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Germany's Macroeconomic Drivers Through the COVID-19 Pandemic and Recovery Period

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Germany's macroeconomic drivers through the COVID-19 pandemic and recovery period

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1. Introduction

The COVID-19 pandemic and subsequent energy crisis have led to significant macroeconomic consequences for Germany and the global economy. The immediate response to COVID-19 through the implementation of containment measures and widespread lockdowns, brought many economic activities and international trade to a halt. As a consequence, heightened uncertainties, disrupted global supply chains, and a sharp decline of domestic activity accelerated the economic downturn, leading to a synchronised global recession in 2020. Simultaneously, governments rolled out unprecedented fiscal stimulus packages. The energy crisis in 2021-22 has amplified the surge in inflation, leading to a strong tightening of monetary policy.

This paper analyses the main drivers of the COVID-19 pandemic and recovery period for Germany through the lens of an estimated structural macroeconomic model. The model is a three-region dynamic stochastic general equilibrium (DSGE) model, consisting of Germany (DE), the rest of the euro area (REA), and the rest of the world (RoW). The structural setup builds on Albonico et al. (2019), Hohberger et al. (2020), and Cardani et al. (2022b). Given the focus on the COVID-19 and post-pandemic period, the model has been extended in two directions: First, it incorporates COVID-related shocks along the dimensions of Cardani et al. (2022a, 2023), and second, it extends the use of commodities in the model following the approaches by Giovannini et al. (2019) and Cardani et al. (2023).

The model is estimated using data from the period 1999q1–2023q4, thereby encompassing the COVID-19 pandemic and recovery period. The methodological approach follows Cardani et al. (2022a, 2023) in which the model allows for heteroskedastic exogenous disturbances that only occur during the COVID-period (2020q1-2022q4). Incorporating a large number of time series information (observables) in the estimation process involves a large number of shocks, but allows to assess the main drivers of macroeconomic variables and to provide a plausible narrative of economic developments. Therefore, the model includes: (i) domestic and foreign demand and supply shocks, including private domestic demand, monetary and fiscal policy shocks, shocks to labour and goods market adjustment and productivity, as well as shocks to foreign activity, trade and commodity prices, and (ii) additional COVID-specific macroeconomic disturbances, such as transitory lockdown shocks (forced savings), shocks to the labour market (labour hoarding), fiscal stimulus and foreign 'risk' shocks. Additionally, (iii) the model includes an endogenous and occasionally binding effective lower bound (ELB) on nominal short-term interest rates as in Hohberger et al. (2019) and Croitorov et al. (2020).

The estimation results suggest a crucial role for transitory lockdown shocks (forced savings) in explaining the contraction and recovery of economic activity in Germany during 2020–21, with significant stabilising effects from fiscal policy measures. Spillovers from global demand and supply shocks also affect Germany's economic activity. The GDP recovery period in 2021-23 indicates offsetting effects between a normalisation of domestic and foreign demand and a slowdown in international trade, coupled with adverse supply shocks. This reflects increasing supply-chain bottlenecks for the German economy. The driving factors behind the surge in Germany's CPI inflation in 2021-22 are primarily attributed to domestic and foreign supply-side factors and rising commodity prices. Adverse productivity and supply shocks (price markup and export price shocks) highlight global supply-chain and capacity constraints. Unlike the global financial crisis (GFC), the inflation dynamics during the 2021-22 surge have been driven particularly by supply-side factors. The estimated shocks in the model closely align with off-model indicators that are not part of the observed data, supporting the empirical plausibility of the identified shocks.

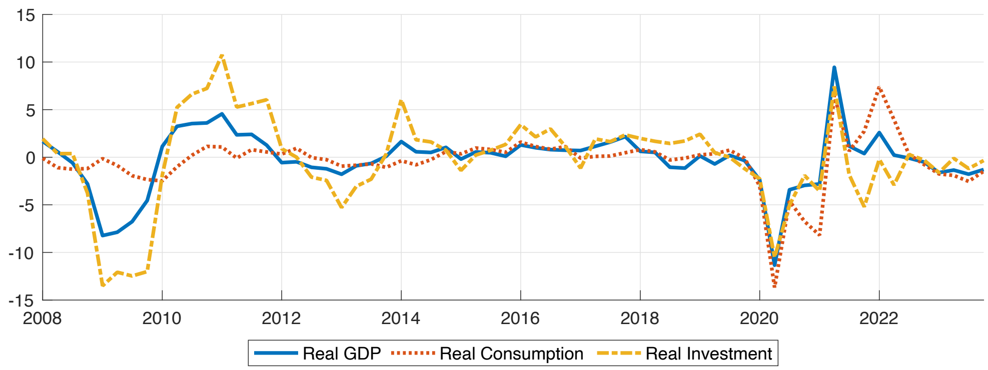
The remainder of the paper proceeds as follows. Section 2 presents stylised macroeconomic facts for the German economy since the onset of the GFC in 2008. Section 3 discusses recent studies with respect to modelling COVID-specific developments and empirical literature on the recent post-pandemic surge in inflation. Section 4 outlines the structure of the model. Section 5 describes the model solution, data, and estimation methodology, and discusses posterior estimates. Section 6 discusses the dynamic responses to shocks characteristic of the COVID-19 period. Section 7 quantifies the main drivers of GDP growth, CPI inflation, and wage growth in Germany. Section 8 compares model-implied results with off-model evidence. Section 9 provides a sensitivity analysis without COVID-specific shocks. Section 10 summarises and concludes the paper.

2. Stylised facts

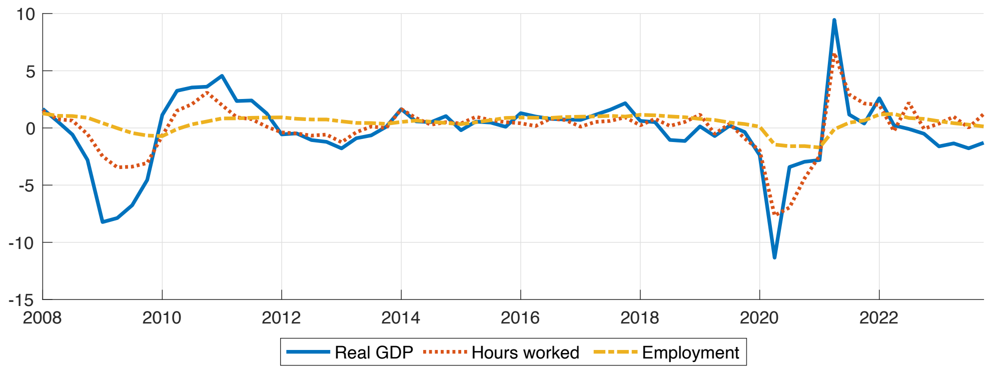
Figure 1 summarises several stylised facts for selected macroeconomic variables during the GFC and the COVID-19 pandemic in Germany. First, the V-shape contraction of economic activity in 2020q2 was more pronounced compared to the more persistent U-shaped recession of the GFC (Figure 1a). Unlike the 2008-09 recession, both private consumption and investment dropped simultaneously during the pandemic in 2020, whereas the GFC recession exhibited a relatively mild downturn in consumption compared to a significant drop in investment growth in 2009.

Second, in both recessions the number of employees remained relatively stable compared to the decline in hours worked (Figure 1b). The wedge between hours worked and employment during the onset of the COVID-pandemic is attributable to the introduction of job retention schemes (short-time work) aimed at moderating employment losses compared to the sharp decline in GDP.

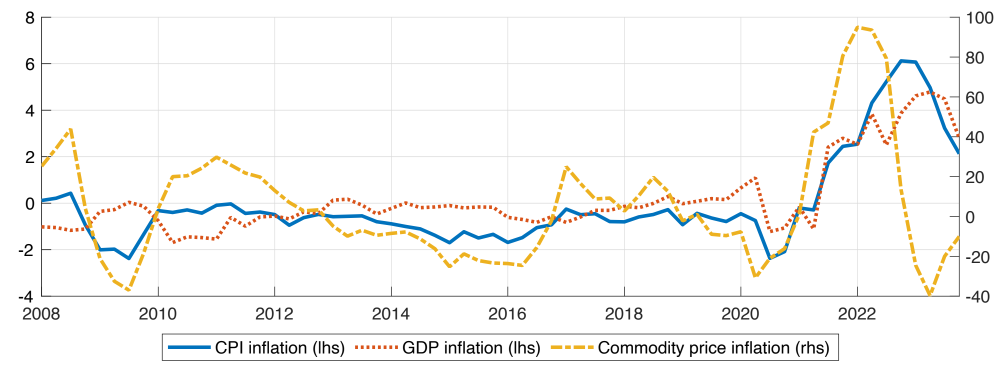
Figure 1: Stylised facts from GFC to COVID-19 in Germany.



(a) Domestic demand components (yoy in %)



(b) Labour market (yoy in %)



(c) Price indices (yoy in %)

Note: Real demand components (inflation rates) are shown in percentage-point deviations from the steady state, which is calibrated to 1.35% (2%) per year, respectively. 1 on the y-axes correspond to 1 pp. Sources: Eurostat and Comext data.

Third, Figure 1c shows that CPI and GDP inflation (lhs) increased significantly from 2021 onward, peaking at 8% and 6.8% in 2022q3 and 2023q2, respectively, when adding the 2% steady-state. The co-movement between GDP and inflation during the 2020 lockdown, similar to the 2008-09 recession, suggests a stronger initial demand-side driver (positive correlation). The prices of commodities (rhs) declined at the start of the pandemic, as during the GFC, and surged in 2021–22 due to the pandemic recovery, global supply chain bottlenecks, geopolitical tensions, and ultimately, Russia's war of aggression against Ukraine. In 2023, oil and energy prices dropped significantly to pre-crisis levels, also contributing to the decline in CPI inflation.

3. Related literature

This paper analyses the macroeconomic drivers of the COVID-19 pandemic and the recovery period in Germany, and compares them with the GFC recession in 2008-09. It relates broadly to three strands of literature.

The first strand relates to the class of estimated structural macroeconomic models for EMU Member States, with a focus on Germany. Several studies have focused on the macroeconomic drivers of Germany's trade balance since the introduction of the euro (e.g. Kollmann et al., 2015; Hohberger et al., 2020; Cardani et al., 2022b). Gadatsch et al. (2016) analyse the effects of fiscal policy measures in Germany during the GFC, whereas Albonico et al. (2019) provide an extensive cross-country comparison of the macroeconomic dynamics among the four largest EMU Member countries during and after the GFC. Regarding COVID-related studies, Funke and Terasa (2022) examines the unconventional fiscal policy measure of a temporary VAT rate cut during 2020q3-20q4 in a calibrated DSGE model for Germany. They find that the tax policy implied a real GDP increase of about 0.3 percentage points (pp) for 2020. Hinterlang et al. (2023) simulate the German fiscal stimulus packages using a calibrated New Keynesian multi-sector general equilibrium model. They find cumulative short-term stabilising effects on output of up to 6 pp over 2020-22.

