDP)
θ	6	Elasticity of substitution between types of labour
δ^T	0.015	Depreciation rate T capital stock
δ^{NT}	0.005	Depreciation rate NT capital stock
δ^g	0.013	Depreciation rate public capital stock
ρ_L	0.95	Persistence of potential employment
ρ_{ucap}	0.95	Potential capacity utilisation persistence
τ^b	0.01	Tax rule parameter on debt
τ^{def}	0.1	Tax rule parameter on deficit
ρ_i	0.6	Interest rate smoothing in Taylor rule
τ_π	2	Reaction to inflation in Taylor rule

Source: Commission services.

Campagne and Poissonnier (2018) use a value of 0.5. Setting a lower value in the present version of QUEST is motivated by the fact that long-term elasticities that matter for cross-country comparison and the assessment of structural reforms tend to be lower that elasticities over the business cycle, as discussed, e.g., in Chetty et al. (2011), and Chetty (2012). Setting the elasticity of substitution between types of labour, θ, at 6 implies a wage mark-up of 20% in the steady state. Concerning adjustment costs on labour, goods, housing and capital we broadly follow earlier QUEST-based estimates. The shares of forward-looking wage setters and tradable price setters, sfw and sfp, that determine the extent to which agents base their decisions on model-consistent expectations, are set to 0.9, whereas perfect foresight is assumed in the non-tradable area with $sfph = sfphouse = sfpland = 1$, and a more mixed behaviour in export pricing with $sfpm = 0.5$, in line with the higher estimates for the backward-looking component in import price inflation in Ratto et al. (2009) . The elasticity of substitution between tradables and non-tradables σ_{tnt} is set to 0.5 in line with the IMF's GIMF model (Kumhof, Laxton, Muir and Mursula, 2010). Price and wage adjustment cost parameters,which determine the slope of price and wage Phillips curves, i.e.the sensitivity of prices and wages to demand and supply shocks, are informed by evidence of average requencies of priceand wage adjustment in the EAand the US.

The output elasticity for public capital α_g is 0.12 in the benchmark setting, which corresponds to the average elasticity found by Bom and Ligthart (2014) in a meta-analysis for all public capital installed by national governments.[8] The tax rule parameters τ^b and τ^{def} are chosen to assure a smooth transition to the long-run debt target. In setting the reaction coefficient to inflation in the Taylor rule, τ_π, at 2 we closely follow the literature.

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[8] A sensitivity analysis is shown for the public investment shock that uses the higher estimate of 0.17 by Bom and Ligthart (2014) for core infrastructure investment.

Table 2.2. **Model parameters – block-specific values**

Parameter	Value						Description
	EA	Non-EA EU	U.S.	Emerging Asia	Japan	Rest of World	
s^r	0.6	0.6	0.6	0.4	0.6	0.5	Share of Ricardian households
s^c	0.2	0.2	0.2	0.2	0.2	0.2	Share of credit-constrained households
s^l	0.2	0.2	0.2	0.4	0.2	0.3	Share of liquidity-constrained households
$1 - npart$	0.71	0.71	0.71	0.71	0.71	0.76	Labour force to population
L	0.64	0.64	0.70	0.70	0.70	0.66	Steady state employment to population
L^g	0.13	0.14	0.12	0.14	0.13	0.11	Public-sector employment
$benrr$	0.40	0.40	0.35	0.30	0.35	0.30	Benefit replacement rate
$\overline{trs}$	0.16	0.16	0.15	0.15	0.15	0.12	Transfer share (share in GDP)
$1/\sigma_T$	0.12	0.12	0.12	0.12	0.12	0.12	Mark-up T sector
$1/\sigma_{NT}$	0.24	0.24	0.20	0.20	0.20	0.20	Mark-up NT sector
s^T	0.4	0.4	0.3	0.5	0.3	0.4	Steady-state share of T
s_m	0.22	0.33	0.24	0.14	0.20	0.24	Steady-state share of imports in T demand
s_{in}^T	0.73	0.76	0.62	0.71	0.67	0.62	Steady-state share of intermediates in output T
s_{in}^{NT}	0.50	0.59	0.45	0.62	0.48	0.46	Steady-state share of intermediates in output NT
s_{int}^T	0.67	0.61	0.72	0.84	0.70	0.79	Steady-state T intermediate share in T
s_{int}^{NT}	0.47	0.43	0.44	0.66	0.45	0.50	Steady-state T intermediate share in NT
$s^{EA,f}$	-	0.29	0.11	0.20	0.03	0.37	Share of bilateral imports of EA
$s^{NEA,f}$	0.56	-	0.07	0.13	0.02	0.22	Share of bilateral imports of Non-EA EU
$s^{US,f}$	0.16	0.05	-	0.28	0.06	0.44	Share of bilateral imports of U.S.
$s^{EMA,f}$	0.17	0.05	0.13	-	0.16	0.49	Share of bilateral imports of Emerging Asia
$s^{JA,f}$	0.08	0.03	0.13	0.43	-	0.33	Share of bilateral imports of Japan
$s^{RofW,f}$	0.17	0.10	0.37	0.33	0.03	-	Share of bilateral imports of Rest of World
$btar$	0.8	0.7	0.8	0.3	2.0	0.4	Baseline government debt-to-GDP ratio
τ_y	0.1	0.1	0.15	0.1	0.1	0.1	Reaction to output gap in Taylor rule

Source: Commission services.

Table 2.2 features block-specific parameter values. Concerning financial market frictions in advanced economies, we set the share of households with full access to financial markets to 60%, which is close to the estimated share of Ricardian households in Ratto et al. (2009), and the population share of credit-constrained households to 20%. We have little knowledge from estimated DSGE models about the share of credit- versus liquidity constrained households and assume half of the constrained households to be credit-constrained and the other half to be entirely liquidity-constrained. Guerrieri and Iacoviello (2017) estimate a wage share of 44% for the US and in 't Veld et al. (2014) a consumption share of 52% for Spain in models with only Ricardian and credit-constrained households. Our shares of credit- and liquidity-constrained households correspond to magnitudes reported in Ampudia et al. (2018), Dolls et al. (2012), and Kaplan et al. (2014) for Western countries. The survey evidence in Ampudia et al. (2018) suggests that 77% of EA households have significant liquid assets. Dolls et al. (2012) report shares of liquidity-constrained and credit-constrained households of together 33-56% for the EA and 27-74% for the US, depending on the criteria used (amount of wealth, home ownership, or self-reported credit constraints). Kaplan et al. (2014) estimate population shares of liquidity-constrained households of approximately 20% for the US, 20% or less for Australia, France, Italy, and Spain, and 30% for Canada, the U.K., and Germany. For emerging economies in our model, predominately grouped in the Emerging Asia and Rest of the world blocks, more difficult access to finance for households is reflected in a larger share of liquidity-constrained households and a smaller share of Ricardian

households. Data on labour force, population and employment are taken from national sources and aggregated for the corresponding blocks. The steady-state import share in demand for tradables and the share of intermediates in tradable and non-tradable sector production are based on input-output tables from the GTAP database (Narayanan and Walmsley, 2008). The shares of bilateral imports are based on the IMF Direction of Trade statistics and aggregated with removal of intra-area trade. The baseline government debt-to-GDP ratio reflects average debt-to-GDP ratios observed over the last 5 to 10 years. The mildly higher reaction coefficient to output in the Taylor rule for the US compared to other regions is motivated by the mandate of the Federal Reserve that suggests a relatively stronger focus on economic activity.

3. SIMULATION PROPERTIES

This section documents some main simulation properties of the QUEST model variant described in the previous section. Model properties are illustrated by the graphical response of key macroeconomic variables to shocks to the model. Results are shown for conventional monetary policy, domestic demand, risk premia, productivity, credit, government investment, unconventional monetary policy, and tariff shocks. The subsections present the impact of the respective shock on GDP, domestic demand components, trade, external balances, wages, employment, price levels, relative prices, interest rates, and public finances, and the spillover to economic activity in other regions. The presentation focuses on the EA as the domestic economy subject to shocks, except for tariff shock that we implement in the U.S. block of the model. For risk premia and productivity shocks we also present scenarios in which, based on empirical evidence, shocks are correlated between regions. We display impulse responses over 10 years for temporary shocks and over 20 years for permanent shocks for which the adjustment towards the new steady state is not completed within one decade.

We simulate the model with the TROLL software, which uses a Newton-Raphson solution algorithm to calculate the simultaneous solution to the equations of the model. As various endogenous variables in the model have leads, representing expectations about the value of these variables in future time periods, an assumption has to be made on the formation of expectations. We assume that expectations are model-consistent, i.e. each period's future expectations coincide with the model's solution for the future. In simulations, this means that the leads in the model equations are equal to the solution values from future periods. TROLL makes use of the Laffargue-Boucekkine-Juillard (LBJ) stacked-time algorithm that solves for multiple time periods simultaneously, i.e. it stacks the equations for the multiple periods into a system of equations and solves them simultaneously. The appendix and Roeger and in 't Veld (1997) provide more details on the model solution method.

3.1. MONETARY POLICY SHOCK

We first turn to the conventional monetary policy shock, which is a temporary shock to ε_t^M in the central bank's Taylor rule (49) in the EA part of the model. More precisely, the monetary policy shock is an exogenous reduction in the policy rate by 100 basis points (bp). The 100 bp reduction stays for two years and is phased out gradually thereafter through the endogenous policy rate persistence incorporated in the Taylor rule. The conduct of monetary policy is assumed to be standard in all regions of the model, i.e. following a Taylor rule and without binding zero-bound restriction.

The response of the domestic economy (EA) to the monetary policy shock is shown in Graph 3.1. EA real GDP increases by (at peak in year 2) 1.2% in response to the interest rate reduction. The rise in output is driven by the response of interest-sensitive domestic demand to the expansionary policy shock. Real private consumption and investment increase by about 0.7% and 2.8% (3.2% for real investment excluding housing) respectively. The interest rate differential leads to a depreciation of the euro against other currencies, which strenghtens exports. The effect of higher domestic demand dominates the terms of trade effect, which is mitigated by destination-market currency pricing, and leads to an increase in imports. Because of a relative increase in import prices the effect of the

monetary expansion and the associated exchange rate depreciation on the current account balance is small.

The strengthening of domestic demand (positive output gap) and the impact of euro depreciation on import prices (terms of trade deterioration despite domestic cost pressure) implies an increase in consumer price (CPI) inflation by 0.9 pp on impact. Employment increases (unemployment falls) temporarily due to the increase in labour demand and a sluggish response of the real wage.

The expansionary monetary shock reduces the government deficit-to-GDP ratio on impact by up to 0.3 pp. There are several factors contributing to the decline: Most directly, lower interest rates reduce the costs of servicing government debt, although the effect is mitigated by the 8-year average maturity of government debt in the model (the interest rate reduction only affects the return on newly issued debt). In addition, stronger domestic demand and economic activity increase direct and indirect tax revenues for given tax rates, and declining unemployment reduces government spending on unemployment benefits. Finally, stronger economic activity raises the denominator of the deficit-to-GDP ratio. The ratio of government debt to GDP declines by 1.4 pp on impact. The budget closure rule adjusts lump-sum taxes to stabilise government debt to GDP at its baseline level, so that debt to GDP returns to its baseline level after one decade.

The monetary stimulus only has a temporary real GDP effect, which are due to the sluggish price and wage adjustment. As relative prices reach their new equilibrium level after about three years and the real interest rate returns to its baseline level, real activity also returns to baseline.

The spillover effect from a monetary policy shock is a priori ambiguous because of offsetting demand and competiveness effects and the monetary policy response in the other regions to the euro devaluation. As can be seen from Graph 3.2, the GDP spillover is slightly positive and the current account is slightly negative. This suggests that the positive GDP spillover is due to an expansionary monetary policy response in the other regions to the depreciation of the euro. The positive spillover is moderate in size, however, peaking at 0.04% for the world excluding the EA. The 1.2% EA GDP increase is associated on impact with 0.2% real GDP increase in non-EA EU countries, which is the largest regional spillover given the strongest trade linkages[9], and 0.02% and 0.04% real GDP increase in the U.S. and Emerging Asia (EMA), respectively.
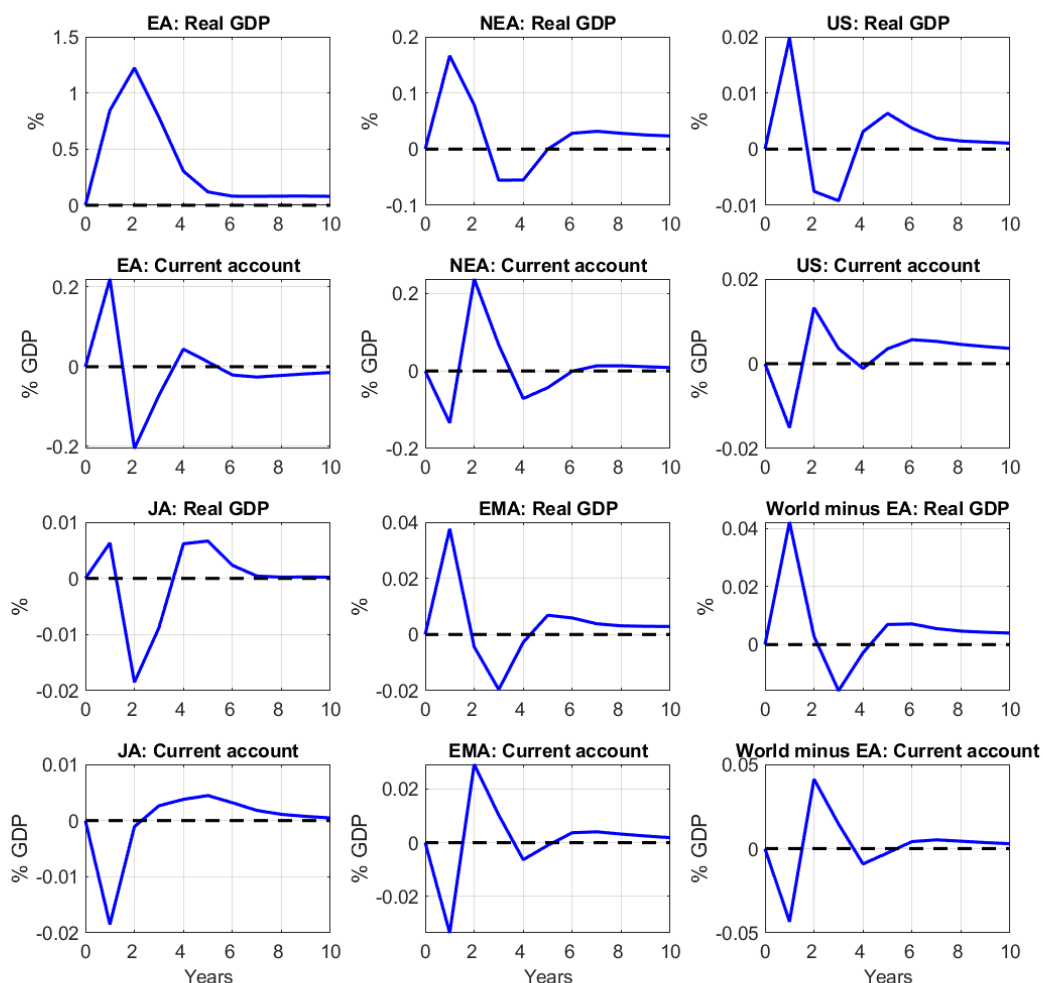
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[9] About 29% of EA imports come from non-EA EU countries plus the UK according to the trade matrix to which the model's trade linkages are calibrated.