The second strand relates to the recent literature that adapts state-of-the art DSGE models to COVID-19 dynamics in order to analyse the drivers of the COVID-19 recession in 2020. For the US, for example, Chen et al. (2020) extends the New York Fed DSGE model by incorporating COVID-specific demand and supply shocks, concluding that the pandemic recession has been rather a demand shock to the US economy. Corrado et al. (2021) estimate a two-sector New Keynesian model on US data and find that the pandemic-induced economic downturn can be explained by a combination of large demand and supply shocks. For the EA, Kollmann (2021) uses a stylised New Keynesian model and argues that the aggregate supply shock has been the main driver of the sharp GDP contraction in the EA in 2020, whereas offsetting demand and supply shocks account for the stability of EA inflation.[1] Cardani et al.

[1] There is also a growing literature on structural models that incorporate both epidemiological and economic dynamics to analyse the effects of the pandemic and containment policies (e.g. Eichenbaum et al.,

(2022a) augment and estimate the European Commission's DSGE model for the EA with COVID-specific shocks and financially-constrained investors. They find that 'forced savings' are crucial to explain quarterly real GDP growth during the 2020 recession period. They also provide substantial comparisons to alternative model specifications. Cardani et al. (2023) provide a model-based comparison of the COVID-related recession period between the EA and the US.

Third, a rapidly growing number of studies have emerged recently on the economic developments during and after the pandemic, with a particular focus on the inflation dynamics in the EA and the US, based on various empirical approaches. For the US, the main drivers of the surge in inflation during 2021-2022 are attributed to a combination of binding supply chain constraints (Comin et al., 2023; di Giovanni, 2022; Blanchard and Bernanke, 2023), fiscal stimulus (di Giovanni et al., 2023; Bayer et al., 2023; Jorda and Nechio, 2023), rising commodity prices combined with expansionary policies (Gagliardone and Gertler, 2023; Reis, 2022; Blanchard and Bernanke, 2023), and tight labour markets (Ball et al., 2022) that point to a non-linear Phillips curve in explaining the surge of post-pandemic inflation (Benigno and Eggertsson, 2023, 2024; Harding et al., 2023). In the EA, Neri et al. (2023) and Pasimeni (2022) find that the increase in commodity prices is one of the main drivers in explaining EA inflation during the pandemic, accounting for more than half of the post-COVID headline inflation. Pasimeni (2022) stresses that price pressure stems mainly from sectors with high import content, suggesting the importance of international supply chain disruptions. Hansen et al. (2023) emphasise the crucial role of import prices, accounting for 40% of the EA's change in the consumption deflator in 2022. Cardani et al. (2023) suggest that demand factors play a larger role in US inflation, while supply factors are more significant for EA inflation. They also highlight the importance of rising commodity prices for the surge in inflation during 2021–22.

Blanchard and Bernanke (2023) estimate a dynamic model of prices, wages, and inflation expectations to analyse the direct and indirect effects of product and labour market shocks on US pandemic-era inflation and wage growth. They find price shocks, i.e. commodity prices, sectoral demand shifts, and supply constraints as main sources of inflation. Several studies apply the approach of Blanchard and Bernanke (2023) to EMU Member States, namely Menz (2024) for Germany, Pisani and Tagliabracci (2024) for Italy, and Ghomi et al. (2024) for Spain. Their common findings suggest that the surge in inflation in these EMU Member States has mainly been driven by commodity price shocks and supply bottlenecks, without major evidence of wage-price spirals. Arce et al. (2024) attribute similar drivers to

2021, 2022). However, the model in this paper does not include an epidemiology block.

the EA aggregate inflation surge, namely labour market tightness, productivity and global supply chain disruptions, as well as energy and food price shocks.

This paper contributes to the existing literature along several dimensions: (i) It estimates a state-of-the-art large-scale multi-country DSGE model for the German economy (DE-REA-RoW) using data from 1999q1-2023q4; (ii) it incorporates heteroskedastic COVID-related domestic and foreign lockdown shocks (transitory saving and investment shocks), shocks to labour demand (labour hoarding) to account for the wedge between hours worked and employees (intensive margin) due to short-time work arrangements, and the use of commodities in production and final consumption demand; (iii) it allows for endogenous, occasionally binding constraints to account for ELB periods; (iv) it uses many time series data (observables) to capture a large number of possible domestic and foreign demand and supply-side drivers of the macroeconomic developments in Germany; (v) it provides off-model evidence for the fit of the model-implied estimated shock pattern.

4. The model

This paper uses a state-of-the-art three-region macroeconomic DSGE model, consisting of Germany (DE), the rest of the euro area (REA), and the rest of the world (RoW). The structural setup builds upon the model used in Hohberger et al. (2020) and Cardani et al. (2022b), but extends the model with (i) COVID-specific shocks following the approach by Cardani et al. (2022a), and (ii) the use of commodities in production and final consumption demand (Cardani et al., 2023).

Concerning the COVID-specific shocks, the following additional exogenous disturbances have been incorporated: (1) A transitory lockdown shock (forced savings), ε_t^{tC}, to capture the lockdown-imposed drop in consumption, (2) a transitory labour demand shock (labour hoarding), ε_t^{tN}, to capture short-time work arrangements, i.e. to distinguish between hours worked and hours paid, (3) a transitory VAT shock, ε_t^{tvat}, to capture the reduction of the German VAT consumption tax during 2020q3-2020q4, and (4) a transitory shock to the investment risk premium, ε_t^{tS}, to capture the lockdown-imposed drop in investment demand. To capture COVID-specific demand contraction in the simplified REA and RoW model blocks, the model also incorporates additional foreign shocks to the time preference (savings shock).

The economy of DE consists of various sectors including households, firms that operate domestically or in the import-export sector, as well as a government and a central bank. In contrast, the regional blocks of REA and RoW have a simpler structure. Within the DE block, there is a distinction between two types of households: Ricardian and liquidity-constrained (LC). Ricardian households are characterised by their access to financial markets, ability to smooth consumption, and ownership of firms through equity. On the other hand, LC households lack access to financial markets and consume all their disposable wage and transfer income each period. Both household types supply labour to domestic firms at a common wage established by a labour union with monopoly power. The REA and RoW blocks only include Ricardian households, who supply labour inelastically.

In the domestic production sector, firms operate under monopolistic competition and produce a variety of differentiated intermediate goods. These intermediate goods are then aggregated into domestic value added by perfectly competitive firms. In the subsequent stage, total domestic output is produced by perfectly competitive firms by combining the domestic value added with commodities. The RoW region is the sole producer of commodities, which includes both energy and non-energy commodities. In the import sector, perfectly competitive firms, known as import retailers, purchase goods from foreign regions and assemble them into a final import good. These final import goods are then combined with domestic output by final good packagers to create final aggregate demand component goods.

The DE government is involved in purchasing final goods and providing lump-sum transfers to households. To finance its expenditure, the government issues debt and imposes various taxes including distortionary taxes on labour, capital, and consumption, along with non-distortionary lump-sum taxes. In contrast, the simplified REA and RoW blocks do not contain any fiscal authority. The monetary authorities, however, set short-term nominal interest rates by following a Taylor rule, which reacts to inflation and the output gap. The following description highlights the primary aspects of the model, with further details available in Appendix A.

4.1. Households

There is a continuum of households, indexed by $j \in [0, 1]$, whereas a share of households (Ricardians ω^s) owns firms and trades assets. The remaining share (1-ω^s) is liquidity-constrained (c) and consumes its entire disposable income in each period ('hand-to-mouth'). Household preferences are defined over consumption and leisure. Additionally, Ricardian utility is determined by the holdings of financial assets.

4.1.1. Ricardian households

Ricardian preferences are given by the infinite horizon expected life-time utility:

$$U_j^s = E_0 \sum_{t=0}^{\infty} (\tilde{\beta}_t)^t u_{j,t}^s(.), \tag{1}$$

where $\tilde{\beta}_t$ is the stochastic discount factor.[2] Ricardian households have full access to financial markets, which allows them to accumulate wealth, $A_{j,t}$, consisting of domestic private risk-free bonds, $B^{rf}_{j,t}$, domestic government bonds, $B^{G}_{j,t}$, one internationally traded bond, $B^{W}_{j,t}$, and internationally traded shares, $P^S_t S_{j,t}$:

$$A_{j,t} = B^{rf}_{j,t} + B^{G}_{j,t} + e_{RoW,t} B^{W}_{j,t} + P^S_t S_{j,t} \tag{2}$$

where P^S_t is the nominal price of shares. The international bond is issued and denominated in foreign currency, therefore, the financial wealth in terms of domestic currency is also influenced by the nominal exchange rate, $e_{RoW,t}$.

Ricardian households gain utility from consumption, $C^s_{j,t}$, and experience disutility from labour, $N^s_{j,t}$, as well as from holding risky financial assets, $U^A_{j,t-1}$. The instantaneous utility function of savers, $u^s(.)$, is defined as:

$$\begin{aligned} u^s_{j,t}(C^s_{j,t}, N^s_{j,t}, \frac{U^A_{j,t-1}}{P^{C,vat}_t}) = & \frac{(C^s_{j,t} - \varepsilon^{tC}_t - h(C^s_{t-1} - \varepsilon^{tC}_{t-1}))^{1-\theta}}{1-\theta} \\ & - \frac{\omega^N \varepsilon^U_t (C_t)^{1-\theta}(N^s_{j,t} + \varepsilon^{tN}_t)^{1+\theta^N}}{1+\theta^N} \\ & - (C^s_{j,t} - \varepsilon^{tC}_t - h(C^s_{t-1} - \varepsilon^{tC}_{t-1}))^{-\theta} \frac{U^A_{j,t-1}}{P^{C,vat}_t}, \end{aligned} \tag{3}$$

where $C^s_t = \int_0^1 C^s_{j,t} dj$, h measures the strength of external habits in consumption, and ω^N is the stochastic weight of the disutility of labour. ε^U_t captures a labour supply shock. ε^{tC}_t captures the non-persistent lockdown shock (forced saving) that constrain consumption outside of habit persistence, ε^{tN}_t captures a labour hoarding shock as in (Cardani et al., 2022a).[3] The disutility of holding risky financial assets, $U^A_{j,t-1}$, takes the following form:

$$\begin{aligned} U^A_{j,t-1} = & \left(\alpha^{b_0} + \varepsilon^B_{t-1}\right) B^G_{j,t-1} + \left(\alpha^{bw_0} + \varepsilon^{bw}_{t-1}\right) e_{RoW,t} B^W_{j,t-1} \\ & + \frac{\alpha^{bw_1}}{2} \frac{(e_{RoW,t-1} NFA_{t-1})^2}{P^Y_{t-1} Y_{t-1}} + \left(\alpha^{S_0} + \varepsilon^S_{t-1}\right) P^S_{t-1} S_{j,t-1}. \end{aligned} \tag{4}$$

Internationally traded bonds are subject to transaction costs which are a function of the average NFA position relative to GDP. The asset-specific risk premium depends on an asset-specific exogenous shock ε^x, $x \in \{B, S, bw\}$, and an asset-specific intercept α^x, $x \in$

[2] $\tilde{\beta}_t = \beta \exp(\varepsilon^c_{t-1})$ features a shock to the subjective rate of time preference (saving shock) ε^c_t.