Graph 3.1. **Conventional monetary policy shock - EA economy response**
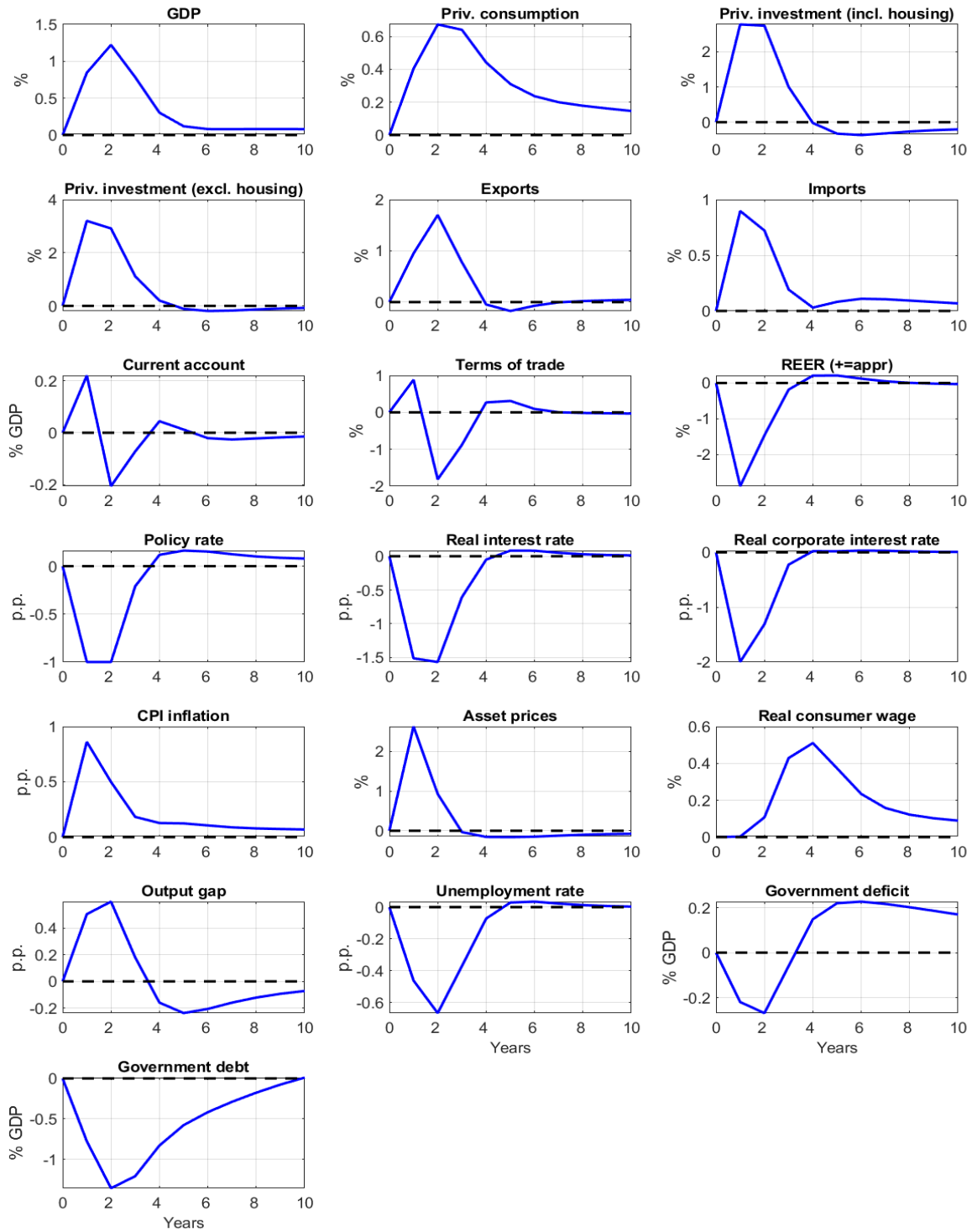
Source: Commission services.

Graph 3.2. **Conventional monetary policy shock - spillover**

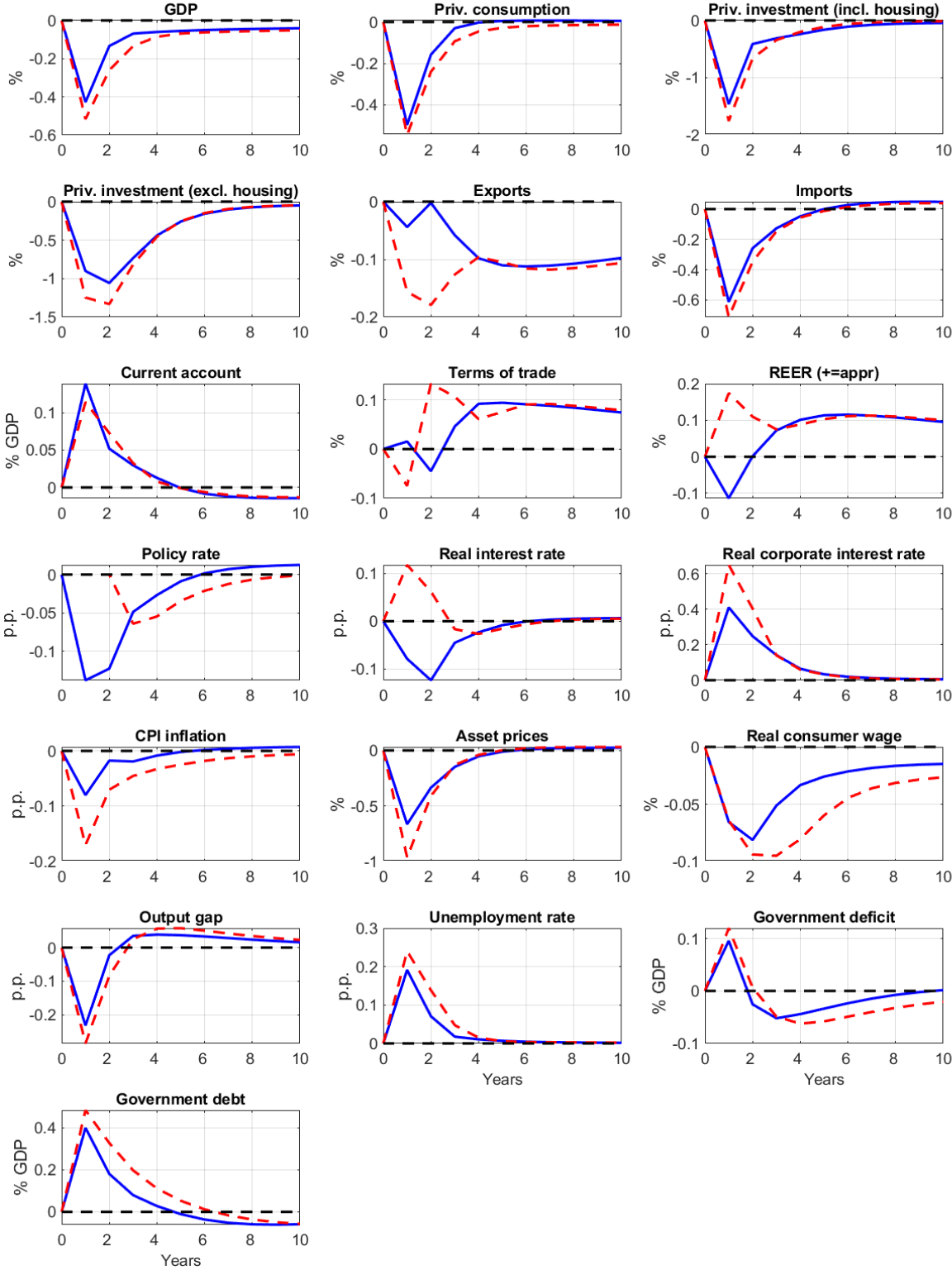
Source: Commission services.

3.2. PRIVATE DOMESTIC DEMAND SHOCKS

This sub-section discusses impulse responses for negative shocks to private domestic demand in the EA. In particular, the scenario combines a tightening of the credit constraint for credit-constrained households, which is a decline in the leverage ratio $1 - \chi$ in equation (27) by 20 pp, with an increase, by annualised 200 basis points, in investment risk, or financing costs, for productive capital and housing investment. The risk premium shock to productive investment is an increase in $\varepsilon_t^{rK,J}$ in equation (18) that generates an increase in the wedge between the return on capital i_t^J in both production sectors and the safe interest rate i_t. The housing risk shock is an increase in ε_t^{rH} and ε_t^{cH} in equations (18) and (27) respectively. The shocks are temporary, but persistent, lasting for one year in full, before decaying gradually. The shocks lead to lower consumption and (productive and construction) investment in the domestic economy. The relative size of the two shocks is such that the per-cent decline in investment is 3-4 times larger than the per-cent decline in consumption.

Graph 3.3 displays the responses of domestic variables under two alternative assumptions on monetary policy. Solid blue lines show impulse responses for the situation in which monetary policy follows the standard Taylor rule in all model regions; dashed red lines are for a setting in which nominal short-

term interest rates remain constant during the first two years, mimicking a situation in which the ZLB on nominal interest rates is temporarily binding.

Graph 3.3. **Private domestic demand shock - EA economy response**
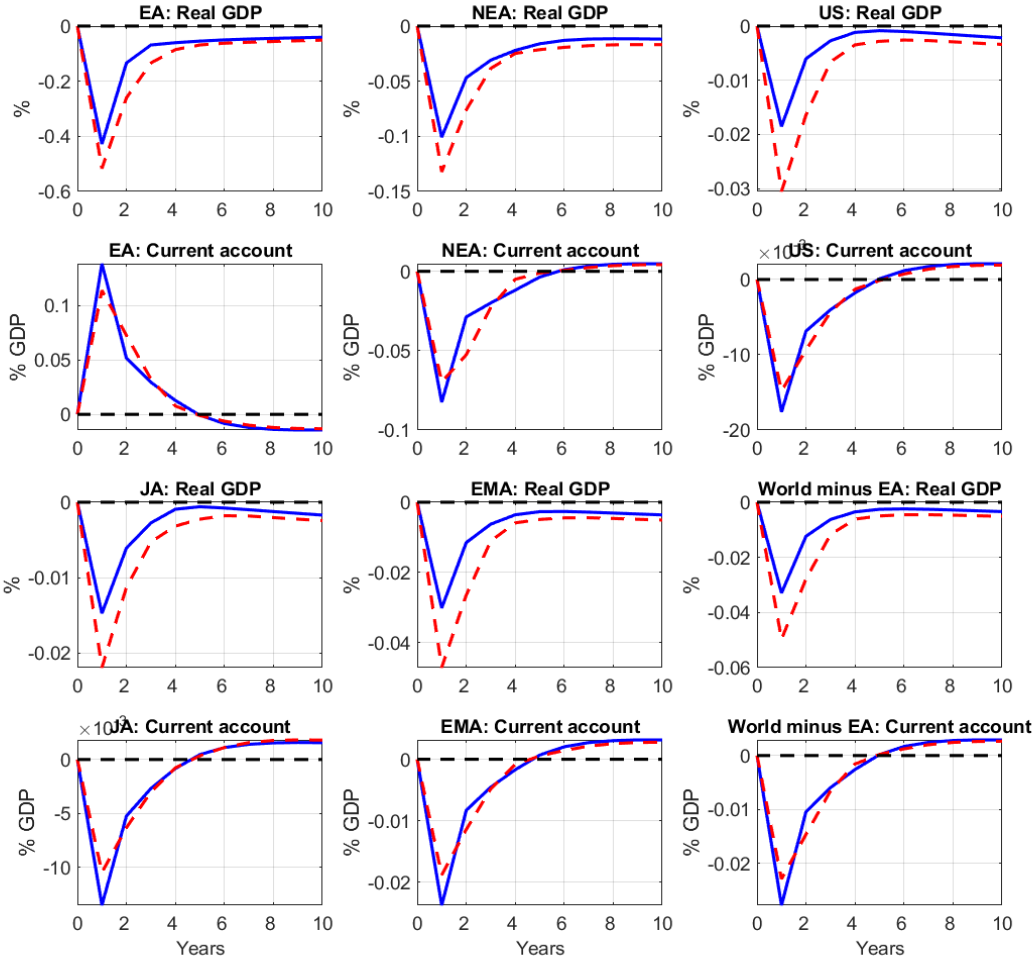

Note: Solid blue lines depict responses with standard monetary policy; red dashed lines depict responses when the zero-interest-rate floor binds in the initial two years.

Source: Commission services.

The initial 0.4% decline of EA real GDP in the scenario without ZLB is driven by a 0.5% fall in real private consumption and 1.5% reduction in real private investment (1.1% for real investment excluding housing) on impact. On the side of trade, imports decline in response to weak domestic demand, whereas pricing in destination-market currency mutes the positive response of export demand to exchange rate depreciation. The trade balance and the current account relative to GDP improve on impact (0.1 pp). Employment and the real wage decline (unemployment increases) due to the fall in labour demand. The short- and medium-term impact of the negative demand shocks is more severe at the ZLB, where EA real GDP drops by 0.4% on impact, driven by 0.5% decline in private consumption and 1.8% decline in private investment.

Without binding ZLB constraint, falling domestic activity and below-target inflation (-0.1 pp for CPI inflation on impact) trigger a temporary reduction in the monetary policy rate (-0.1 pp on impact) and an associated decline in the real interest rate (-0.1 pp). With initially binding ZLB (during the first 2 years), monetary expansion is delayed and the real interest rate rises on impact, which adds to deflationary pressure. The additional negative impact on domestic demand is small. However, the increase in the real interest rate leads to capital inflow, which appreciates the euro and reduces exports.