[3] Aggregate consumption, C_t, in the second term of the right-hand side is introduced as normalisation to ensure a balanced steady-state growth path.

$\{b_0, S_0, bw_0\}$. By incorporating a disutility for holding risky assets, the model reflects households' preference for safe assets, such as risk-free short-term bonds. This preference creates an endogenous gap between the returns on risky assets and those on safe bonds (Albonico et al., 2019).

The j^{th} Ricardian household faces the following budget constraint:

$$\begin{aligned} P_t^{C,vat} C_{j,t}^s + A_{j,t} &= (1-\tau^N) W_t (N_{j,t}^s + \varepsilon_t^{tN}) + (1+i_{t-1}^{rf}) B_{j,t-1}^{rf} + (1+i_{t-1}^{G}) B_{j,t-1}^{G} \\ &+ (P_t^S + P_t^Y D_t) S_{j,t-1} + (1+i_{t-1}^{W}) e_{RoW,t} B_{j,t-1}^{W} \\ &+ T_{j,t}^s - tax_{j,t}^s, \end{aligned} \tag{5}$$

where $P_t^{C,vat}$ is the private consumption deflator[4], W_t denotes the nominal wage rate, $N_{j,t}^s$ is the employment in hours, $T_{j,t}^s$ are government transfers and $tax_{j,t}^s$ lump-sum taxes paid by savers. i_t^{rf}, i_t^G, and i_t^W are returns on domestic private risk-free bonds, domestic government bonds, and internationally traded bonds, respectively. Transfers include unemployment benefits, $BEN_{j,t}^s$, defined as the gap between actual and potential hours multiplied with benefit replacement rate, τ^u:

$$T_{j,t}^s = BEN_{j,t}^s + \omega^s P_t T_t, \tag{6}$$

$$BEN_{j,t}^s = \tau^u W_t \Big(N_t^{pot} - (N_{j,t}^s + \varepsilon_t^{tN}) \Big). \tag{7}$$

Ricardian households receive nominal profits in form of dividends, D_t. Gross nominal return on shares S_t is defined as:

$$1 + i_t^S = \frac{P_t^S + P_t^Y D_t}{P_{t-1}^S}. \tag{8}$$

Ricardian households maximise the present value of the expected stream of future utility by choosing the amount of consumption, $C_{j,t}^s$, and next period asset holdings, $B_{j,t}^{rf}$, $B_{j,t}^G$, $S_{j,t}$, $B_{j,t}^W$, subject to their budget constraint (Eq. 5), The optimality conditions can be found in Appendix A.1.

[4] $P_t^{C,vat}$ is the VAT adjusted private consumption deflator, $P_t^{C,vat} = (1 + \tau^C + \varepsilon_t^{tVAT}) P_t^C$, where τ^C is the tax rate on consumption (VAT) and ε_t^{tVAT} captures the VAT-tax cut during 2020q3-2020q4 implemented by the German government.

4.1.2. Liquidity-constrained households

Liquidity-constrained (LC) households do not have access to financial markets. Their instantaneous utility function, $u^c(.)$, is:

$$u^c_{j,t}(C^c_{j,t}, N^c_{j,t}) = \frac{(C^c_{j,t} - \varepsilon^{tC}_t - h(C^c_{t-1} - \varepsilon^{tC}_{t-1}))^{1-\theta}}{1-\theta} - \frac{\omega^N \varepsilon^U_t (C_t)^{1-\theta}}{1+\theta^N}(N^c_{j,t} + \varepsilon^{tN}_t)^{1+\theta^N}. \tag{9}$$

In each time period, they consume their entire net disposable income, which consists of after-tax (paid) labour income and lump-sum transfers from the government:

$$P^{C,vat}_t C^c_{j,t} = (1-\tau^N) W_t (N^c_{j,t} + \varepsilon^{tN}_t) + T^c_{j,t} - tax^c_{j,t} + P^{C,vat}\left(\varepsilon^{tC}_t - \frac{1}{6}\sum_{i=8}^{13} \varepsilon^{tC}_{t-i}\right). \tag{10}$$

During the COVID-19 pandemic, this constraint is eased such that even LC households can save (forced savings), ε^{tC}_t, which will be gradually spent post-pandemic.

4.1.3. Wage setting

Households supply differentiated labour services, $N^r_{j,t}$, with $r = \{s, c\}$, in a monopolistically competitive labour market. A labour union aggregates labour hours from both types of households into a unified labour service and supplies it to the intermediate goods producing firms. Given the same labour demand schedule, each household works the same average number of hours. The union maximises the weighted average of the members' discounted future utility stream with respect to the wage, subject to the combined budget constraints of the households and the demand for differentiated labour by intermediate-goods producers.

Nominal wage rigidity takes the form of quadratic adjustment costs for changing nominal wages according to $adj^w_t = \frac{\gamma^w(\sigma^n-1)}{2} W_t N_t (\pi^w_t - \pi^w)^2$, where σ^n is the inverse of the steady gross wage markup and π^w_t is the wage inflation. Real wage rigidity is modelled in the spirit of Blanchard and Galí (2007), implying a gradual adjustment of past reals wages to changes in the price level. The wage rule is determined by equating the marginal utility of leisure, U^N_t, to the weighted average of the marginal utility of consumption, λ_t, times the real wage adjusted for a wage markup. The wage equation is:

$$\mu^w \left[\frac{U^N_t}{\lambda_t} - \tau^u \frac{W_t}{P^{C,vat}_t} - \mu^w_t\right]^{1-\gamma^{wr}} \left[(1-\tau^N)\frac{W_{t-1}}{P^{C,vat}_{t-1}}\right]^{\gamma^{wr}} = (1-\tau^N)\frac{W_t}{P^{C,vat}_t}, \tag{11}$$

where μ_t^w is the cyclical gross wage markup:

$$\mu_t^w = \gamma^w \left[\frac{\partial adj_t^w}{\partial W_t} - \beta E_t \frac{\lambda_{t+1}}{\lambda_t} \frac{1}{\pi_{t+1}^{C,vat} + 1} \frac{\partial adj_{t+1}^w}{\partial W_t} \right]. \tag{12}$$

μ^w is the steady state gross wage markup, γ^w and γ^{wr} represent the degree of nominal and real wage rigidity, respectively, and ε_t^U captures a labour supply shock (wage markup). The marginal utility of leisure is defined as: $U_t^N = \omega^N (C_t)^{1-\theta} (N_t)^{-\theta^N}$, and λ_t the weighted average of the marginal utility of consumption.

4.2. Production sector

The total domestic output is a combination of domestic value added and commodities. Value added consists of a bundle of differentiated goods produced by monopolistically competitive firms, which utilise capital and labour in their production processes.

4.2.1. Total output demand

Perfectly competitive firms produce total output, O_t, by combining value added, Y_t, with (imported) commodities, CO_t, using the following CES production function:

$$O_t = \left[\left(1 - s^{CO} \exp(\varepsilon_t^{CO})\right)^{\frac{1}{\sigma^o}} (Y_t)^{\frac{\sigma^o - 1}{\sigma^o}} + \left(s^{CO} \exp(\varepsilon_t^{CO}\right)^{\frac{1}{\sigma^o}} (CO_t)^{\frac{\sigma^o - 1}{\sigma^o}} \right]^{\frac{\sigma^o}{\sigma^o - 1}}. \tag{13}$$

s^{CO} represents the commodity input share, influenced by the exogenous process ε_t^{CO}. σ^o refers to the elasticity of substitution between factors. Each firm maximises its expected profits:

$$\max_{Y_t, IS_t} P_t^O O_t - P_t^Y Y_t - P_t^{CO} CO_t, \tag{14}$$

subject to the production function (13). The first order conditions for the demand for value added and commodities are:

$$Y_t = \left(1 - s^{CO} u_t^{CO}\right) \left(\frac{P_t^Y}{P_t^O}\right)^{-\sigma^o} O_t, \tag{15}$$

$$CO_t = s^{CO} u_t^{CO} \left(\frac{P_t^{CO}}{P_t^O}\right)^{-\sigma^o} O_t. \tag{16}$$

Commodities are assumed to be produced only by RoW. Consequently, all commodities used by Germany are imported from RoW, and their price is taken as given:

$$P_t^{CO} = e_{Row,t} P_{Row,t}^{CO} + \tau^{CO} P_t^{Y0}, \tag{17}$$

where $e_{Row,t}$ is the exchange rate, τ^{CO} and P^{Y0} are the excise duty and the (global) GDP trend deflator, respectively. The total output aggregate price index is given by:

$$P_t^O = \left[(1 - s^{CO} u_t^{CO})(P_t^Y)^{\sigma^o - 1} + s^{CO} u_t^{CO} (P_t^{CO})^{\sigma^o - 1} \right]^{\frac{1}{1-\sigma^o}}. \tag{18}$$

4.2.2. Value added and intermediate goods producers

Value added, Y_t, is produced by firms operating in a perfectly competitive market. These firms combine a variety of differentiated goods, $Y_{i,t}$, which are produced by firms in a monopolistically competitive market. The differentiated goods are produced using a Cobb-Douglas production function with labour, $N_{i,t}$, private capital, $K_{i,t-1}$, and public capital, $K_{i,t-1}^G$, as input factors:

$$Y_{i,t} = \left[A_t^Y \Big((N_{i,t} + \varepsilon_t^{tN}) - FN \Big) \right]^{\alpha} (CU_{i,t} K_{i,t-1})^{1-\alpha} (K_{t-1}^G)^{1-\alpha_G} - A_t^Y FC_i. \tag{19}$$

α is the steady state labour share, A_t^Y is an exogenous common labour-augmenting stochastic productivity scalar, $CU_{i,t}$ and FN are firm-specific levels of capacity utilisation and labour overhead, respectively. FC_i represents fixed costs in production. Gross investment, $I_{i,t}$, drives the law of motion for private capital $K_{i,t} = I_{i,t} + (1-\delta)K_{i,t-1}$, with the depreciation rate δ. Public capital, $K_{i,t-1}^G$, follows an analogous accumulation equation with output elasticity α_G. A_t^Y is a non-stationary process with two types of technology shocks, ε_t^A and ε_t^{GA}. They are related to a non-stationary process and its autoregressive component ρ^A:

$$log(A_t^Y) - log(A_{t-1}^Y) = g_t^A + \varepsilon_t^A, \tag{20}$$

$$g_t^A = \rho^A g_{t-1}^A + (1-\rho^A) g^A + \varepsilon_t^{GA}, \tag{21}$$

where g_t^A g^A are the time-varying growth and the long-run growth of technology, respectively.