Graph 3.4. **Private domestic demand shock - spillover**

Note: Solid blue lines depict responses with standard monetary policy; red dashed lines depict responses when the zero-interest-rate floor binds in the initial two years.

Source: Commission services.

The demand contraction in Figure 3.3 increases the government deficit-to-GDP ratio by up to 0.1 pp due to lower direct and indirect tax revenues and higher expenditure on unemployment benefits; weaker economic activity also lowers the denominator of the deficit-to-GDP ratio. The ratio of government debt to GDP increases by 0.4% on impact. The government debt-to-GDP ratio increases more strongly and persistently in the ZLB case. The non-reduction in real interest rates under the ZLB contributes to the stronger initial debt increase, but the effect is moderate and gradual given the 8-year average maturity of debt in the model. A stronger impact comes from the stronger price level decline in the ZLB case, which implies a persistent reduction in nominal GDP compared to the scenario with standard monetary policy. The persistent drop in nominal GDP reduced the denominator of the debt-to-GDP ratio.

Spillover (Graph 3.4) from lower EA private sector demand to real GDP and the current accounts in the other regions is negative on impact due to lower exports to the EA. The size of spillover depends on the region and its trade linkages with the EA. The GDP spillover is strongest for the non-EA EU (around -0.1% on impact), and weaker for Japan, Emerging Asia, and the U.S. (real GDP decline by between -0.01% and -0.02%) on impact.

3.3. INTERNATIONAL RISK PREMIUM SHOCK

This sub-section presents results for a combination of adverse corporate ($\varepsilon_t^{rK,J}$ in equation 18) and housing investment (ε_t^{rH} and ε_t^{cH} in equations 18 and 27, respectively) risk premium shocks that are common across main economic regions (EU, U.S., and Japan). On impact the corporate nominal interest rate is increasing by 100 bps for two consecutive years. Afterwards the shock vanishes over time, with an AR(1) parameter of 0.84 at quarterly frequency.

Standard open-economy DSGE models have difficulties in replicating observed degrees of business cycle co-movements across countries. Academic research has pursued different avenues to generate stronger cross-country transmission of financial and real-sector shocks, notably the inclusion of internationally operating banks on the financial side and trade in intermediate inputs, capturing the idea of integrated value chains on the production side (see Box 3.1). Trade in intermediates is included in this paper's version of QUEST as explained in section 2 along with other spillover channels (see Box 3.2). Nevertheless, endogenous international spillover remains moderate as shown in Figure 3.4 for the EA private demand shock and confined mainly to trade exposure.

> Box 3.1. **SPILLOVER IN DSGE MODELS**
>
> The problem for DSGE models to generate and reproduce sizable spillover effects is well recognised in the literature. Justiniano and Preston (2010) in a well-known paper estimated an open-economy model for the Canadian economy during 1982-2007. The authors found that U.S. factors explained no more than 1% of output and inflation fluctuation in Canada, which is at odds with reduced-form evidence by a large margin. Starting from the finding of negligible spillover in the standard New Keynesian (NK) model the literature has discussed and developed model extensions to strengthen the amount of international spillover. This box summarises findings from this line of research on the basis of selective examples from the literature.
>
> A first avenue, explored by Justiniano and Preston (2010) themselves, is to relax the assumption of independent disturbances and allow for the existence of common or cross-country spillover between shocks (examples could include global commodity price shocks, financial panics, or technological innovations). In the example of Justiniano and Preston (2010) correlation of shocks lifts the co-movement in output and inflation volatility between Canada and the U.S. from 1% to around 10-20%, which is similar to data for the short horizon, but falls short of replicating the cross-country co-movement over the medium term. Similarly, Chen and Crucini (2016) study business cycle co-movement with internationally correlated technology shocks. Alpanda and Aysun (2014) show in an estimated two-country model with the euro area (EA) and the U.S. that allowing for cross-border correlation in financial shocks considerably improves the ability to replicate international co-movement in macroeconomic time series. Aysun (2016) also uses an estimated EA-U.S. two-country model and shows that common or correlated demand and financial shocks can replicate the EA-U.S. co-movement in economic activity, demand and inflation found in the data.

A second avenue enriches the modelling of international linkages to increase the potential of endogenous transmission between countries. Bergholt and Sveen (2014) focus on trade integration, extent the standard one-sector NK model to two sectors (manufacturing and services) that differ in terms of technology, trade linkages and adjustment frictions, and emphasise the role of trade in intermediates for the international transmission of shocks. In particular, Bergholt and Sveen (2014) analyse spillover from technology shocks and conclude that trade in intermediate inputs propagates important characteristics of technology shocks across countries. A positive technology shock in the foreign economy, e.g., has similar implications for the domestic country that imports intermediate goods, because cheaper imported intermediate inputs reduce production costs in the domestic economy and move the supply curve to the right. According to Bergholt and Sveen (2014) the two-sector model with trade in intermediates generates cross-country correlation in GDP growth of more than 0.7 in response to technology shocks and attributes 60% of domestic GDP volatility to foreign shocks, which is similar to the longer-term values of Canada-U.S. co-movement reported by Justiniano and Preston (2010). One can add that trade in intermediates also dampens the negative cross-country correlation in output in response to shocks moving the nominal exchange rate. In particular, the price competitiveness loss associated with domestic currency appreciation is mitigated by the reduction in the domestic-currency price of imported intermediate inputs. Duval et al. (2016) also provide evidence for the importance of global supply chains for international business cycle correlation.

Cross-border exposure of banks and portfolio holdings is another area of modelling through which international linkages can generate significant endogenous co-movement and spillover in economic activity. Not surprisingly, this line of research has become particularly prominent in the aftermath of the global financial crisis. Alpanda and Aysun (2014) introduce cross-border bank lending in an EA-U.S. model and show that the channel strengthens spillover in economic activity, although spillover from this endogenous propagation is more moderate than the co-movement achieved by allowing for internationally correlated shocks in the model. Iacoviello and Minetti (2006) build a model with differences in credit frictions for domestic and foreign lenders. The model generates co-movement in economic activity, which, however, still falls short of the positive correlation in real GDP growth between European countries and the U.S. The paper by Ueda (2012) builds a model with credit constraints and financial intermediaries that engage in cross-border borrowing and lending. Adverse shocks in one country propagate to other countries in this set-up and lead to business cycle synchronisation in goods, factor and financial markets. In a similar spirit, Kollmann et al. (2011) introduce a global bank with cross-border deposits and loans and a capital requirement in a two-country model to generate endogenous transmission of (large) loan losses that lead to simultaneous declines in economic activity. The estimated EA-U.S. model version by Kollmann (2013) equally concludes that financial shocks generate positive co-movement in economic activity in the presence of internationally operating financial intermediaries with credit frictions.

The choice between model extensions has implications for the pattern of macroeconomic spillover and co-movement across countries. Modelling global value chains strengthens the transmission of shocks in the real economy, including its supply side. Strengthening financial linkages reinforces particularly the transmission of financial shocks. The different mechanisms also have implication for the relative strength of co-movement across macroeconomic variables. The integration of value chains tends to increase output correlation across countries for given levels of domestic demand. Financial linkages, to the contrary, generate the cross-country co-movement in economic activity primarily by strengthening the cross-country co-movement in domestic demand. Prima facie, financial transmission channels alone appear therefore less suited to replicate episodes in which the co-movement in economic activity exceeds the co-movement of domestic demand across countries. Backus et al. (1992) in an early paper found that GDP co-movement exceeded consumption co-movement for some country pairs, whereas the opposite pattern, i.e. consumption co-movement exceeding GDP co-movement, prevailed at the sample average. Financial channels with occasionally binding constraints, finally, emphasise the possibility of state-dependent spillover. Financial contagion and the tightening of borrowing constraints in these models amplify co-movement across countries in periods of deep recession without generating a symmetric co-movement during booms.

Box 3.2. **SPILLOVER CHANNELS IN THE QUEST MODEL**

Simple open-economy versions of the New Keynesian model tend to produce small endogenous cross-country spillover and co-movement in macroeconomic variables. The version of QUEST used in this paper goes beyond the simple model by adding trade in intermediate inputs. Trade in intermediates generally strengthens the positive correlation of output across countries with integrated value chains. This box sketches the international transmission to aggregate demand, aggregate supply and financial shocks in the model to illustrate these points.

Consider, first, a positive shock to aggregate demand in the domestic economy. This shock leads to an increase in domestic activity and import demand as the most direct source of positive GDP spillover and co-movement. With trade in intermediate inputs, the positive spillover to import demand and foreign GDP relates to import of final goods and imports of intermediate inputs into domestic production.

Stronger domestic activity and inflation pressure will also imply some tightening of domestic monetary policy in "normal" times. The monetary tightening partly offsets the domestic demand expansion, which weakens import demand, but it also causes nominal and real appreciation of the domestic currency, which strengthens import demand due to substitution from domestic goods towards cheaper imports.

The monetary policy response strengthens imports and positive GDP spillover when the price elasticity of import demand (substitution effect) is high enough to offset the negative impact from dampening domestic demand (income effect). The price elasticity of trade, however, is limited in our model in the short and medium term, primarily due to the assumption of destination or importer currency pricing (also referred to in the paper as "pricing to market") that implies that prices are sticky in destination market currency. The appreciation of the exchange rate does not improve the price competitiveness of imports on impact in this case. It rather increases the export revenue in foreign exporters' currency. The latter effect does not strengthen foreign exports to the domestic economy, but it should positively affect activity in the foreign economy through a positive income effect. Additionally, the model includes sluggish adjustment of imports to changes in the relative price, which also reduces the prices elasticity of trade in the short and medium term.

The model does not include financial market channels other than the monetary policy response to higher domestic demand and the related exchange rate dynamics that would affect the international transmission of the demand shock in the short and medium term. The model includes a country risk premium that depends on the economies net foreign asset (NFA) position. Notably, the risk premium increases and leads to an increase in domestic interest rates when the NFA position deteriorates. The mechanism ensures that borrowing from abroad and net import demand remain bounded in the long term as explained by Schmitt-Grohé and Uribe (2003).

The transmission of a positive shock to aggregate supply in the domestic economy has an ambivalent impact on net trade and international spillover. The positive supply shock, e.g. a positive shock to total factor productivity (TFP), increases real income in the domestic economy. The positive income (or, wealth) effect strengthens domestic demand and the demand for imports. The reduction in the policy rate that the Taylor rule implies in response to higher potential output and lower inflation pressure further strengthens interest-sensitive components of domestic demand.

Lower production costs and a policy-induced depreciation of the nominal exchange rate also improve the competitiveness of domestic goods (substitution effect) if lower production costs and nominal depreciation reduce the foreign-currency price of domestic goods. With trade in intermediates, the competitiveness gain shifts more towards trade in intermediate inputs. Foreign goods take advantage of cheaper intermediates from the domestic economy that reduces foreign production costs. In this regard, as discussed by Bergholt and Sveen (2014), the spillover through cheaper intermediate imports is similar to a positive technology shock in the foreign region itself.

The assumption of importer currency pricing in the model dampens the competitiveness effect, however.

The income effect still raises import demand in the domestic economy, where-as the substitution from foreign to domestic intermediate and final goods, which would strengthen net exports, is weakened or even absent in the short and medium term. Instead of improving price competitiveness, nominal rigidity in importer currency prices raises the profits of exporters in the domestic economy in response to a positive TFP shock, which strengthens domestic demand and related imports. The co-movement in real GDP between the domestic and the foreign economy should become more positive if weaker real effective depreciation of the domestic currency dampens the competitiveness effect. In addition, as in the case of the demand shock, there is sluggish adjustment of trade volumes to changes in demand that mitigates spillover in the short and medium term.

The inclusion of investment demand in the model should also increase positive spillover in the short and medium term. In particular, persistent positive TFP shocks raise the profitability of investment in the domestic economy. Investment demand increases, which also raises the demand for (net) imports and deteriorates the trade balance. The increase in import demand is weaker in a model with only (Ricardian) consumption. The Ricardian households tend to smooth the use of additional income from a temporary TFP shock over time, which leads to an improvement in the trade balance, as described in Backus et al. (1992).

The financial shocks have limited particular impact on spillover in the model given the absence of globally operating intermediaries that transmit changes in financial conditions across countries. The model includes shocks to the borrowing capacity of credit-constrained households, which are introduced as shock to the loan-to-value (LTV) ratio. These shocks act as shocks to domestic consumption demand. The transmission to domestic GDP, trade and foreign economic activity is therefore similar to the transmission of savings shocks to Ricardian households' consumption demand or investment risk shocks to investment demand. Shocks to country (currency) risk premia, as another type of financial shock, affect the nominal ex-change rate for given interest rate differentials. In particular, an increase in the risk premium will lead to depreciation of the domestic currency.

Currency depreciation triggers substitution effects in international trade when goods are prices in producer currency. Importer currency pricing, which is adopted in this paper, dampens the competitiveness and substitution effect in the short and medium term for intermediate inputs and final goods. Depreciation of the domestic currency rather leads to increasing export revenue in domestic currency terms and less imported inflation compared to producer currency pricing. The result is a more positive response of domestic demand to the currency depreciation, but a less positive net export response. Investment declines dues to the capital outflow triggered by the risk premium shock.

Financial contagion has arguably been important for international co-movement during the financial crisis. Empirical evidence (see Box 3.3) on the co-movement of financing costs across world regions supports the idea of financial spillover. Against this background, the simulation in this subsection imposes positive co-movement of risk premia across the EA, non-EA EU plus the UK (NEA), U.S. and Japan to account for the well-documented co-movement between financially integrated regions and to compensate for missing channels of financial contagion in the model. Hence, the 100 bp shock described above is applied simultaneously to the EA, NEA, U.S. and Japan in the following scenario.

Box 3.3. **EMPIRICAL EVIDENCE FOR INTERNATIONAL SHOCK CORRELATION**

Box 3.1 above has reviewed the ability of DSGE models to capture spillover and co-movement in economic activity across countries and regions. As shown by several studies (e.g. Alpanda and Aysun 2014, Aysun 2016, Chen and Crucini 2016, and Justiniano and Preston 2010), allowing for cross-country correlation in real and financial shocks amplifies cross-country co-movement in economic activity.

Co-movement in economic activity is also observed across the regions of the world economy that are included in this paper's model configuration. Table 1 shows the cross-correlation of the annual growth rates of GDP for the euro area (EA), the rest of the EU plus the UK (NEA), the Unites States (US), emerging Asia (EMA), Japan (JA), and the rest of the world (RoW). Data cover the period 1996-2013 and exclude the global recession, during which business cycles have been strongly synchronised around the globe.