Following the approach by Cardani et al. (2022a), the model incorporates a transitory labour demand shock (labour hoarding, ε_t^{tN}) to capture short-time work arrangements during the onset of COVID-19, i.e. employees working fewer hours while remaining employed, thereby introducing a wedge between hours worked (production function) and hours paid (wage income). It enters as a transitory shock to hours worked. Dividends are defined as:

$$D_{i,t} = P_{i,t}^Y Y_{i,t} - W_t (N_{i,t} + \varepsilon_t^{tN}) - P_t^I (I_{i,t} + \varepsilon_t^{tS}) - adj_{i,t}, \tag{22}$$

where W_t and $P_{i,t}^I$ are the nominal wage rate and the price of investment goods, respectively.

ε_t^{tS} represents an investment-specific lockdown shock. Following Rotemberg (1982), firms face quadratic adjustment costs, $adj_{i,t}$, associated with the output price, $P_{i,t}^Y$, labour input, $N_{i,t}$, private investment, $I_{i,t}$, and capacity utilisation, $CU_{i,t}$. The adjustment cost definitions and optimality conditions can be found in Appendix A.2.

4.3. International trade

Final good packagers combine domestic output and imported goods to supply different sectors in the economy with components of aggregate demand. Imported goods are a bundle of imports sourced from different origins and are put together by import retailers.

Final good packagers

The final aggregate demand-component goods are manufactured by perfectly competitive firms that combine domestic output, $O_t^{\mathcal{Z}}$, with imported goods from REA and RoW, $M_t^{\mathcal{Z}}$, using a CES production function. The demand for final goods, $\mathcal{Z} = \{C, G, I, I^G, X\}$, comes from households and the government, private and public investors, as well as exporters of final goods, respectively:

$$\mathcal{Z}_t = A_t^{p^{\mathcal{Z}}} \left[(1 - s_t^{M,\mathcal{Z}})^{\frac{1}{\sigma^z}} (O_t^{\mathcal{Z}})^{\frac{\sigma^z - 1}{\sigma^z}} + (s_t^{M,\mathcal{Z}})^{\frac{1}{\sigma^z}} (M_t^{\mathcal{Z}})^{\frac{\sigma^z - 1}{\sigma^z}} \right]^{\frac{\sigma^z}{\sigma^z - 1}}, \tag{23}$$

σ^z represents the elasticity of substitution of imports, and $A_t^{p^{\mathcal{Z}}}$ is a shock to productivity in the sector producing goods, $\mathcal{Z}$. $s_t^{M,\mathcal{Z}}$ is a sector-specific stochastic import share, where $s_t^{M,\mathcal{Z}} = exp(\varepsilon_t^{M,\mathcal{Z}}) s^{M,\mathcal{Z}}$. $s^{M,\mathcal{Z}}$ denotes the steady state import share of $\mathcal{Z}$. Demand for domestic output and imported goods is given by:

$$O_t^{\mathcal{Z}} = (A_t^{p^{\mathcal{Z}}})^{\sigma^z - 1} \left(1 - s_t^{M,\mathcal{Z}} \right) \left(\frac{P_t^O}{P_t^{\mathcal{Z}}} \right)^{-\sigma^z} \mathcal{Z}_t, \tag{24}$$

$$M_t^{\mathcal{Z}} = (A_t^{p^{\mathcal{Z}}})^{\sigma^z - 1} s_t^{M,\mathcal{Z}} \left(\frac{P_t^M}{P_t^{\mathcal{Z}}} \right)^{-\sigma^z} \mathcal{Z}_t, \tag{25}$$

The price deflator associated to the demand components is:

$$P_t^{\mathcal{Z}} = (A_t^{p^{\mathcal{Z}}})^{-1} \left[(1 - s_t^{M,\mathcal{Z}}) (P_t^O)^{1-\sigma^z} + s_t^{M,\mathcal{Z}} (P_t^M)^{1-\sigma^z} \right]^{\frac{1}{1-\sigma^z}}. \tag{26}$$

Total non-commodity imports are defined as:

$$M_t = M_t^C + M_t^I + M_t^G + M_t^{IG} + M_t^X. \tag{27}$$

Import retailers

Final non-commodity imports are produced by perfectly competitive firms that combine goods from the foreign regions into a final import good. The demand for goods from country l is:

$$M_{l,t} = s^M_{l,t}\Big(\frac{P^M_{l,t}}{P^M_t}\Big)^{-\sigma^{FM}} M_t \frac{size}{size_l}, \tag{28}$$

and the import prices deflator is:

$$P^M_t = \left[\sum_l s^M_{l,t}(P^M_{l,t})^{1-\sigma^{FM}}\right]^{\frac{1}{1-\sigma^{FM}}}. \tag{29}$$

σ^{FM} represents the price elasticity of demand for country l's goods, and $P^M_{l,t}$ is the price of its good. The good from country l is purchased at the export price of country l, $P^X_{l,t}$. Hence, the import price for the domestic country is defined as:

$$P^M_{l,t} = e_{l,t}P^X_{l,t}. \tag{30}$$

4.4. Fiscal policy

The government raises taxes on consumption, τ^C, corporate profits, τ^K, lump-sum taxes, tax_t, and wage income tax, τ^N_t. It finances consumptive purchases, G_t, investments, IG_t, and transfers, T_t. The tax on commodity imports, τ^{CO}, is fixed. τ^{FN} denotes a labour hoarding subsidy. Nominal debt evolves as:

$$B^G_t = (1+i^G_t)B^G_{t-1} - R^G_t + P_tG_t + P_tIG_t + P_tT_t, \tag{31}$$

where R^G_t are the nominal government revenues:

$$R^G_t = (\tau^C + \varepsilon^{tVAT}_t)P_tC_t + \tau^K\Big(P_tY_t - W_t(N_t + \varepsilon^{tN}_t) - \delta P_tK_{t-1}\Big) \tag{32}$$

$$+ \tau^N_t(N_t + \varepsilon^{tN}_t)W_t + \tau^{CO}P^{CO}_tCO_t + \tau^{FN}W_t\Big((N_t + \varepsilon^{tN}_t) - N_t\Big) + tax_t. \tag{33}$$

Lump-sum taxes, tax_t, adjust residually as government budget closure:

$$tax_t = \rho_\tau tax_{t-1} + \eta^{deft}\left(\frac{\Delta B^G_{t-1}}{Y_{t-1}P^Y_{t-1}} - DEFTAR\right)$$

$$+ \eta^{BT}\left(\frac{B^G_{t-1}}{Y_{t-1}P^Y_{t-1}} - BTAR\right) + \varepsilon^{tax}_t, \tag{34}$$

where $DEFTAR$ and $BTAR$ are the targets on government deficit and government debt, respectively, and ε_t^{tax} captures a shock. The government increases (decreases) taxes when the level of government debt and the government deficit is above (below) the debt and deficit target. On the spending side, government consumption, G_t, investment, IG_t, and transfers, T_t follow AR(1) processes and are subject to idiosyncratic shocks (ε^G, ε^{IG} and ε^T).

4.5. Monetary policy

Monetary policy follows a Taylor (1993)-type policy rule subject to an ELB constraint. The target interest rate, $i_{EA,t}^{not}$, responds sluggishly to (quarterly annualised) deviations of EA-wide CPI inflation ($\pi_{EA,t}^{C,QA}$) and EA output gap ($\hat{Y}_{EA,t}^{QA}$) from their respective target levels:[5]

$$i_{EA,t}^{not} - \bar{i} = \rho_{EA}^i(i_{EA,t-1} - \bar{i}) + (1 - \rho_{EA}^i)\left[\eta_{EA}^{i\pi}0.25\left(\pi_{EA,t}^{C,QA} - \bar{\pi}_{EA}^{C,QA}\right) + \eta_{EA}^{iy}\hat{Y}_{EA,t}^{QA}\right]. \tag{35}$$

$\bar{i} = \bar{r} + \bar{\pi}^{Yobs}$ is the steady state nominal interest rate, which equals the sum of the steady state real interest rate and trend inflation. The policy parameters (ρ^i, $\eta^{i\pi}$, η^{iy}) capture interest rate inertia and the response to the EA inflation and EA output gap, respectively.

The effective policy rate, $i_{EA,t}$, corresponds to the target nominal short-term rate as long as the latter is above the ELB, (i^{LB}). The effective policy rate satisfies:

$$i_{EA,t} = max\{i_{EA,t}^{not}, i^{LB}\} + \varepsilon_{EA,t}^i, \tag{36}$$

where $\varepsilon_{EA,t}^i$ captures a monetary policy shock. More details on the ELB treatment will be explained in section 5.

4.6. Commodities

Following Cardani et al. (2023), commodities are traded at destination-specific prices, influenced by exogenous supply shocks.[6] The total demand for commodities, CO_t, comprises household energy consumption, C_t^E, and the demand for industrial supplies in final goods production, IS_t. Final household consumption is represented as a CES aggregate of commodities used for consumption and final manufactured goods C_t^{FG}:

$$C_t = \left[(s_t^E)^{\frac{1}{\sigma^E}}(C_t^E)^{\frac{\sigma^E-1}{\sigma^E}} + (1 - s_t^E)^{\frac{1}{\sigma^E}}(C_t^{FG})^{\frac{\sigma^E-1}{\sigma^E}}\right]^{\frac{\sigma^E}{\sigma^E-1}}, \tag{37}$$

[5]Potential output, $Y_{EA,t}^{pot}$, is defined as the output level that prevails when labour input equals steady state per capita hours worked, the capital stock is utilised at full capacity, and TFP equals its trend component.

[6]Unlike Giovannini et al. (2019), this model incorporate an endogenous supply equation where commodity demand is affecting global commodity prices.

where s_t^E represents the energy share and σ^E the elasticity of substitution.

4.7. Closing the economy

The resource constraint of the DE economy is:

$$Y_t P_t^Y + \tau^{CO} CO_t P_t^{Y0} = P_t^C C_t + P_t^I I_t + P_t^{IG} IG_t + P_t^G G_t + TB_t, \tag{38}$$

where TB_t is the trade balance, defined as the difference between exports and (non-commodity) imports:

$$TB_t = P_t^X X_t - \sum_l \frac{size_l}{size} P_{l,t}^M M_{l,t} - P_{RoW,t}^{CO} CO_{RoW,t} e_{RoW,t}. \tag{39}$$

Domestic holding of the internationally traded bond, B_t^W, evolves according to:

$$e_{RoW,t} B_t^W = (1 + i_{t-1}^{bw}) e_{RoW,t} B_{t-1}^W + TB_t + ITR P_t^Y Y_t. \tag{40}$$

ITR represents international transfers that allow to calibrate a non-zero steady state of the trade balance. The sum of all countries' net foreign assets are zero:

$$\sum_l NFA_{l,t} size_l = 0. \tag{41}$$

4.8. The REA and RoW blocks

The REA and RoW (subscript $k = REA, RoW$) model blocks include a budget constraint for the representative household, demand functions for both domestic and imported goods, a linear production technology, a New Keynesian Phillips curve, and a Taylor rule. Both regions do not take capital accumulation into account. The simplified model blocks are subject to various shocks, including those affecting labour productivity, price markups on final output, the subjective discount rate, the relative preference for domestic versus imported goods, and monetary policy surprises.