Table 1. **Correlation of annual GDP growth - 1996-2013 (excl. 2008-2010)**

	EA	NEA	U	R	EMA	JA
EA	1					
NEA	0.75	1				
US	0.44	0.69	1			
RoW	0.46	0.42	0.17	1		
EMA	0.28	0.23	-0.16	0.54	1	
JA	-0.05	0.20	0.01	0.59	0.63	1
St. Dev. (in %)	1.31	1.09	1.19	1.25	1.71	1.28

Source: AMECO

 The country composition of regions here differs to some extent from the composition in the model. Notably, NEA includes only Denmark, Sweden and UK; EMA includes China, India, Indonesia and Korea; the RoW comprises Australia, Brazil, Canada, Mexico, New Zealand, Norway, Russia, Switzerland and Turkey.

The data indicate that the dispersion of growth rates around there mean has been similar across regions, with NEA at the lower and EMA at the upper end of the distribution. The positive co-movement of growth rates has been particularly pronounced between the EA and the NEA, which is unsurprising given the strong trade linkages between the two regions. Similarly, co-movement has been comparably strong between the U.S. and NEA and between Japan and EMA. The Japanese business cycle, to the contrary, appears largely decoupled from the EA and the U.S.

The data also point to a strong cross-regional co-movement of changes to productivity (TFP) growth as indicated in Table 2, which provides the empirical rationale for considering a scenario with cross-regional correlation of TFP shocks. Co-movement of the changes in trend productivity appears particularly pronounced between the U.S. and EU countries. Japan appears to be largely detached from the U.S., whereas innovations to EMA productivity growth are negatively correlated with all other regions.

Table 2. **Correlation of trend TFP growth rates - 1996-2011 (excl. 2008-10)**

	EA	NEA	U	R	EMA	JA
EA	1.00					
NEA	0.54	1.00				
US	0.58	0.80	1.00			
RoW	0.29	0.77	0.87	1.00		
EMA	-0.45	-0.30	-0.66	-0.55	1.00	
JA	0.29	0.51	0.04	0.32	0.42	1.00
St. Dev.	0.03	0.14	0.08	0.04	0.11	0.05

Notes: Correlation of second differences of the logarithm of trend TFP; EA series covers only 1997-2011

Sources: AMECO for EA, NEA, US and JA; own calculations based on Penn World Tables for EMA and RoW.

Data also display cross-regional correlation of short-term interest rates, monetary policy shocks and financial risk. Table 3 displays the correlation of short-term interest rate differentials towards the U.S. for the different regional blocks at annual frequency. The table suggests that the EA and Japan have been moving closely together in terms of interest rate differentials towards the US, whereas correlation between the EA, on the one side, and the NEA or the RoW, on the other side, has been moderate.

Table 3. **Correlation of interest rate differentials with US - 1996-2011 (excl. 2008-10)**

	EA	NEA	US	RoW	EMA	JA
EA	1.00					
NEA	0.22	1.00				
US			1.00			
RoW	0.11	0.79		1.00		
EMA	0.44	0.59		0.75	1.00	
JA	0.86	-0.09		-0.17	0.30	1.00
St. Dev. (in %)	1.32	1.92		4.29	2.51	1.91

Notes: Correlation of interest rate differentials with US.

Sources: EA, NEA, U, JA are from AMECO; ROW and EMA are own calculations based on IMF WEO and IFS data.

Positive co-movement of interest rate differentials does not reveal the source of co-movement. The co-movement can be endogenous, i.e. the economies' business cycles move together and lead to similar monetary policy stances, or endogenous, i.e. the central banks deviate in similar ways from their standard response to output and inflation.

Table 4 provides evidence for the exogenous part of co-movement. It shows the cross-regional correlation of monetary policy shocks for the EA, NEA and the U.S. economies. The shocks are retrieved by estimating Taylor rules with inflation, output growth and endogenous interest rate persistence for each of the blocks. NEA is proxied by the UK, which is the largest economy of this region, and German policy rates are used for the EA region in the years prior to EMU.

The results in Table 4 show a positive correlation between the monetary policy shocks across the three regions, which suggests that central banks have deviated in similar ways from the policy rates suggested by the Taylor rule. The co-movement is likely to capture the reaction to factors omitted in the estimated Taylor rules and the Taylor rules in the QUEST model, such as global commodity price shocks, (soft) exchange rate targets, or (leaning against) particular financial market developments.

Table 4. **Correlation of monetary policy shocks - 1996-2013 (excl. 2008-10)**

	EA	NEA	U
EA	1		
NEA	0.51	1	
US	0.55	0.39	1
St. Dev. (in %)	0.44	0.84	0.79

Notes: Correlations of residuals from Taylor rule estimations for EA (GER until 1998), UK (NEA) and US.

Source: Own calculations based on annual data.

Finally, there is also evidence in the data for the cross-regional co-movement of financial risk indica-tors. Table 5 shows the correlation across the regions of average corporate bond spreads for the peri-od 1997-2013. Spreads for the EA, the UK and the U.S. have moved closely together, whereas Japan has been rather decoupled from the former and moved more closely with EMA and the RoW.

Table 5. **Correlation of corporate bond spreads - 1997-2013 (excl. 2008-10)**

	EA	UK	US	RoW	EMA	JP
EA	1.00					
UK	0.97	1.00				
US	0.84	0.75	1.00			
RoW	0.42	0.27	0.77	1.00		
EMA	0.37	0.46	0.41	0.35	1.00	
JP	0.01	0.09	0.04	0.70	0.69	1.00
St. Dev. (in bps)	84.46	81.61	60.78	112.12	133.69	30.87

Note: Annual data.

Sources: Bank of America Merrill Lynch; FRED St. Louis Fed.

Table 6. **AR(1) coefficients on corporate bond spreads – 1997q1-2007q4**

	EA	UK	US	RoW	EMA	JP
AR(1)	0.84*	0.84*	0.76*	0.89*	0.63*	0.82*

Note: Quarterly data, R on 1999q1:2007q4, EMA on 1992q2:2007q4.

Sources: Bank of America Merrill Lynch; FRED St. Louis Fed, significant at 1% level.

Table 7. **Correlation of residuals of AR(1)on quarterly corporate bond spreads – 1997q1-2007q4**

	EA	UK	US	R	EMA	JP
EA	1					
UK	0.76	1				
US	0.76	0.72	1			
R	0.73	0.55	0.63	1		
EMA	0.40	0.36	0.39	0.12	1	
JP	0.14	0.00	0.29	0.14	0.29	1
St. Dev. (in bps)	28.23	26.00	30.30	54.62	47.80	19.88

Note: Quarterly data, R on 1999q1:2007q4, EMA on 1992q2:2007q4

Sources: Bank of America Merrill Lynch; FRED St. Louis Fed at 1% level.

Autoregressions for the corporate bond spreads further indicate a similar persistence in risk premia (see Table 6 for quarterly frequencies) in the largest economies (EA, UK, U.S., Japan) and strong positive correlation in the innovations recovered by these risk-premia regressions (Table 7).

The response of the domestic economy to the risk premium shock is shown in Graph 3.5. A marked difference between the scenario with normal monetary policy response (solid line) and with a binding zero-interest-rate (dashed line) can be observed. In the first case real GDP drops by 0.4% in year 2. This decline is driven by a reduction in real consumption, a strong fall in investment; total investment down by 2.6% in year 2.

Under the normal monetary policy assumptions, the central bank can attenuate the adverse effect of the risk premium on the real corporate interest rate by decreasing the policy rate. The policy rate is reduced sufficiently to reduce the risk-free real rate despite the decline in the inflation rate. Under ZLB-constrained monetary policy, the real interest rate increases, causing a stronger drop in both

private investment and private consumption. This causes an even stronger decline of the inflation rate, which amplifies the initial negative shock on private demand via its effect on the real interest rate. In the short and medium term, the adverse impact of higher risk premia on domestic demand is compensated partly by an increase in net exports under both monetary regimes, driven in particular by lower import demand.
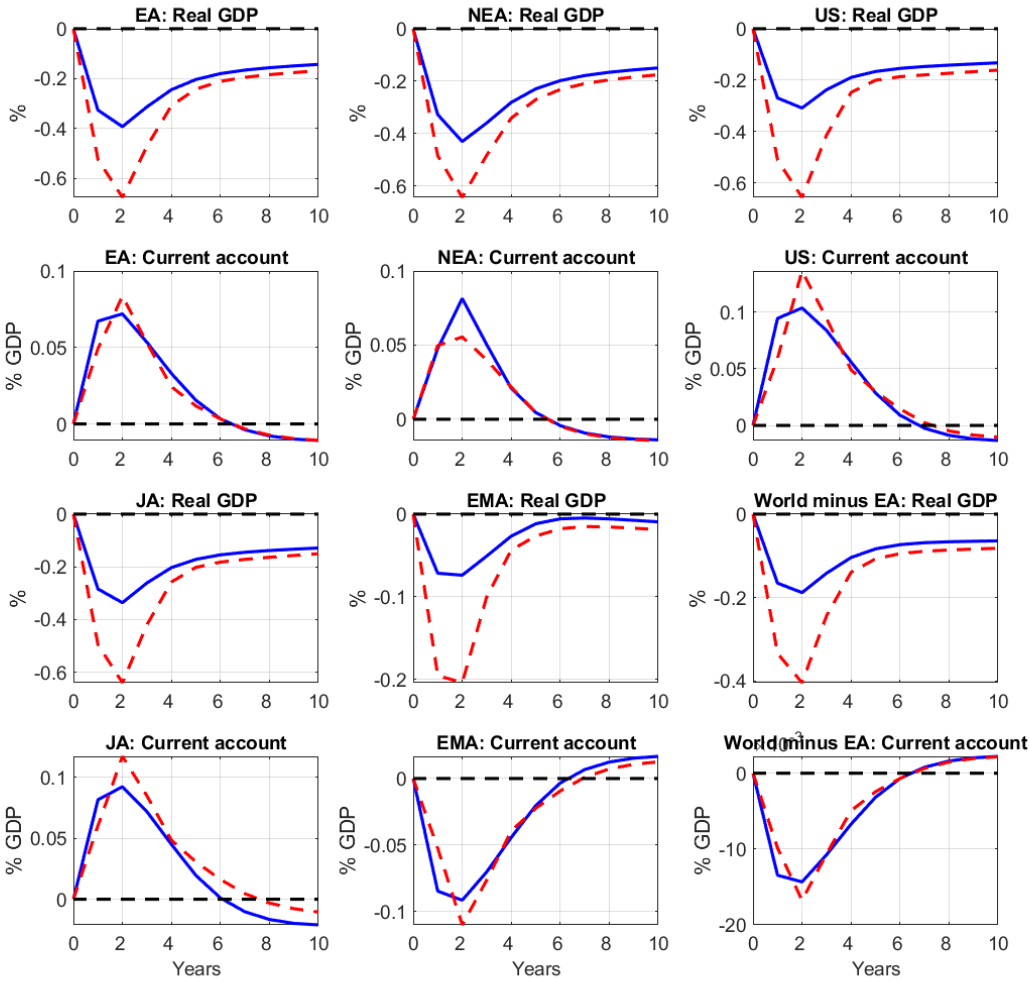
Graph 3.5. **International risk premium shocks - EA economy response**
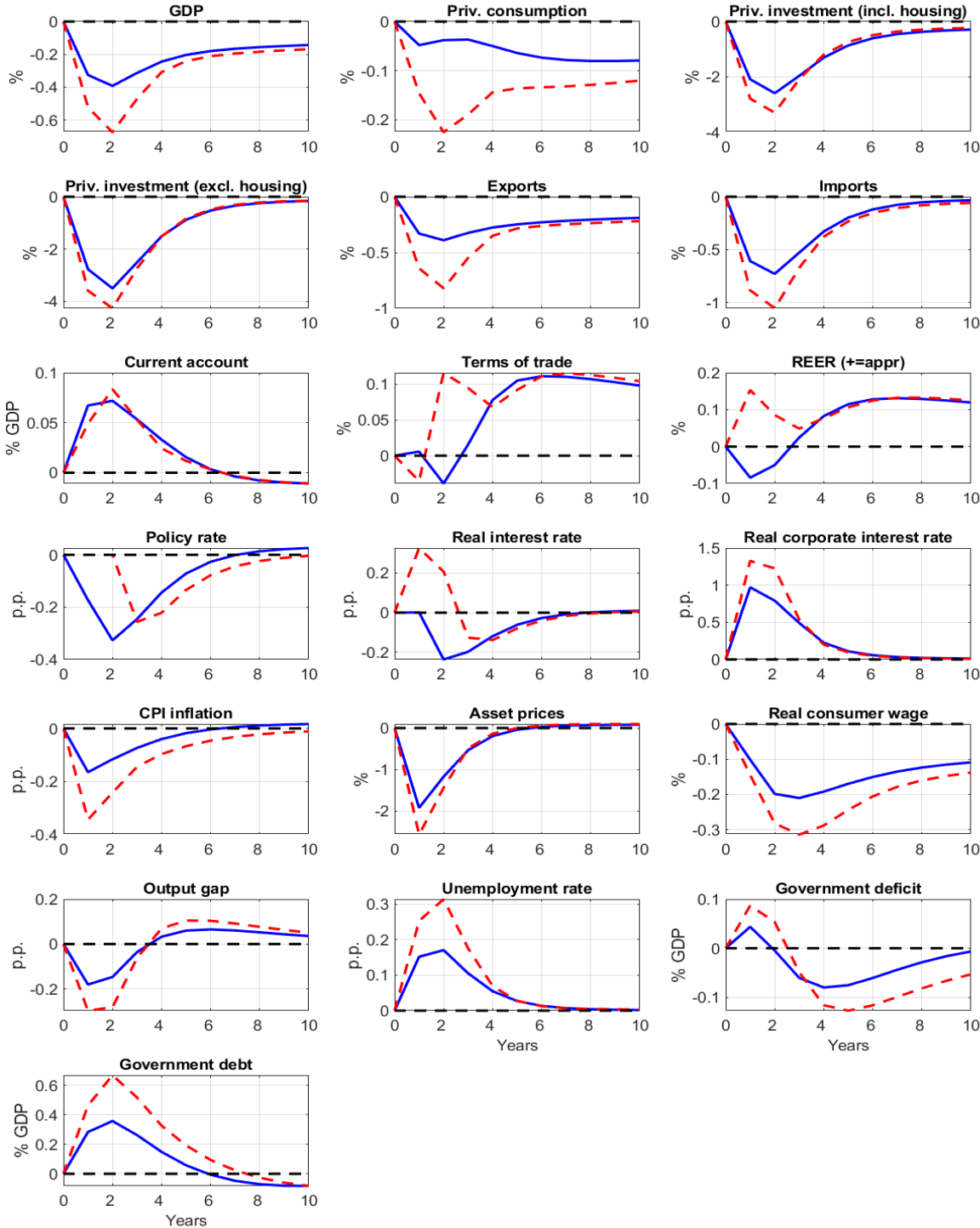
Note: Solid blue lines depict responses with standard monetary policy; red dashed lines depict responses when the zero-interest-rate floor binds in the initial two years.

Source: Commission services.

The swift reduction in interest rates and, consequently, the gradual decline in government bond yields and associated lower debt servicing costs, less adverse tax base effects and the less pronounced decline in the price level and nominal GDP in the scenario with monetary accommodation explain the discrepancy between the two scenarios with respect to the evolution of government deficit and debt.

Given that the risk premium shock in this sub-section is assumed to occur in EA, NEA, U.S. and Japan at the same time, co-movement of economic activity between these regions is strong. Graph 3.6 shows that the real GDP of the four regions declines to similar extent, given the same shock size and duration. Spillover to EMA is negative, because lower activity in EA, NEA, U.S. and Japan shrinks the market size for EMA exporters. The negative impact on GDP in EMA is mitigated by stronger EMA investment, however, as capital flows to the region in response to higher investment risk in industrialised countries.

Graph 3.6. **International risk premium shocks - spillover**

Note: Solid blue lines depict responses with standard monetary policy; red dashed lines depict responses when the zero-interest-rate floor binds in the initial two years.

Source: Commission services.

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3.4. PERSISTENT SHOCK TO TECHNOLOGY GROWTH

In the aftermath of the 2009 financial crisis, a significant slowdown of TFP growth has been observed in many countries, which is one reason for a protracted growth slowdown. The TFP slowdown may be a consequence of increased financial frictions that make it more difficult for new innovative firms to enter the market, or for incumbents to finance the adoption of new technologies, as argued by Anzoátegui et al. (2016), and Varga et al. (2016). In this sub-section, we present a scenario in which TFP growth is temporarily, but persistently lower in the EA. The persistent shock to TFP growth implies a permanent decline in the TFP level, $\varepsilon_t^{TFP,J}$ in equation (4), by 1.5% within 15 years.

Endogenous international spillover of technology shocks is moderate in the model, due to partly offsetting income and competitiveness effects and the limited number of transmission channels, notably trade in intermediate and final goods; see Box 2 for a discussion. There is strong evidence for a strong correlation between technology shocks across blocks, however, associated, e.g., with technology diffusion. To account for the co-movement between shocks, we use the approach described by Andrle et al. (2015) to calibrate the correlation between shocks. It implies that 50% of the EA TFP shock spill over to TFP in the NEA, 28% to TFP in EMA (proxied by spillover to China), 12% to TFP in Japan, and 7% to TFP in the U.S.

Graph 3.7 shows the domestic economy's response to the technology shock. Real GDP declines gradually for two decades and is subsequently levelling off at around -2%. The permanent negative supply shock signals a reduction of future (permanent) income and therefore also leads to a decline of private consumption and housing investment (at -1.3% after 20 years). Under normal monetary policy, corporate investment responds negatively only with a lag, because of a reduction of the monetary policy rate on impact. However, eventually the negative technology shock requires a downward adjustment of the capital stock and investment declines (at -1.0% for productive investment and -2.2% for total investment, including housing investment, after 20 years). The anticipated permanent TPF level shift, the associated decline of private consumption, and euro appreciation make the shock deflationary on impact. The deflationary effect strengthens in case of the ZLB constraint, where the real interest rate increases initially, leading to a more negative demand response, stronger euro apprecation and, by consequence, stronger downward pressure on price growth.

REER appreciation and slowing world demand lead to a visible decline of EA real exports. Imports also decline because of reduced domestic income. The current account increases persistently during the transition period, leading to a build-up of net foreign assets (NFA) in line with households desire to keep permanent consumption levels up. The adjustment on the labour market is mainly passing through wages. Unemployment rises only temporarily, more strongly under the assumption of inactive monetary policy (given more pronounced demand contraction), whereas the real wage declines steadily to a permanently lower level in line with the decline in labour productivity.

The adverse TFP shock increases the government deficit-to-GDP ratio and government debt-to-GDP on impact. The deterioration of government finances passes through automatic stabilisers, notably lower tax revenues, and the adverse denominator effect. The budget closure rule that adjusts lump-sum taxes to stabilise government debt to GDP at its baseline level implies a tax increase and an associated improvement in the government balance.

The spillover (see Graph 3.8) of the negative permanent technology shock from the EA to all other regional blocks is detrimental, i.e. a positive correlation between the contraction of economic activity in the EA and elsewhere, causing a decline in real GDP in all regional blocks. The spillover relates most directly to the assumption of co-movement in the TFP shocks across regions. In addition, the intensity of the spillover increases with the degree of bilateral trade integration.
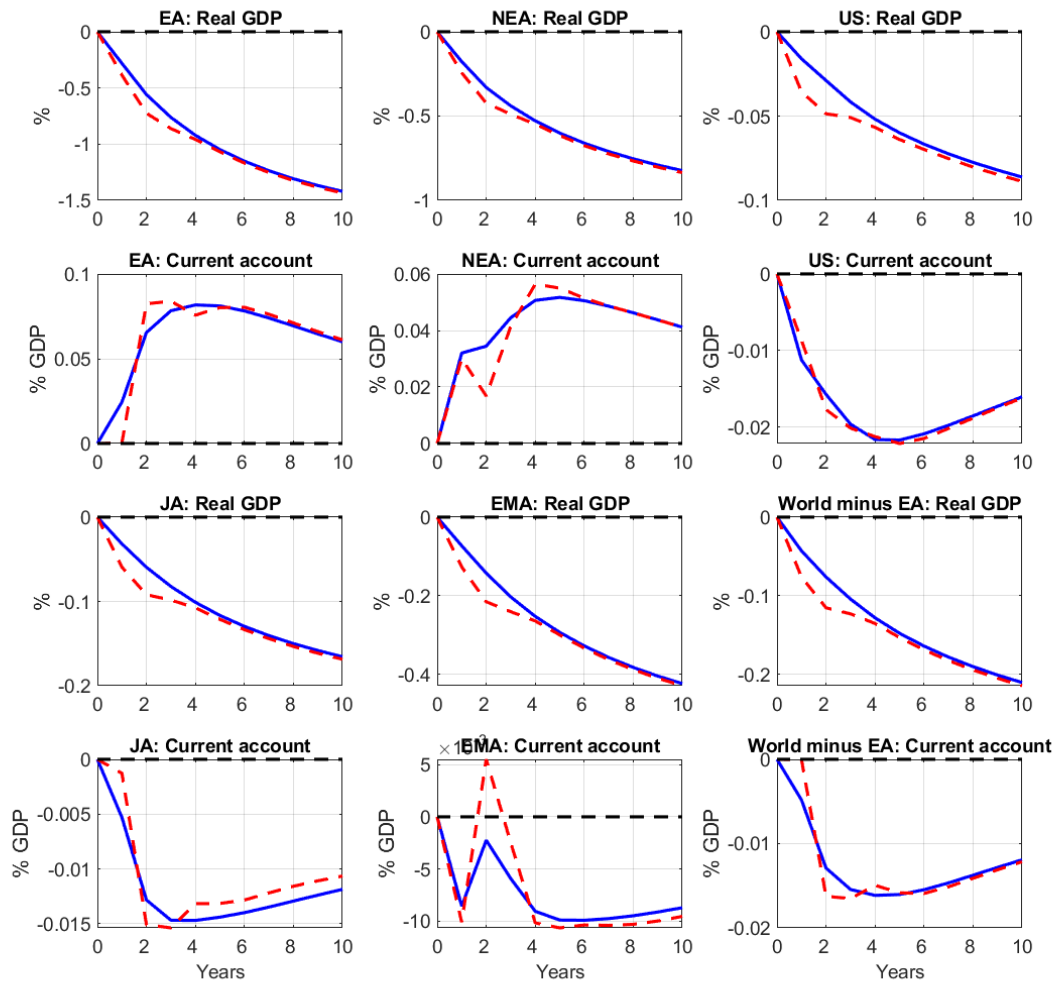
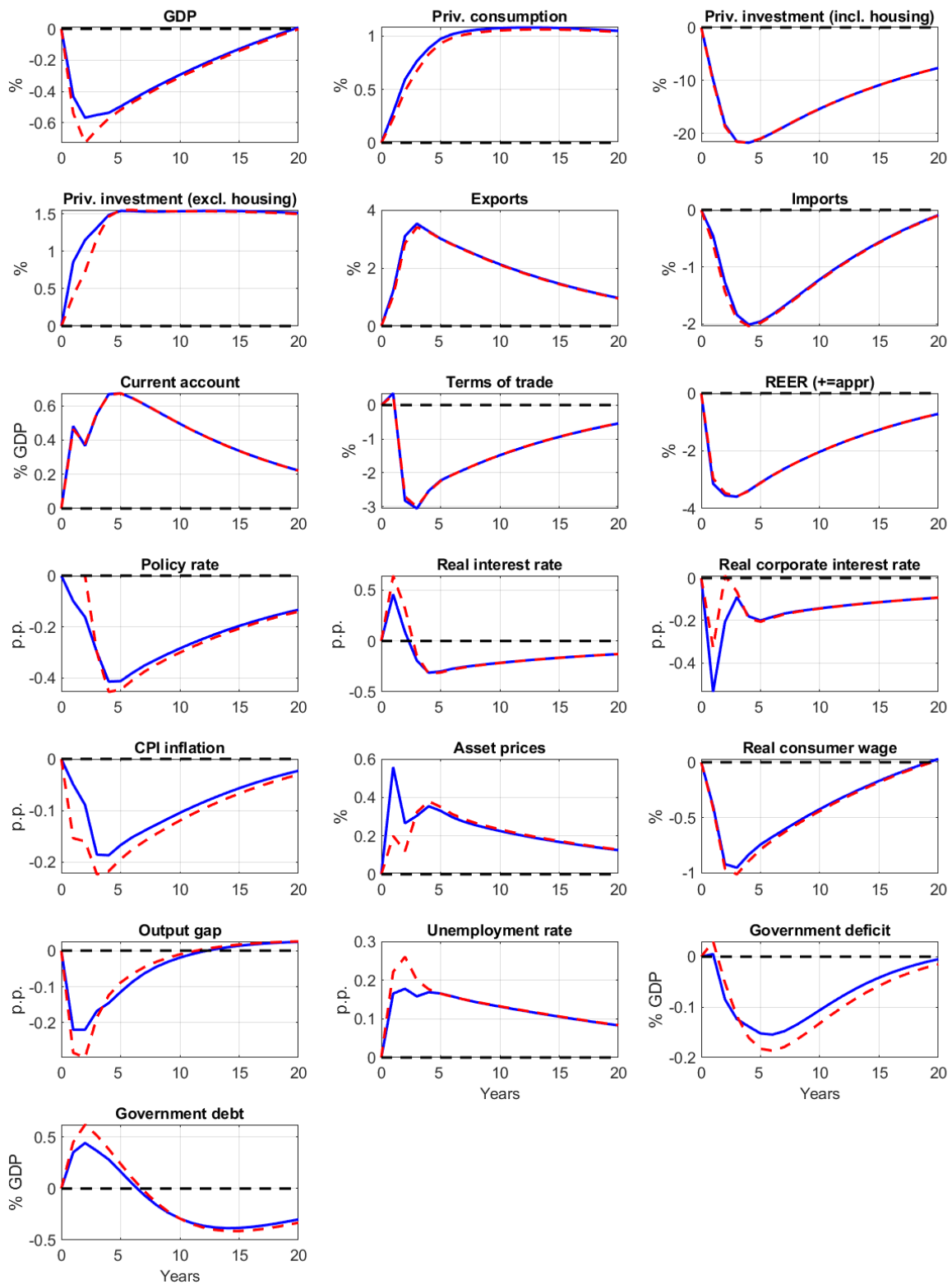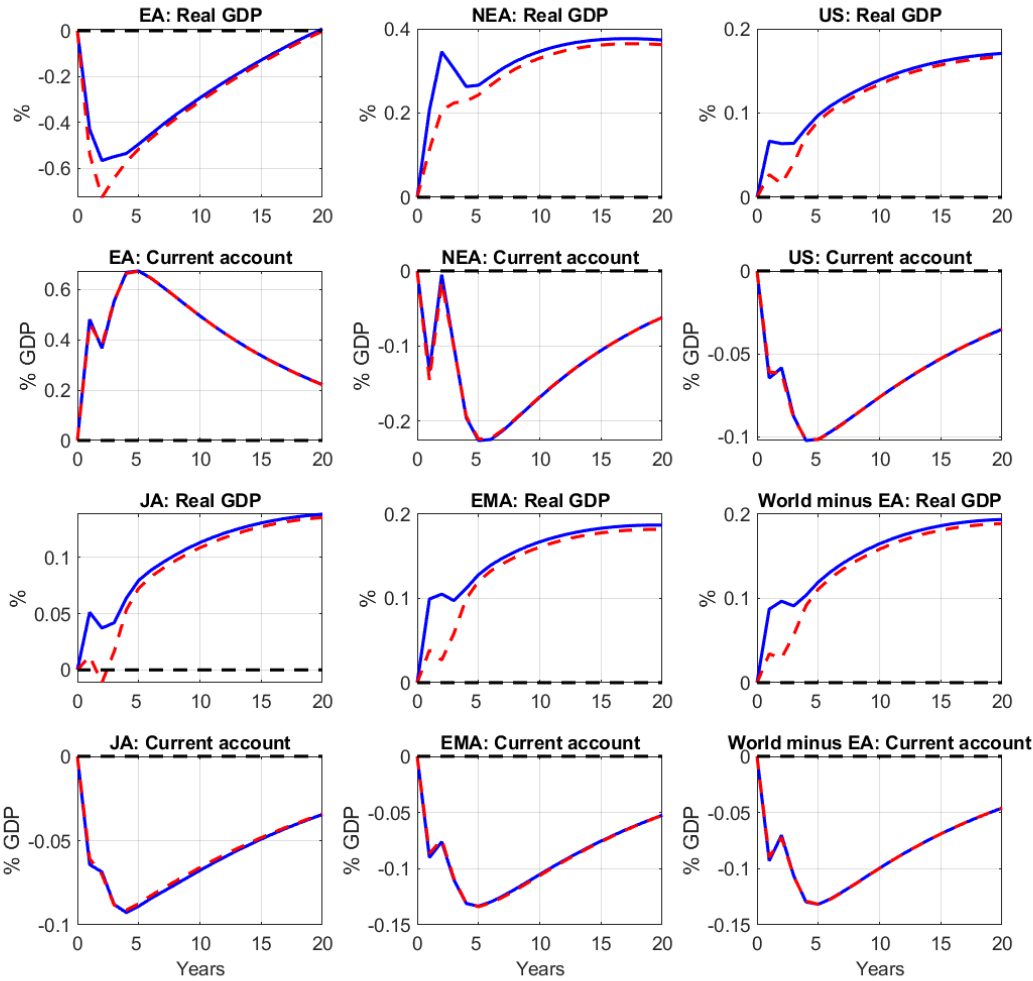Graph 3.7. **Permanent technology shock - EA economy response**
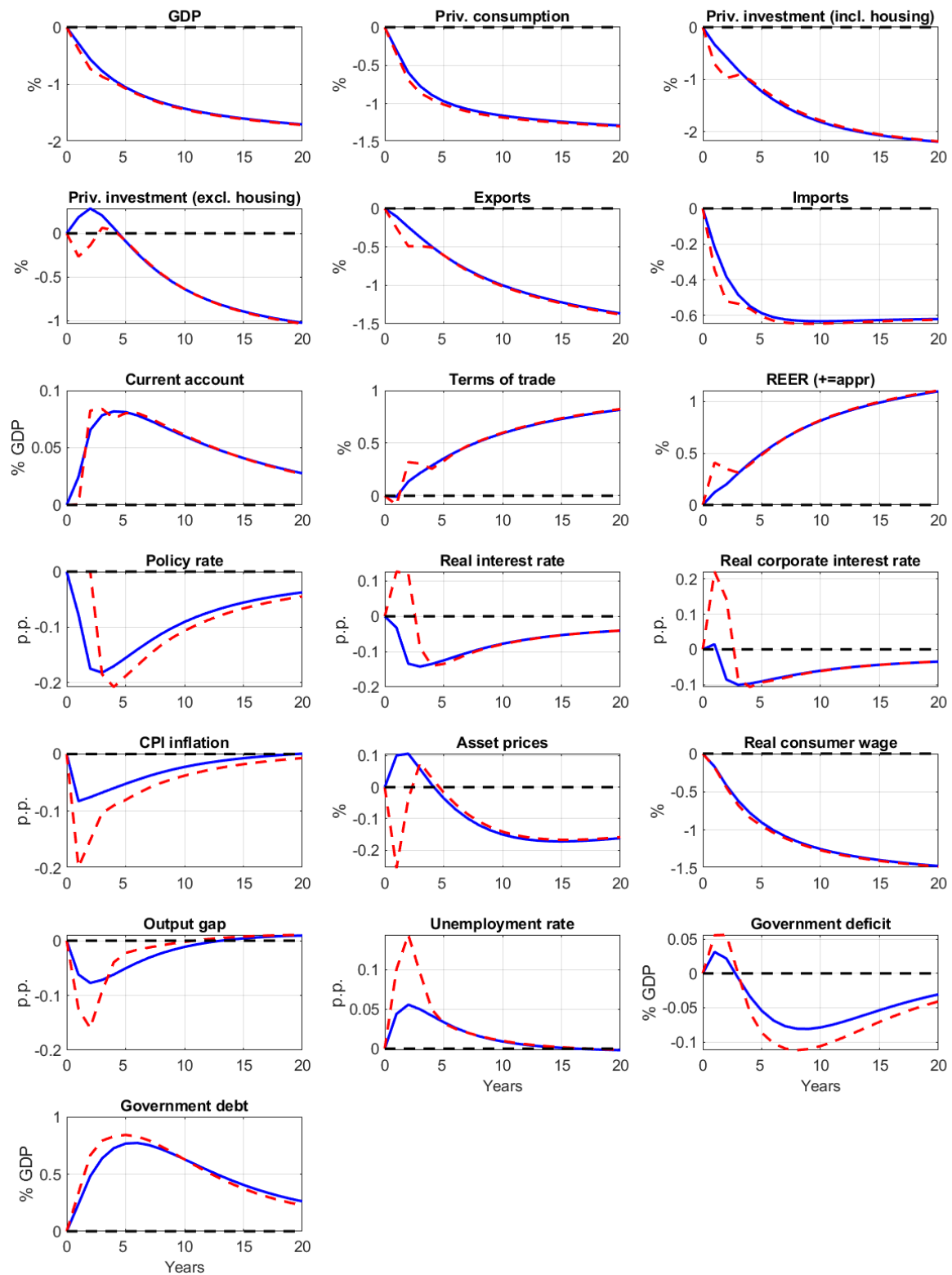
Note: Solid blue lines depict responses with standard monetary policy; red dashed lines depict responses when the zero-interest-rate floor binds in the initial two years.