The household budget constraint in the REA, as a commodity importer, is defined as:

$$Y_{REA,t} P_{REA,t}^Y + \tau^{CO} CO_{REA,t} P^{Y0} = P_{REA,t}^C C_{REA,t} + TB_{REA,t}, \tag{42}$$

where $\tau^{CO} CO_{REA,t} P^{Y0}$ represents the excise duty.

Final aggregate demand, $C_{k,t}$, is a combination of domestic output, $Y_{k,t}^C$, and imported goods, $M_{k,t}^C$, using the following CES function:

$$C_{k,t} = A_{k,t}^p \left[(1 - \varepsilon_{k,t}^M s_k^M)^{\frac{1}{\sigma_k^c}} (Y_{k,t}^C)^{\frac{\sigma_k^c - 1}{\sigma_k^c}} + (\varepsilon_{k,t}^M s_k^M)^{\frac{1}{\sigma_k^c}} (M_{k,t}^C)^{\frac{\sigma_k^c - 1}{\sigma_k^c}} \right]^{\frac{\sigma_k^c}{\sigma_k^c - 1}}. \tag{43}$$

σ_k^c represents the import elasticity of substitution, $A_t^{p^C}$ is a shock to productivity in the sector producing goods, C, and s_t^M is the import share. The demand for domestic and imported goods is obtained from profit maximisation:

$$Y_{k,t}^C = (A_{k,t}^{p^C})^{\sigma_k^c - 1}\Big(1 - \varepsilon_{k,t}^M s_k^M\Big)\Big(\frac{P_{k,t}^Y}{P_{k,t}^C}\Big)^{-\sigma_k^c} C_{k,t}, \tag{44}$$

$$M_{k,t}^C = (A_{k,t}^{p^C})^{\sigma^c - 1}\varepsilon_{k,t}^M s_k^M \Big(\frac{P_{k,t}^M}{P_{k,t}^C}\Big)^{-\sigma_k^c} C_{k,t}, \tag{45}$$

where the consumer price deflator, $P_{k,t}^C$, is:

$$P_{k,t}^C = (A_{k,t}^{p^C})^{-1}\Bigg[(1 - \varepsilon_{k,t}^M s_k^M)(P_{k,t}^Y)^{1-\sigma_k^c} + \varepsilon_{k,t}^M s_k^M (P_{k,t}^M)^{1-\sigma_k^c}\Bigg]^{\frac{1}{1-\sigma_k^c}}. \tag{46}$$

The good producers use labour as input factor, $Y_{k,t} = A_{k,t}^Y N_{k,t}$, where $A_{k,t}^Y$ represents trend productivity. The price setting equation follows a New Keynesian Phillips curve:

$$\pi_{k,t}^Y - \bar{\pi}_k^Y = \beta \frac{\lambda_{k,t+1}}{\lambda_{k,t}}(\pi_{k,t+1}^Y - \bar{\pi}_k^Y) + \phi_k^Y log(\frac{Y_{k,t}}{\bar{Y}_k}) + \varepsilon_{k,t}^Y, \tag{47}$$

where $\lambda_{k,t} = (C_{k,t} - h_k C_{k,t-1})^{-\theta_k}$ is the marginal utility of consumption, and $\varepsilon_{k,t}^Y$ is a cost-push shock.

REA and RoW total nominal exports are defined as: $P_{k,t}^X X_{k,t} = \sum_l P_{l,k,t}^X M_{l,k,t}$, with the bilateral export price being defined as the domestic price subject to a bilateral price shock, $P_{l,k,t}^X = exp(\varepsilon_{l,k,t}^X) P_{k,t}^Y$.

Combining the two region's FOCs with respect to international bonds derive the uncovered interest parity (UIP) condition:

$$E_t\Bigg[\frac{e_{RoW,EA,t+1}}{e_{RoW,EA,t}}\Bigg](1 + i_{RoW,t}) = (1 + i_{EA,t}) + \varepsilon_{EA,t}^{bw} + \alpha_{EA}^{bw0} + \alpha_{EA}^{bw1}\frac{e_{RoW,EA,t}B_{EA,t}^w}{P_{EA,t}^Y Y_{EA,t}}, \tag{48}$$

where $\varepsilon_{EA,t}^{bw}$ captures a euro exchange rate shock (shock to the bond premium between EA and RoW), and α_{EA}^{bw1} is a debt-dependent country risk premium on NFA holdings to ensure long-run stability of the model (Schmitt-Grohe and Uribe, 2003).

4.9. RoW commodity supply

The RoW exclusively supplies two distinct commodities, namely oil, CO^{Oil} and non-oil commodities, CO^{IS}, such as natural gas and materials, to domestic and foreign firms. ε_t^{CO} captures exogenous commodity supply shocks. The RoW producer combines oil (Oil) and non-oil (IS) commodities into bundles, CO, that are either exported to DE and REA or used domestically. The price of the commodity bundle is specific to its destination and includes a shock term, $\varepsilon_{l,t}^{P,CO}$, where $l = (DE, REA)$, aiming to reflect price variations due to differing commodity baskets. Therefore:

$$P_{l,t}^{CO} = \varepsilon_{l,t}^{PCO}\left[s_l^{Oil}\left(P_t^{Oil}\right)^{1-\sigma^{CO}} + (1 - s_l^{Oil})\left(P_t^{IS}\right)^{1-\sigma^{CO}}\right]^{\frac{1}{1-\sigma^{CO}}}, \tag{49}$$

$$P_t^{CO} = \left[s^{Oil}\left(P_t^{Oil}\right)^{1-\sigma^{CO}} + (1 - s^{Oil})\left(P_t^{IS}\right)^{1-\sigma^{CO}}\right]^{\frac{1}{1-\sigma^{CO}}}. \tag{50}$$

Commodity prices are exogenous and follow:

$$P_t^{CO} = \frac{P_t}{A_t^{CO}}, \quad \text{where CO=(Oil, IS)} \tag{51}$$

where A_t^{CO} is the exogenous commodity-specific productivity technology.

5. Model solution and econometric approach

Model solution

The following non-linear system summarises the observation and state equations of the model:

$$y_t^{obs} = \Psi_1(\Theta) S_t, \tag{52}$$

$$S_t = \Psi_1(\Theta) S_{t-1} + \Theta_\varepsilon(\theta)\varepsilon_t, \quad \varepsilon_t \sim N(0, Q_t I) \tag{53}$$

In observation equation (52), y_t^{obs} denotes the vector of observables at time t, and $\Psi_1(\Theta)$ links the model variables to the data. The state equation (53) describes the transition of the system's state variables, S_t, where $\Psi_1(\Theta)$ and Θ_ε are the coefficient matrices. Following Cardani et al. (2022a), the model shocks, ε_t, follow a normal distribution with time-varying covariance matrix $Q_t I$, such that the state equation (53) incorporates deterministic heteroskedasticity:

$$Q_t = \begin{cases} Q^{COVID} & \text{for } t \in \{2020q1 : 2022q4\}, \\ Q & \text{otherwise.} \end{cases} \tag{54}$$

For the pandemic period 2020q1-2022q4, $Q_t = Q^{COVID}$ incorporates temporary COVID-specific shocks, whereas prior to COVID-19, $Q_t = Q$, implies zero standard deviations (and zero expectations) for these shocks.

Estimation procedure and filtering

The estimation proceeds in three steps:

1. A subset of parameters is calibrated to match historical long-run properties, such as steady-state ratios.

2. The remaining parameters are estimated using data over the sample period 1999q1 - 2023q4. The full-sample estimation procedure incorporates the estimation of heteroskedastic COVID-specific variances during the period 2020q1–2022q4, thereby allowing for time-varying shock disturbances Q_t.[7] The estimation employs a linear Kalman filter and a parallelised slice sampling algorithm to draw parameters from their posterior distribution using Markov Chain Monte Carlo methods.[8] We use the Dynare software to solve the linearised model and to perform the estimation (Adjemian et al., 2024).

3. The model accounts for endogenous effective lower bound (ELB) periods using the OccBin approach by Guerrieri and Iacoviello (2015). More precisely, the paper employs a piecewise linear Kalman filter, as in Giovannini et al. (2021), to identify the structural shocks until 2023q4 given the parameter estimates, accounting for ELB periods.[9]

Data

The estimation process employs both quarterly and annual data spanning from 1999q1 to 2023q4. The model is estimated at a quarterly frequency, integrating interpolated annual data for series not available at higher frequencies. The data for Germany and the Euro Area aggregate (EA19) are taken from Eurostat. Bilateral trade flows are derived from trade shares using the GTAP trade matrices, covering both goods and services. The annual data for the RoW are compiled from the IMF International Financial Statistics (IFS) and World Economic Outlook (WEO) databases. The estimated model incorporates 41 observed series and accounts for 41 exogenous shocks. Details on the observed time series can be found in Appendix D. The extensive number of shocks corresponds to the large set of observables

[7] Cardani et al. (2022a, 2023) employ a two-step approach, where the parameters are estimated using data only until 2019q4 in a first step. In a second step, they estimate the variances of heteroskedastic COVID-specific shocks using data for the pandemic period (2020q1–2021q4 or 2020q1–2022q4, respectively), while keeping all other parameters unchanged by initialising the system's state and covariance matrix at their estimates from the first step.

[8] The slice sampler algorithm was introduced by Neal (2003). Planas et al. (2015) reconsider the slices along the major axis of the ellipse to better fit the distribution than any Euclidean slices. The slice sampler has been shown to be more efficient and to offer better mixing properties than the Metropolis-Hastings sampler (Calés et al., 2017). The slice sampler has been used, e.g., by Giovannini et al. (2019) and Hohberger et al. (2019, 2023).

[9] Cardani et al. (2023) provides additional methodological details. Similar approaches of retrieving endogenous duration of ELB periods have been used, e.g., by Hohberger et al. (2019) and Croitorov et al. (2020).

utilised for the estimation.