Source: Commission services.

Graph 3.8. **Permanent technology shock - spillover**

Note: Solid blue lines depict responses with standard monetary policy; red dashed lines depict responses when the zero-interest-rate floor binds in the initial two years.

Source: Commission services.

3.5. DELEVERAGING SCENARIO

Two stylised features characterise the boom and bust episode of the early 2000s: increasing leverage in the household sector, accompanied by a housing boom and increasing house prices, and the subsequent household deleveraging and house price decline. This section illustrates the bust phase, characterised by a combined reduction of residential investment (bursting of a housing bubble) and credit tightening of banks. Previous empirical work (e.g., in 't Veld et al., 2014) has shown that the deleveraging episode is best characterised as a combination of an adverse housing demand (bursting of house price bubble), captured by an increase of ε_t^{rH} and ε_t^{cH} in equations (18) and (27), and an adverse loan supply shock, proxied by a fall in the leverage ratio $1 - \chi$ in equation (27). The major negative impact of these shocks comes via a persistent fall in residential investment, offset only partly by corporate investment and private consumption (private consumption responds negatively to credit tightening and positively to falling residential investment, as household relocate spending).

Graph 3.9. **Deleveraging scenario - EA economy response**

Note: Solid blue lines depict responses with standard monetary policy; red dashed lines depict responses when the zero-interest-rate floor binds in the initial two years.

Source: Commission services.

The fall in domestic demand lowers inflation and gives room for a protracted decline in the policy rate. It is associated with capital outflow and an (overshooting) depreciation of the euro. The exchange rate depreciation facilitates the adjustment via an increase in exports and a reduction of imports. The current account position increases persistently. With a ZLB constraint binding during the first 2 years, the negative effect on domestic demand is initially stronger, since declining inflation raises the real interest rate in the short run in the absence of a monetary policy reaction.

Graph 3.9 presents impulse responses for a permanent 23 pp reduction in the loan-to-value ratio for credit-constrained households that account for 20% of EA households. The tightening of the credit constraint kicks in gradually over three years and illustrates a period of household deleveraging. It occurs together with a highly persistent increase in the risk premium on housing investment by annualised 450 bp that is also phased in over three years.

Graph 3.10. **Deleveraging scenario - spillover**

Note: Solid blue lines depict responses with standard monetary policy; red dashed lines depict responses when the zero-interest-rate floor binds in the initial two years.

Source: Commission services.

Deleveraging implies a reduction of credit-constrained households' consumption and residential investment. The housing risk shock adds a decline of residential investment by non-constrained households. Credit-constrained consumption declines by up to 1.7% and credit-constrained housing

investment by about 50% in the setting with standard monetary policy (blue solid lines). While the decline in residential investment brings total investment down by more than 20%, productive investment in the tradable and non-tradable sectors increases by around 1.5% in the long term. The increase in productive investment derives from a reallocation of resources away from consumption and housing investment, supported by a long period of expansionary monetary policy in the context of low demand (negative output gap) and low inflation that stimulates interest-sensitive demand components. The reduction in the policy rate also leads to EA real effective depreciation by up to 3.6%, which strengthens exports, reduces imports and increases the current account to GDP ratio by up to 0.7 pp in the medium term. The government balance improves in the medium term, despite the contraction in activity, because of the shift in demand from residential investment to tax-richer private consumption. Expansionary monetary policy adds to the effect by gradually reducing the costs of debt service. Government debt relative to GDP increases on impact, however, due to the negative denominator effect.

Spillover from EA private sector deleveraging to the other regions' GDP is very small on impact as shown in Graph 3.10, but positive, i.e. GDP increases. Despite the contraction in EA GDP and EA REER depreciation, EA imports increase. Demand shifts from residential investment to consumption and firm investment, which have both higher import content than the former. The largest positive GDP effect occurs for NEA in line with its strongest bilateral trade linkages to the EA.

3.6. GOVERNMENT INVESTMENT SHOCK

This sub-section discusses the model economy's adjustment to a temporary increase in government expenditure. More precisely, Graph 3.11 and Graph 3.13 show impulse responses for a 1-year increase in EA government investment (IG_t) by 1% of (ex ante) GDP. The impulse responses in Graph 3.11 use an output elasticity of public capital of 0.12, in line with the average elasticity reported in Bom and Ligthart (2014).
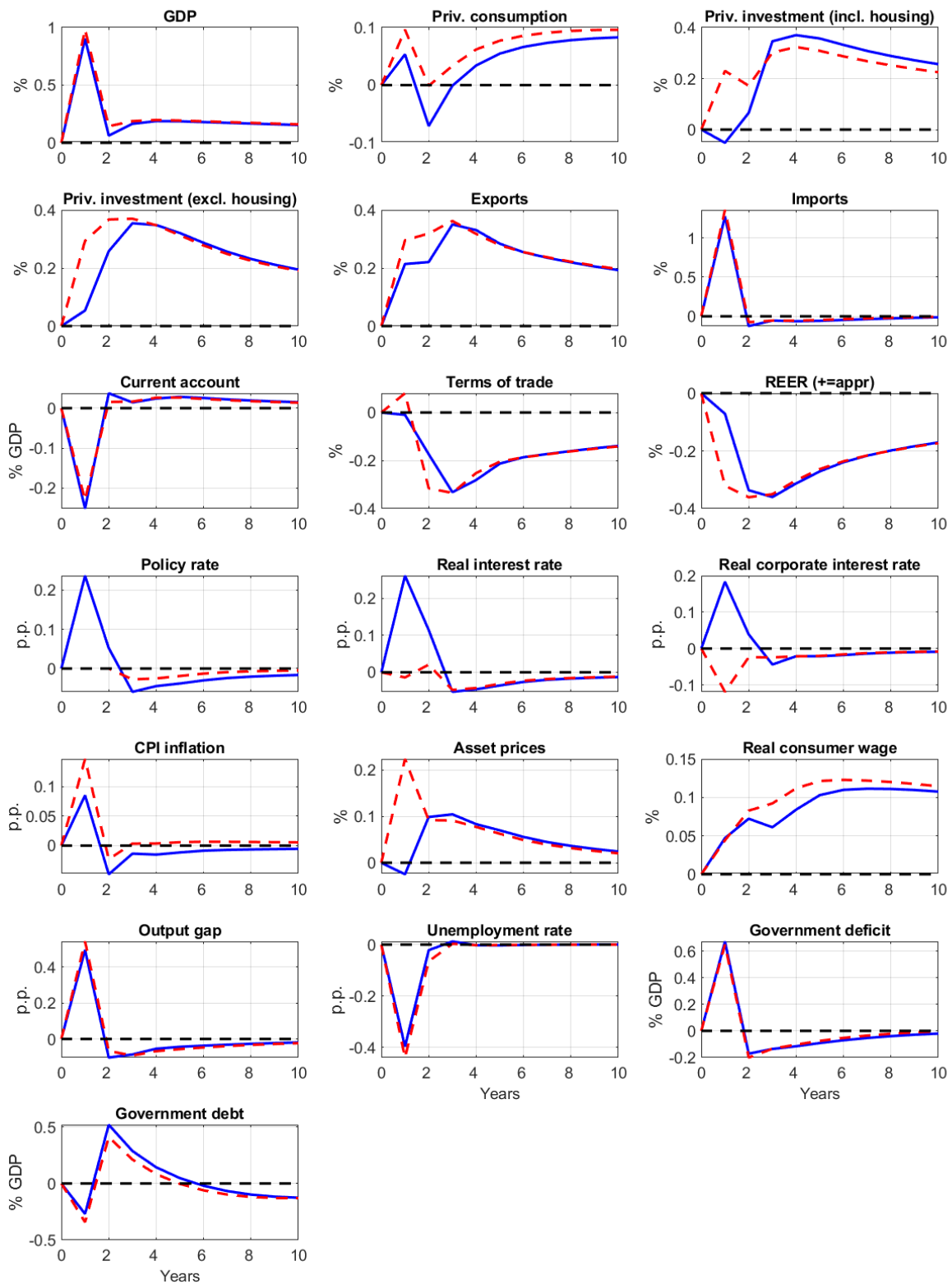
The increase in government investment raises domestic demand and activity, with real GDP increasing by 0.9% on impact in the setting with standard monetary policy (blue solid line) in Graph 3.11. The policy rate increase dampens the positive response of private consumption and investment in the short term. Under both monetary policy assumptions, however, higher government investment crowds in private productive investment in the medium term, because public capital (infrastructure) raises the productivity of the private capital stock.

The positive supply-side effects of the government investment shock lead to a depreciation of the EA REER, i.e. domestic goods prices increase less than the prices of foreign goods. Real imports increase by 1.2% in response to increased domestic demand. The current account falls temporarily by 0.3 pp on impact. The 1-year fiscal stimulus in Graph 3.11 increases the government deficit in the short term as higher tax revenue from stronger economic activity only partly offsets higher investment expenditure.

In the ZLB environment (red dashed lines) in which the central bank does not raise short-term interest rate during the first two years despite strengthening domestic demand and inflation, the first-year GDP multiplier of the government investment shock increases from 0.9 to 1.0. Private consumption and investment increase more strongly on impact absent an increase in the policy and real interest rate.