Calibrated parameters

Steady state ratios in the model are calibrated to match the average historical data for DE, REA and RoW. The steady state shares of DE, REA, and RoW in world GDP are 5.4%, 14.5%, and 80.1%, respectively. The trade-related parameters, specifically the degree of openness and import preferences, reflect the average import content of demand components as computed by Bussière et al. (2013). For Germany, the steady state ratios of private consumption, investment, and government expenditure to GDP are 55%, 19%, and 21%, respectively. The global trend GDP growth rate and trend inflation rate are 1.25% and 2% per year, respectively. The annual depreciation rate of capital is 5.9%. The rate of time preference is set at 0.25% per quarter. Additionally, the steady state share of Ricardian households is calibrated to be 61%, based on the survey by Dolls et al. (2012). The steady state government debt to annual GDP ratio is 62%. Table B.1 in Appendix B presents an overview of selected calibrated parameters.

Posterior estimates

Table 1 reports the prior and posterior estimates, as well as the 90% highest posterior density (HPD) intervals, for selected key model parameters. The estimated EA monetary policy parameters suggest a strong response to EA inflation (2.03) compared to the EA output gap (0.03), together with relatively high interest rate inertia (0.90). Estimated habit persistence is 0.88, implying a slow adjustment of consumption to changes in income. Risk aversion and the inverse labour supply elasticity are 1.48 and 2.92, respectively, and similar to those in the literature (e.g., Hohberger et al., 2020; Cardani et al., 2022b). Concerning international trade estimates, the price elasticity of import demand is 1.02, and the price elasticity of commodity demand is 0.19. The posterior estimates also suggest sticky prices (31.8), wages (25.8), and investments (59.1). The estimated parameters for REA and RoW can be found in Table B.2 in Appendix B. Table B.3 and Table B.4 in Appendix B report the main estimated shock processes for DE, and REA and RoW, respectively.

Table 2 reports the posterior estimates of the pandemic-specific innovations that have specifically affected the COVID-19 period. The estimation suggests a mixture of demand-side (lockdown shocks) and supply-side shocks (labour market). More precisely, it indicates a pronounced incidence of consumption-specific lockdown shocks (4.75%). It also suggests substantial labour hoarding shocks (2.57%), in line with the measures and labour market policies adopted by Germany. The estimated VAT-tax cut during the period 2020q3-2020q4 is 1.7%. Given the simplified REA and RoW model structure, the estimation suggests a transitory (lockdown) and persistent savings shock (risk shock) for REA to capture the

Table 1: Prior and posterior distribution of key estimated DE model parameters.

		Prior distribution		Posterior distribution
		Distr	Mean St.Dev	DE
EA Monetary Policy				
Interest rate persistence	ρ^i	G	0.85 0.05	0.91 (0.88, 0.93)
Response to inflation	$\eta^{i,\phi}$	G	2.00 0.20	1.78 (1.56, 2.19)
Response to GDP	$\eta^{i,y}$	G	0.10 0.04	0.05 (0.03, 0.11)
Preferences				
Consumption habit persistence	h	B	0.50 0.20	0.90 (0.83, 0.92)
Risk aversion	θ	G	1.50 0.20	1.33 (1.16, 1.70)
Inverse Frisch elasticity of labour supply	θ^N	G	2.50 0.50	3.72 (2.21, 4.86)
Import price elasticity	σ^z	G	2.00 0.40	1.93 (1.64, 2.19)
Oil price elasticity	σ^o	G	0.5 0.1	0.40 (0.32, 0.48)
Nominal and real frictions				
Price adjustment cost	γ^P	G	20 12	40.8 (33.7, 49.9)
Nominal wage adjustment cost	γ^w	G	20 12	17.3 (9.2, 19.4)
Real wage rigidity	γ^{wr}	B	0.47 0.20	0.85 (0.54, 0.89)
Employment adjustment cost	γ^N	G	20 12	1.8 (1.5, 2.3)
Capacity utilisation quadratic adj cost	$\gamma^{CU,2}$	G	0.003 0.0012	0.003 (0.002, 0.005)
Investment adjustment cost	$\gamma^{I,2}$	G	40 25	38.2 (19.1, 67.5)
Fiscal policy				
Lump-sum tax persistence	ρ^{tax}	B	0.85 0.06	0.82 (0.75, 0.89)
Tax response to deficit	η^{def}	B	0.03 0.008	0.03 (0.02, 0.04)

Note: Cols. (1)-(2) list model parameters. Cols. (3)-(4) indicate the prior distribution function (B: Beta distribution; G: Gamma distribution). Col. (5) shows the mode and the 90% HPD intervals of the posterior distributions of model parameters.

COVID-19 pattern during 2020 and the recovery in 2021-2022. For the RoW, the estimation suggests an additional persistent savings shock (risk shock) to capture the pattern of the pandemic period.[10]

[10]The interpolated annual data for RoW provide a less pronounced contraction of GDP growth in 2020q2, for which the estimation does not suggest proper identification of the consumption-specific lockdown shock as in DE and REA.

Table 2: Prior and posterior distribution of estimated COVID-specific innovations.

		Prior distribution		Posterior distribution
		Distr	Mean St.Dev	
DE COVID-specific shocks (standard deviations in %)				
Consumption-specific lockdown shock	ε^{tC}	G	5	4.75
			2	(4.03, 7.36)
Investment-specific lockdown shock	ε^{tS}	G	5	2.27
			2	(1.10, 5.80)
labour hoarding shock	ε^{tN}	G	5	2.57
			2	(1.85, 4.77)
VAT tax shock	ε^{tVAT}	G	2	1.70
			0.8	(0.91, 3.03)
REA COVID-specific shocks (standard deviations in %)				
Consumption-specific lockdown shock	ε^{tC}	G	5	6.97
			2	(4.99, 9.78)
Risk shock	$\varepsilon^{t\beta}$	G	5	8.30
			2	(3.91, 10.13)
RoW COVID-specific shocks (standard deviations in %)				
Risk shock	$\varepsilon^{t\beta}$	G	5	13.76
			2	(12.63, 17.44)

Note: This table reports the mode and the standard deviation (in %) of the posterior distributions of DE, REA and RoW COVID-specific shock innovations.

ELB environment - Non-linear smoothing

This paper implements the ELB as in Hohberger et al. (2019) and Croitorov et al. (2020), following the piecewise linear Kalman filter algorithm by Giovannini et al. (2021). Given the parameter estimates of the model, the algorithm identifies structural shocks that account for endogenous ELB periods using the OccBin approach of Guerrieri and Iacoviello (2015). Thus, it generates a sequence of smoothed variables and shocks that are consistent with the occasionally binding constraint.[11] The sequence of regimes for Germany, i.e., non-binding or binding ELB, is reported in Table B.5 in Appendix B.

[11]See Giovannini et al. (2021) and Cardani et al. (2023) for a detailed description of the methodological details.

6. Dynamic transmission of shocks

This section examines the estimated dynamic effects of shocks characteristic of the COVID-19 pandemic and recovery period from 2020 to 2023. Accordingly, it compares the dynamic transmissions between scenarios where the ELB on the short-term nominal interest rate is binding (piecewise) and when it is not binding (linear). When the ELB is binding, economic contraction during the COVID-19 period, marked by decreasing output and inflation rates, is not countered by expansionary monetary policy to alleviate the downturn in economic activity. Conversely, during 2021-23, negative supply-side shocks leading to rising inflation rates and a slowdown in economic activity are further intensified by monetary tightening aimed at reducing inflation.

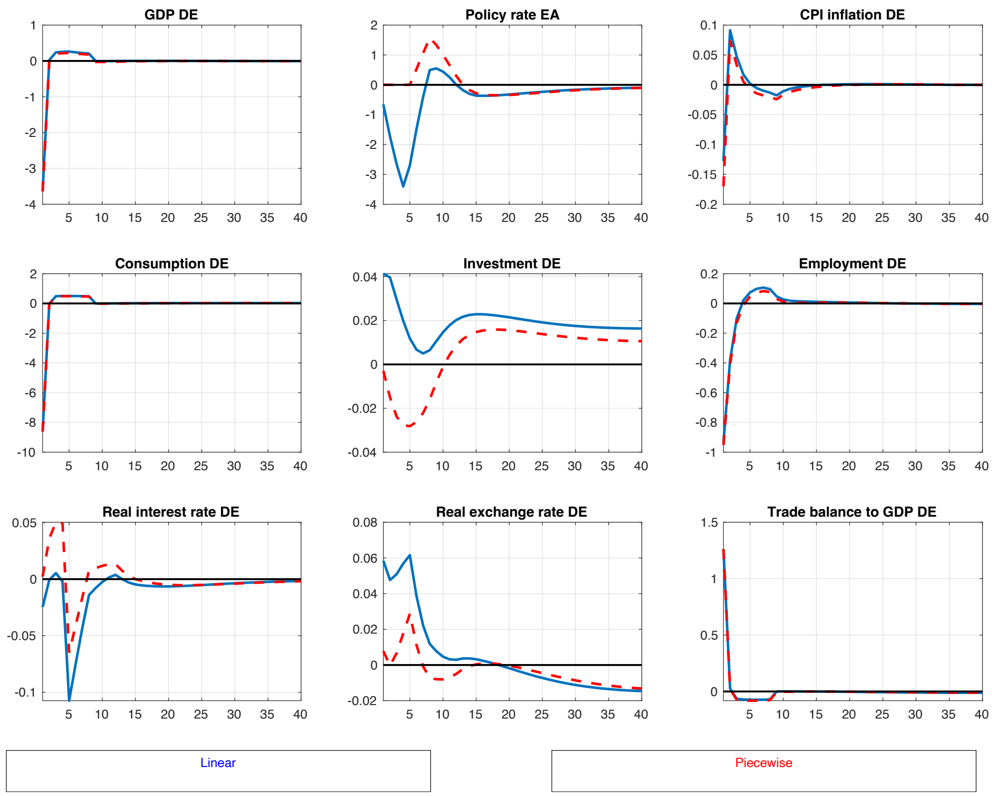
Therefore, this section presents generalised impulse response functions (GIRFs) for the following shocks: (i) a transitory lockdown shock, (ii) a risk shock in RoW, (iii) a shock to commodity prices (oil), and (iv) supply-side shocks (retail markup and export prices) that capture binding capacity constraints. The GIRFs are considered within a constrained monetary policy setup where short-term interest rates cannot be adjusted. Specifically, following the sequence of regimes in Table B.5, GIRFs with an effective ELB, consistent with the estimated timing and duration of the ELB regime in the model, are obtained by performing the following steps: Set 2020q2 as the starting point - a period in which the ELB is binding for an additional 6 quarters (see Table B.5) - remove the respective estimated shock, and simulate the model with all remaining shocks. Then, perform simulations by adding the respective estimated shock. The difference between the two scenarios provides the GIRFs under the ELB (red-dashed).

All shocks are performed using the estimated shock variance and persistence. Each panel displays the dynamic responses of real GDP, the policy rate, CPI inflation, private consumption, private investment, total hours worked, the real interest rate, the real effective exchange rate (REER), and the trade balance-to-GDP ratio. Real variables are presented in percent deviations from their respective steady states, whereas the policy rate (annualised), CPI inflation (annualised), and the trade balance-to-GDP ratio are expressed as deviations from the steady state in basis points and percentage points, respectively.

Transitory lockdown shock

Figure 2 illustrates the dynamic responses to the transitory lockdown shock, which accounts for the majority of the GDP and consumption contraction during the lockdown in the second quarter of 2020. Based on the estimated magnitude of this non-persistent saving shock and the constrained ELB, it reduces private consumption and real GDP by 8.5% and 3.6%, respectively, for one quarter (2020q2). The reduction in consumption demand, coupled

Figure 2: Dynamic responses to a lockdown shock (forced saving).



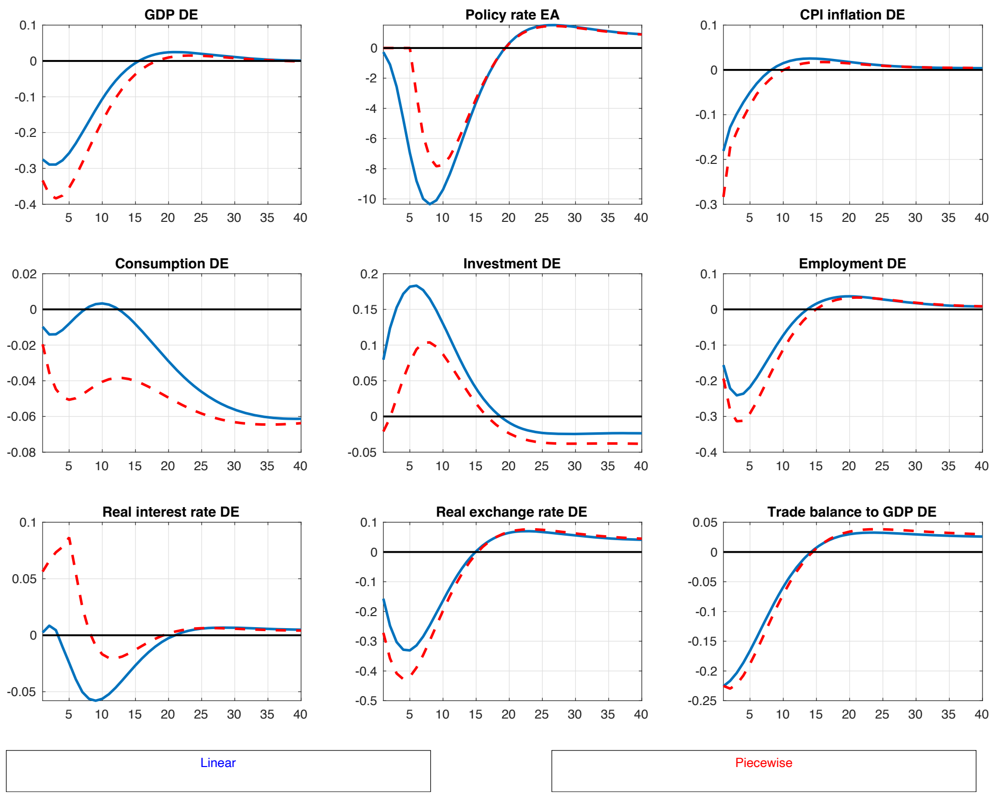
Note: The trade balance (normalised by GDP), inflation (p.a.), and real interest rate (p.a.) responses are expressed as percentage point, the policy rate (p.a.) as basis point, deviations from steady state. All other responses are percent deviations from steady state. The size of the shock corresponds to the estimated shock variance.

with the absence of monetary stimulus, also decreases investment demand in the short term (red-dashed line). This effect mirrors a risk or uncertainty shock, where consumption and investment move together. The drop in GDP leads to a temporary decline in employment (hours worked), though this decline is less pronounced due to labour adjustment costs. In the short run, the trade balance improves because of reduced domestic and import demand. The impact on CPI inflation is relatively minor, attributed to the transitory nature of the shock and price stickiness. Additionally, the lockdown shock encompasses both demand-side disturbances (precautionary behaviour of households) and supply-side disturbances (enforced business closures).

Risk shock in RoW

Figure 3 displays the dynamic transmission for a negative foreign demand shock. This shock is modelled as an additional disturbance to household time preference - a temporary increase in savings - during the COVID-19 pandemic, which decreases foreign consumption,

Figure 3: Dynamic responses to a risk shock in RoW.



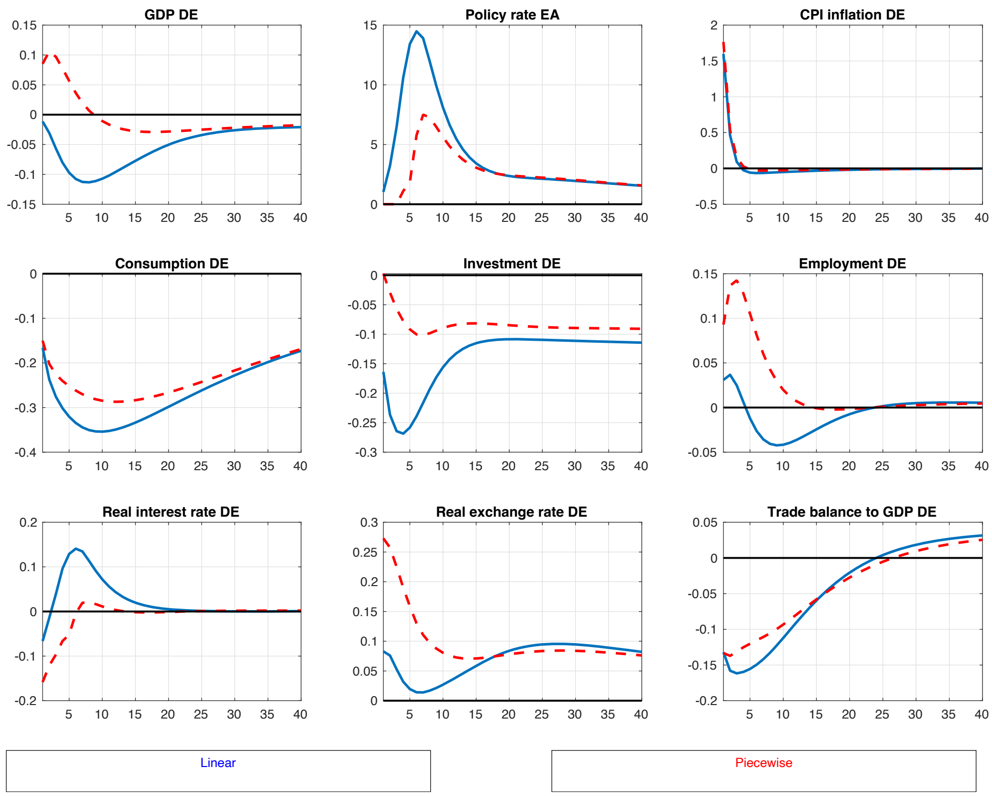
Note: The trade balance (normalised by GDP), inflation (p.a.), and real interest rate (p.a.) responses are expressed as percentage point, the policy rate (p.a.) as basis point, deviations from steady state. All other responses are percent deviations from steady state. The size of the shock corresponds to the estimated shock variance.

output, and prices. Unlike the lockdown shock in Figure 2, this additional savings shock exhibits habit persistence, resulting in a sluggish adjustment process. Regarding spillovers to the German economy, the shock induces a 0.4% decline in real GDP in the absence of monetary accommodation. This decline mainly results from the appreciation of the real effective exchange rate (REER) and its negative impact on the trade balance due to reduced import demand from RoW. The decrease in economic activity also reduces employment, real wages, and consequently, domestic consumption. The rise in real interest rates triggers an immediate decline in investment demand (compared to the linear case). Given the ELB constraint during 2020-2021, the spillover from RoW mimics the dynamic effects of an additional risk shock for Germany.

A rise in commodity prices

Figure 4 shows the macroeconomic response to an increase in oil prices. Based on the estimated shock size, the higher oil price elevates both the prices of domestically manufac-

Figure 4: Dynamic responses to an increase in commodity prices.



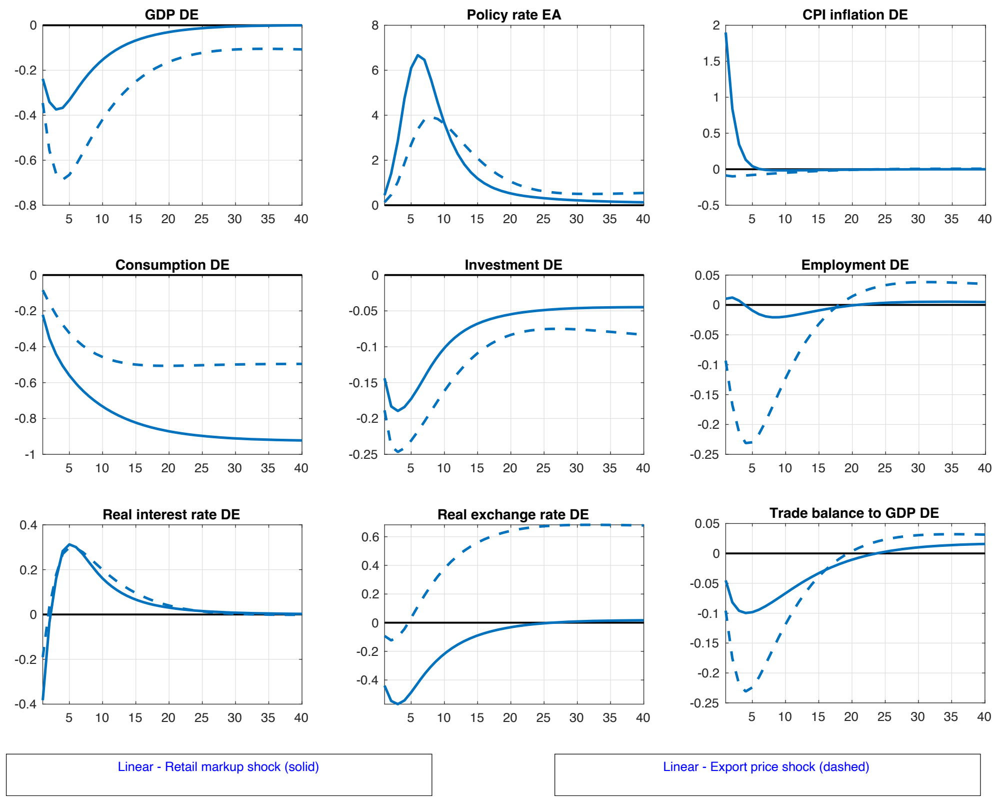
Note: The trade balance (normalised by GDP), inflation (p.a.), and real interest rate (p.a.) responses are expressed as percentage point, the policy rate (p.a.) as basis point, deviations from steady state. All other responses are percent deviations from steady state. The size of the shock corresponds to the estimated shock variance.

tured goods and CPI inflation, with an impact of up to 1.8 percentage points due to the energy component in final consumption demand. The dynamic effects heavily depend on the response of monetary policy. Under active monetary policy, an increase in interest rates leads to higher real rates in the medium term, which dampens domestic demand (investment) and output. The trade balance deteriorates due to higher commodity import prices and REER depreciation. In the case of passive monetary policy, i.e. a delayed monetary tightening due to the ELB, a decline in real rates mitigates the negative effects on investment. Additionally, lower real wages are compensated by an increase in hours worked, resulting in positive short-term effects on GDP.