Spillover from the positive EA government investment shock to other regions is positive and driven by trade linkages (Graph3.12). In particular, higher domestic demand increases import demand in the EA. Real GDP and current account balances in other regions increase on impact. The GDP spillover is strongest for the non-EA EU (0.2% real GDP increase on impact) given the regions strong bilateral trade links with the EA. GDP spillover to the three other regions is much smaller (0.04-0.07% real GDP increase).
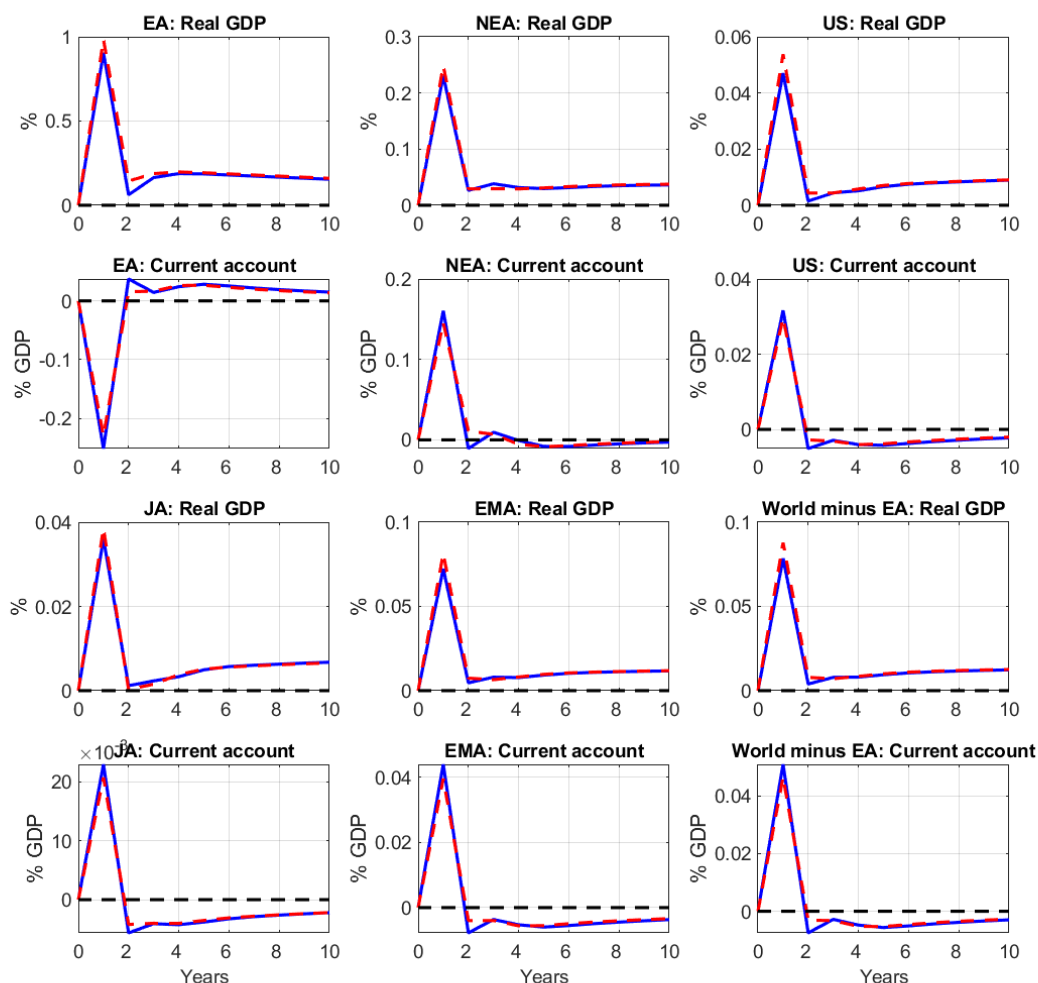
Graph 3.11. **Temporary public investment shock (average productivity) - EA economy response**

Note: Solid blue lines depict responses with standard monetary policy; red dashed lines depict responses when the zero-interest-rate floor binds in the initial two years.

Source: Commission services.

Note: Solid blue lines depict responses with standard monetary policy; red dashed lines depict responses when the zero-interest-rate floor binds in the initial two years.

Source: Commission services

3.7. UNCONVENTIONAL MONETARY POLICY

The following investigates the impact of unconventional monetary policy, notably quantitative easing (QE) policy, in the model. The model does not include an explicit modelling of unconventional monetary policy. However, the impact of QE can be approximated by shocks to private-sector financing costs ($\varepsilon_t^{rK,J}$, ε_t^{rH}, ε_t^{cH}), to the demand for foreign assets (ε_t^{rBF}), and to private savings (through a shock to the discount factor β^r), as explained in Box 3.4.

Box 3.4. **INTRODUCING QUANTITATIVE EASING IN THE QUEST MODEL**

This box summarises the introduction of quantitative easing (QE) in the QUEST model. Priftis and Vogel (2016) and Hohberger et al. (2019) introduce QE as a policy extending the size of the central bank's (CB's) balance sheet. In particular, the CB purchases long-term (government) bonds with the objective of reducing the interest spread between short and long maturity bonds (flattening of the yield curve), and it finances the purchase of long-term bonds by additional liquidity provision to the private sector.

QE as described above affects portfolio allocation and financing costs when bonds of different maturity are imperfect substitutes. In Priftis and Vogel (2016) and Hohberger et al. (2019), agents face (quadratic) costs when the maturity composition of their portfolios deviates from the long-term average structure. QE triggers portfolio rebalancing in this setting, with implications for (relative) asset demand and prices (interest rates). In particular, CB purchases of long-term bonds reduce the supply of long-term relative to short-term bonds to the private sector. With imperfect substitutability between maturities, this has a similar (but more targeted) impact on the long-term interest rate than a reduction of the short-term interest rate that would also reduce rates at the longer end of the yield curve.

The transmission of QE to real variables then works through portfolio rebalancing and a reduction in private saving. Faced with the fall in the yield of long-term government bonds, private portfolio holders shift demand towards riskier equity and towards foreign assets. Stronger demand for equity improves the supply of funds and lowers the financing costs for productive investment in physical capital. Investment demand increases, leading to stronger domestic demand and a higher capital stock in the medium term. Portfolio reallocation towards foreign (foreign-currency) assets triggers a depreciation of the domestic currency, where eexchange rate depreciation strengthens net export demand and economic activity in the domestic economy. Declining long-term yields also lower the average return on private portfolios, which reduces the incentive for households to save out of disposable income. The lower savings translate into higher consumption demand, which also strengthens aggregate demand and economic activity in the domestic economy.

Taken together, QE translates into a combination of (1) increased demand for physical investment, analogously to investment (equity) risk premium reduction, (2) higher demand for foreign assets, analogously to the effect of increasing risk prema on domestic economy assets, and (3) an increase in consumption demand, analogously to the effect of an increase in the rate of time preference.

As in the previous scenarios, the shock originates in the EA. The shock is a temporary, but persistent shock that reduces the private-sector financing costs by 30 basis points on impact, which is in the order of magnitude of QE effects as discussed in Altavilla et al. (2015), Andrade et al. (2016), and De Santis (2016). As for the financial risk scenario in subsection 3.3, we assume financial shock correlation across regions as proxy for spillover in international financial markets and positive co-movement of financial conditions across industrialised countries. In particular, one third of the QE-related EA shocks spills over to financial market conditions in the non-EA EU, the U.S., Japan, and Emerging Asia. We assume the ZLB on short-term policy rates to be binding in all model regions during the first two years.

Graph 3.14 illustrates the effects of the QE scenario in the EA. The decline in financing costs raises private investment by initially 1.0%. Consumption increases by 0.2% as households reduce their savings rate. Capital outflow leads to depreciation of the euro exchange rate, which strengthens exports. Imports increase on impact in line with stronger domestic demand, but fall below baseline in the medium term in line with REER depreciation. Real GDP increases to 0.5% above baseline in the second year and CPI inflation, driven by stronger domestic activity and currency depreciation, by 0.5 pp on impact. The government balance improves initially in response to automatic stabilisers, a positive denominator effect, and the initial decline in the real interest rate. Note that the policy rate increases after the first two years, which raises the real interest rate and, together with the decay of the QE shock, offsets expansionary effects of the initial shock in the medium term.

Spillover to real GDP in the U.S., Japan, and Emerging Asia (Graph 3.15) is positive and driven by the assumption of co-movement in financial conditions and the absence of monetary tightening in the short term.
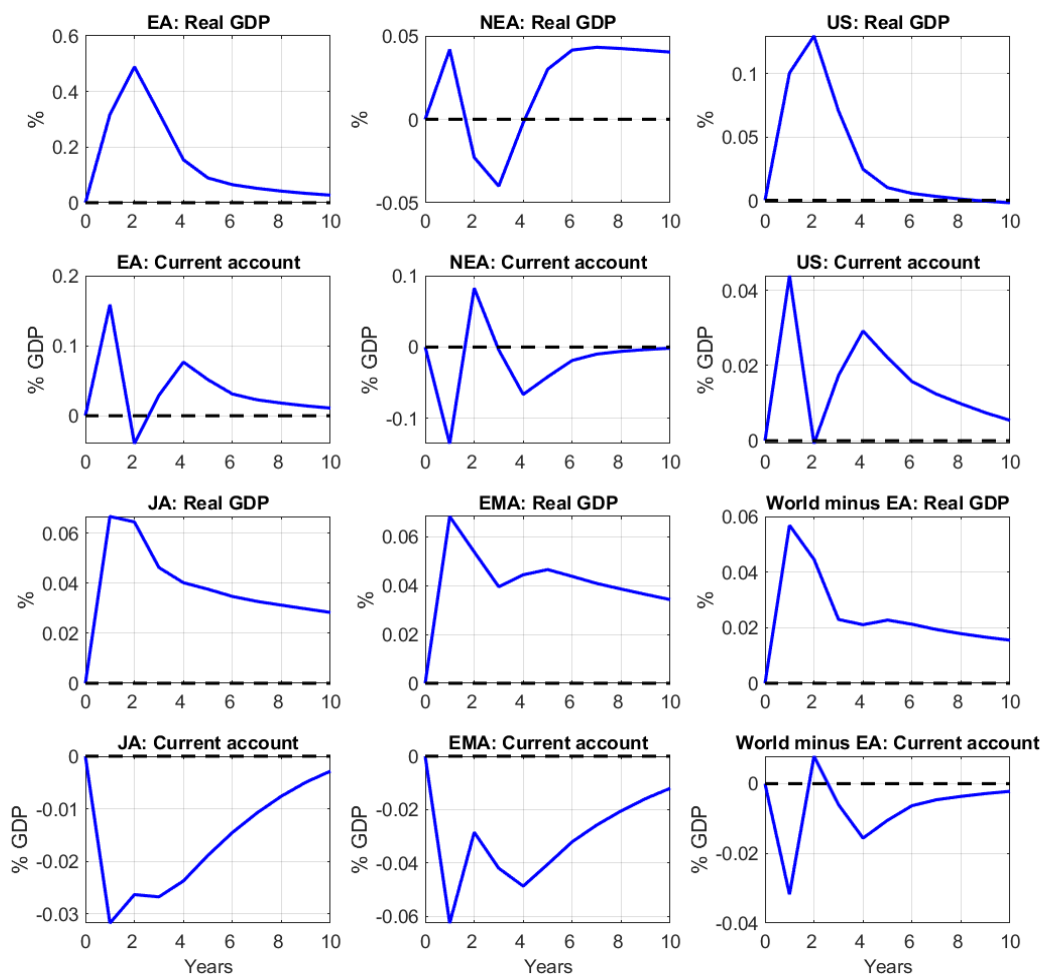
Graph 3.14. **Unconventional monetary policy shock - EA economy response**
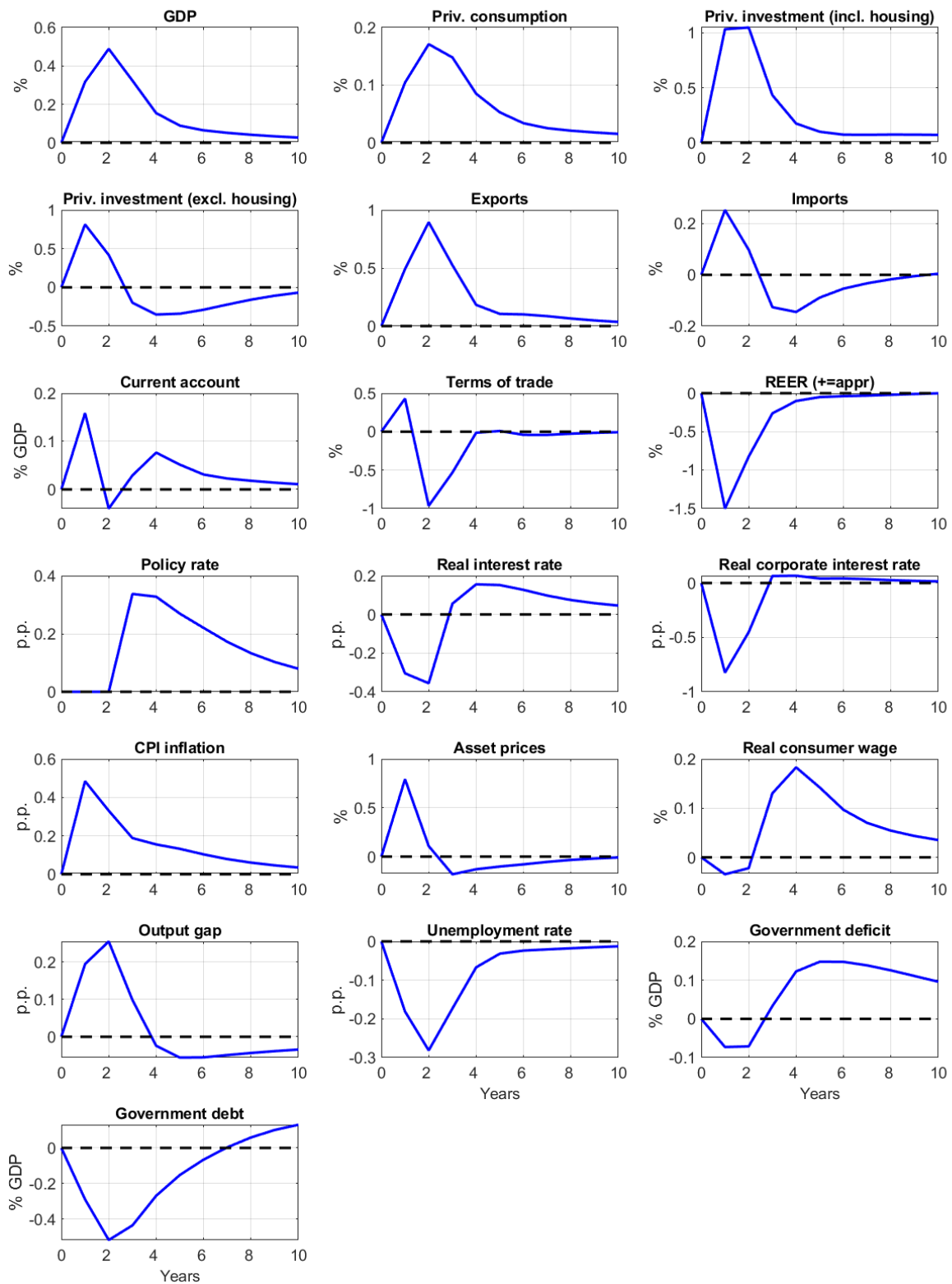
Note: The zero-interest-rate floor binds in the initial two years to proxy a situation in which the target ("shadow") interest rate suggested by the Taylor rule is lower than zero bound.
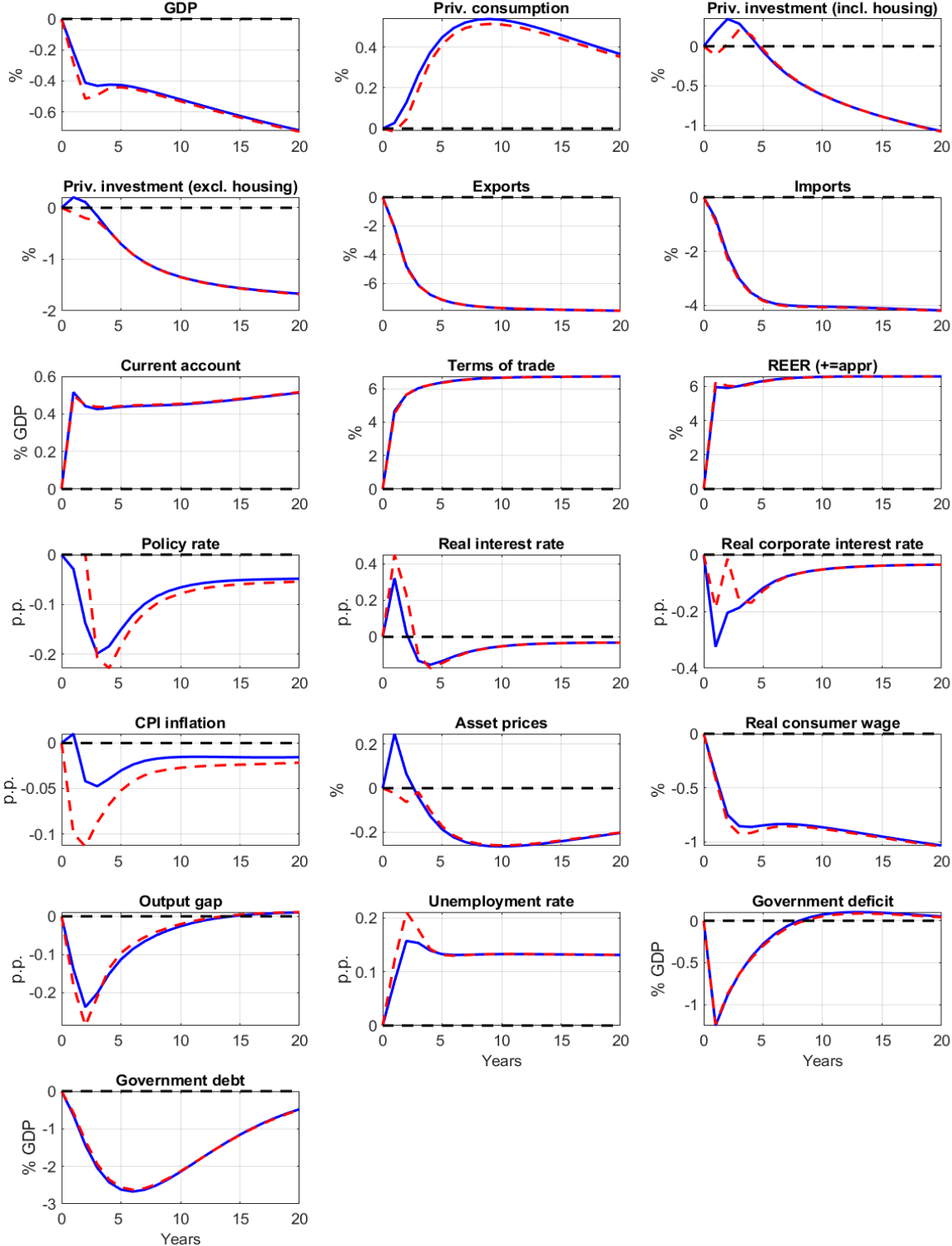
Source: Commission services.

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Graph 3.15. **Unconventional monetary policy shock - spillover**

Note: The zero-interest-rate floor binds in the initial two years to proxy a situation in which the target ("shadow") interest rate suggested by the Taylor rule is lower than zero bound.

Source: Commission services.

3.8. UNILATERAL TARIFF SHOCK

This final scenario discusses the impact of a permanent tariff (t_t^f in equation 64) on all U.S. imports of 10% of the import value. Size and shock duration are purely illustrative as is the assumption of unilateral imposition, i.e. no retaliation by other regions. The government rebates revenue from import tariffs to households through lower (non-distortionary) taxes in the scenario. Graph 3.16 displays the response of U.S. aggregate variables to the import tariff.

Graph 3.16 shows that U.S. imports decline by 4% in the long term in response to tariff imposition. Exports also decline in response to strong effective exchange rate appreciation. Private investment demand, notably productive investment, declines in the context of rising after-tariff import prices, which also include imports of intermediate inputs, and in response to expected weaker economic activity in the future. Consumption demand, however, increases despite the falling purchasing power of wages. The increase in consumption demand is due to the scenario assumption that tariff revenue is rebated to households, which strenghens demand by financially constrained consumers. The U.S. current account balance increases, because the import decline (negative income effect and expenditure

switching) dominates the fall in exports (dollar appreciation). Real GDP declines by around 0.4% in the short term. A binding zero lower bound (ZLB) on short-term nominal intererest rates (red dashed line) does amplify the negative initial response of the U.S. GDP due to the initial absence of monetary easing, i.e. a (stronger) initial increase in the real interest rate.
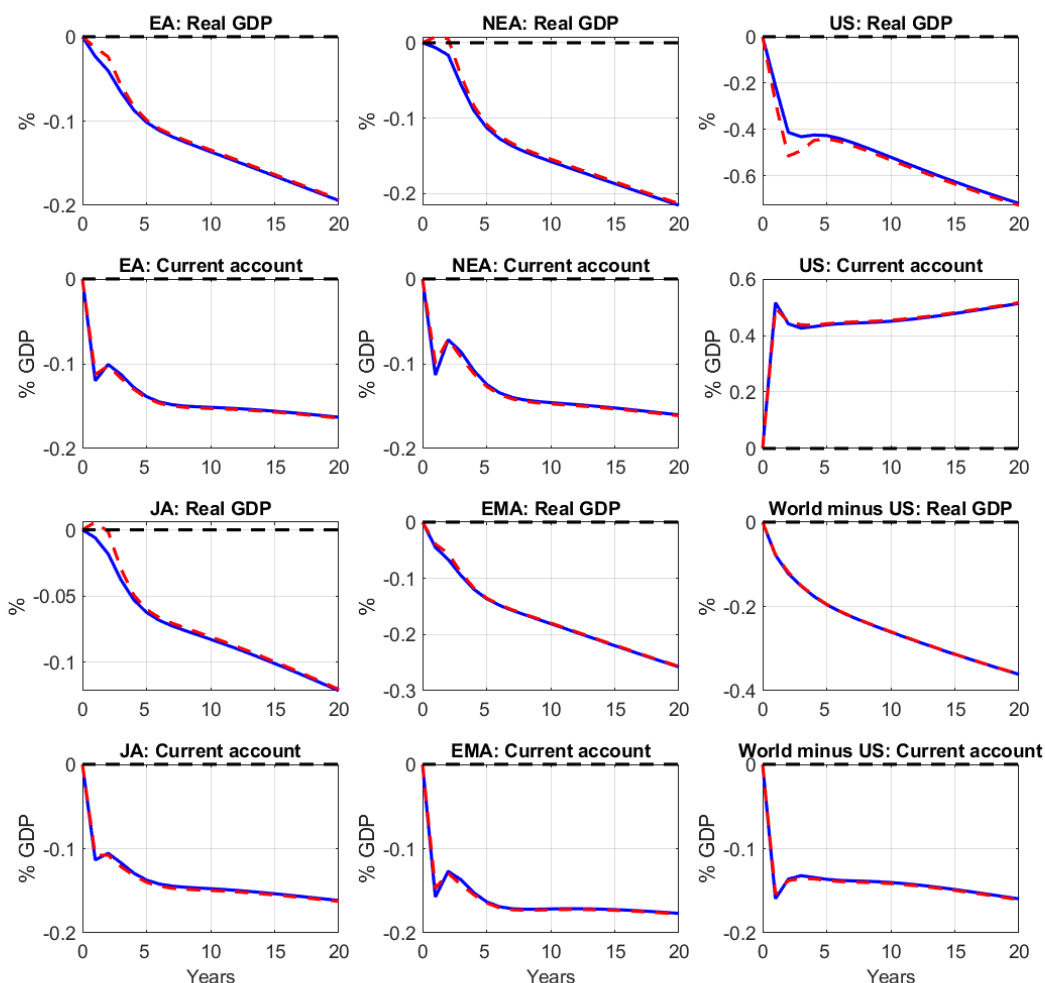
Graph 3.16. **Unilateral tariff shock – U.S. economy response**

Note: Solid blue lines depict responses with standard monetary policy; red dashed lines depict responses when the zero-interest-rate floor binds in the initial two years.

Source: Commission services.

Graph 3.17. **Unilateral tariff shock - spillover**

Note: Solid blue lines depict responses with standard monetary policy; red dashed lines depict responses when the zero-interest-rate floor binds in the initial two years.

Source: Commission services.

Spillover of the U.S. tariff shock to real GDP in the EA, the the non-EA EU plus the UK (NEA), Japan, and Emerging Asia is negative, with the size depending on the region's trade exposure to the U.S. (Graph 3.17). The negative impact in terms of GDP on the aggregate world economy excluding the U.S. is even stronger. The latter result is due to the negative impact of the U.S. tar-iff on economies that have strong trade linkages with the U.S. and are not included in any of the previously mentioned country groupings (e.g. Canada and Latin America). The current account in all foreign regions deteriorates in response to the tariff.

4. CONCLUSION

This paper has documented the structure and simulation properties of a core version of the QUEST macroeconomic model. QUEST is a multi-region New Keynesian DSGE model developed and maintained by the European Commission. The model is flexible with respect to the geographic set-up and the sectorial configuration. The version used in this paper comprises tradable goods, non-tradable

goods and housing sectors. It includes the following regions: Euro Area, the non-EA EU, the United States, Japan, Emerging Asia, and the rest of the world.

The paper presents simulation results for a series of goods, factor, financial market, and policy shocks, namely shocks to monetary policy, consumption, risk premia, productivity, credit constraints, government spending, unconventional monetary policy, and (unilateral) import tariffs. While the scenarios are illustrative, they reflect important elements of the Global recession and the EA crisis (global risk shocks, private sector demand shocks and deleveraging) and of policy responses (fiscal policy, unconventional monetary policy) and challenges (protectionism) in recent years.

The paper shows the impact of these shocks on real GDP, domestic demand components, trade, external balances, wages, employment, price levels, relative prices, interest rates, and public finances and discusses how the structure of the model and its theoretical underpinnings shape the transmission of shocks to real and financial variables in the domestic economy as well as international spillover. In view of macroeconomic conditions in recent years, the paper presents simulations under standard monetary policy and for an environment in which the zero lower bound (ZLB) on monetary policy is binding in different regions.

The presentation of impulse responses uses the EA as domestic economy in which the shocks originate, except for the tariff shock for which the U.S. is the domestic country. The general properties of the results also apply to shocks in other regional blocks of the model, with some differences related to regional specifcities, such as the strength of financial constraints, the degree of economic openness, and the size of economic sectors and government.

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APPENDIX

There are various ways of solving forward-looking models with rational expectations. Most of them are based on linearisations of the model around the steady state and then applying closed-form solution algorithms to the linearised system, like the method suggested by Blanchard and Kahn (1980). TROLL uses a method developed by Laffarque (1990), Boucekkine (1995) and Juillard (1996) to solve the nonlinear model by a Newton-Raphson solution algorithm. The latter approach has the advantage of increased accuracy and applicability to economies that are not operating close to a steady state initially, but it has the drawback that terminal conditions must be specified explicitly.

The stacked-time solution algorithm in TROLL essentially works as follows. Let y_t ($n \times 1$) and x_t (k× 1) be vectors of endogenous and exogenous variables respectively. The model can be written compactly as:

$$f_t(y_{t-1}, y_t, E_t y_{t+1}, x_t) = 0$$

where f_t is a vector of *n* nonlinear dynamic equations. The presence of predetermined state variables y_{t-1} and forward-looking expectations (jump variables) $E_t y_{t+1}$ introduces simultaneity across time periods. A way of solving the model (with starting date *t*) is to stack the system for the T+1 periods:

$$F(z, x; t) = \begin{bmatrix} f_t(z_t, x_t) \\ \vdots \\ f_{t+j}(z_{t+j}, x_{t+j}) \\ \vdots \\ f_{t+T}(z_{t+T}, x_{t+T}) \end{bmatrix} = 0$$

where $z_{t+j} = (y_{t+j-1}, y_{t+j}, E_t y_{t+j+1})$. This stacked system of equations is then solved with the Newton-Raphson method subject to the predetermined variables y_{t-1} and the terminal conditions y_{t+T+1}.

The QUEST model deals with the requirement of selecting terminal conditions by specifying the terminal conditions in differences (additional methods are discussed and compared in Roeger and in 't Veld 1997). Knowing that the model reaches a steady state implies knowledge about the change of variables between two successive periods in the distant future. With the system formulated in efficiency units, as is the case for QUEST, we know that the percentage change of y_t^j is equal to zero in the steady state for any shock and any steady state reached by the model solution. Defining a new vector of jump variables $\Delta y_t^j = y_t^j - y_{t-1}^j$, we have $\Delta y_{t+T+1}^j = 0$ if we choose T large enough such that the model will have reached a steady state in period t+T. In other words, we can reformulate the model such that the terminal conditions are invariant to the policy shock. A small cost associated with this method is the necessity to extend the mode by adding *m* equations defining the vector Δy_t^j, where *m* is the number of jump variables in the model.

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