Supply-side disruptions

Figure 5 illustrates the linear dynamic responses (IRFs) to two exemplary supply shocks characteristic of the COVID-19 recovery period from 2021 to 2023: (i) a retail price markup shock (represented by solid lines), and (ii) a permanent increase in DE export prices (rep-

Figure 5: Dynamic responses to supply-side shocks (Retail markup and export price).



Note: The trade balance (normalised by GDP), inflation (p.a.), and real interest rate (p.a.) responses are expressed as percentage point, the policy rate (p.a.) as basis point, deviations from steady state. All other responses are percent deviations from steady state. The size of the shocks correspond to the estimated shock variances.

resented by dashed lines). The former constitutes a wedge between production costs and consumer prices. This can be interpreted as a consumption-specific price markup by retailers.[12] Figure 5 focuses on linear IRFs as both shocks are key drivers of GDP and CPI inflation for 2022-23, when the ECB had already started raising interest rates from the ELB during that period.

Both shocks can be viewed as proxies for binding capacity constraints, capturing the dynamics of the Global Supply Chain Pressure Index by Benigno et al. (2022) and mimicking the effects of supply chain disruptions. Both dampen domestic economic activity (consumption and investment); however, only the retail price markup shock significantly increases CPI inflation. Consequently, the shocks differ in their inflation-output trade-off. While the retail

[12] The shock, $Atp^{\mathcal{C}}$, is a negative productivity shock for the final consumption good, $\mathcal{C}$, as described in Equation 23. A similar shock impacting inflation dynamics in the Euro Area has been identified by Cardani et al. (2023).

markup shock raises CPI inflation by almost 2 percentage points, its negative impact on real GDP is smaller (up to 0.4%) compared to the export price shock, which reduces real GDP by up to 0.7% after one year.

7. Estimated drivers of macroeconomic variables

Historical shock decompositions (SDs) attribute the dynamics of endogenous (observed) model variables to different (groups of) exogenous shocks. This process provides insight into the relative importance of exogenous factors in driving economic fluctuations. This subsection offers a quantitative evaluation of the main estimated drivers of Germany's historical data pattern during the period 2008q1-2023q4.[13] The assessment considers the endogenous ELB periods obtained from non-linear smoothing, as discussed in subsection 5. The approach for extending standard linear (additive) historical shock decomposition to account for occasionally binding constraints is detailed in Appendix C.[14]

Figures 6 - 8 exhibit the SDs of real GDP growth, CPI inflation, and nominal wage growth in Germany. In each subplot, the continuous black line represents the historical data, from which the steady state (1.25% p.a. for GDP and 2.0% p.a. for inflation) has been subtracted. The vertical red bars illustrate the contribution of each respective (group of) exogenous shocks to the data, ensuring that the sum of all exogenous drivers matches the historical data. Given the substantial number of shocks, we categorise them as follows: (1) domestic supply shocks, which include productivity, price, and wage markup shocks; (2) domestic demand shocks, encompassing private savings and investment risk premiums; (3) monetary policy shocks; (4) fiscal policy shocks; (5) commodity price shocks, including oil and industrial supplies; (6) international trade shocks, involving preferences for domestically produced versus foreign goods, export and import price markups, and exchange rate shocks; (7) world demand and supply shocks, containing foreign (REA and RoW) demand and supply shocks; (8) COVID-specific shocks, covering lockdown and labour market shocks; and (9) initial values.[15]

Real GDP growth

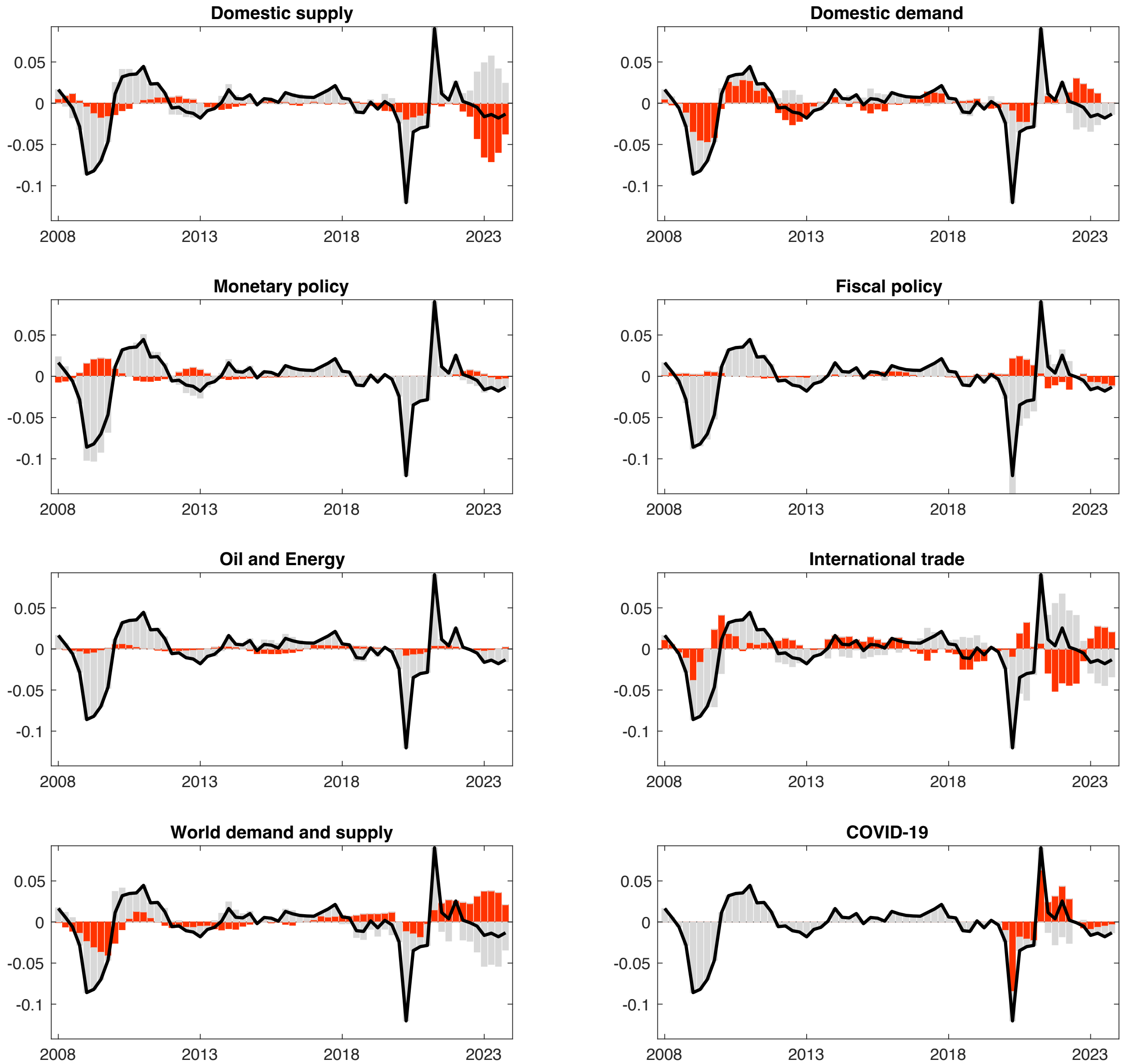
Comparing the GFC recession in 2008-09 with the COVID-19 pandemic, Figure 6 reveals

[13] Focusing on the GFC and COVID-19 crisis periods, the SDs illustrate the reduced sample size from 2008 to 2023. In Figures B.1 and B.2 of Appendix B, the historical drivers of real GDP growth and inflation are shown over the full sample period, using the same shock groupings as discussed in this section.

[14] A similar methodology for adapted piecewise linear smoothed shock decomposition is presented in Croitorov et al. (2020) and Cardani et al. (2023). The latter also provides methodological details in their Appendix.

[15] Figures 6 - 8 do not display the initial values as their impact is minimal given the estimation's initialisation in 1999.

Figure 6: Historical decomposition of real GDP growth (yoy)



Note: Real GDP growth is shown in percentage-point deviations from steady state, which is calibrated to 1.25% per year. 0.01 on the y-axis corresponds to 1 pp.

significant differences in the dynamic patterns of Germany's real GDP growth. The recession during the GFC proved to be more persistent compared to the COVID-specific growth volatility in 2020, which was primarily driven by the imposed lockdown and containment measures. The main drivers of these two crisis periods also differ substantially. During the GFC, lower domestic and world demand were major contributors to the recession, whereas monetary policy easing and, to a lesser extent, fiscal expansion played a positive role in mitigating the recession's severity. The normalisation of demand and investment conditions led to a relatively quick recovery in 2010.

The COVID-19 recession, on the other hand, is characterised by both demand and supply disturbances. The model highlights the significant impact of imposed lockdown shocks in DE and the REA, particularly due to the transitory (forced) savings shock, which caused a drop in domestic consumption, and increased investment risk. These factors together accounted for an 8 percentage point (pp) contraction in 2020q2 from the trend. Given the global ramifications of COVID-19, spillovers from world demand and supply shocks also contributed to the decline in real GDP growth in 2020, averaging 1 pp. The positive contribution of international trade during 2020 stems from the reduction in German import demand from REA and RoW, which positively affects GDP growth through increased net exports. Discretionary fiscal policy played a crucial role in stabilising GDP growth in 2020, contributing up to 2 pp on average. The stabilising impact of the government stimulus packages aligns with the findings of Funke and Terasa (2022) and Hinterlang et al. (2023).

The subsequent recovery phase during the pandemic years 2021-23 is characterised by counterbalancing factors. The normalisation of domestic demand (including the easing of lockdown and containment measures) and the recovery of world demand contributed positively to real GDP growth. However, a slowdown in international trade and negative supply shocks acted as downward pressures, keeping growth rates moderately low. Regarding international trade, the model identifies a significant export price shock, reflecting increasing supply-chain bottlenecks that negatively impacted economic activity in Germany by up to 4 pp in 2021-22. The moderate positive contributions from monetary policy, despite the monetary tightening (raising interest rates) in 2022, arise because our model-implied policy rate was higher than the observed policy rate. This gap was closed by negative (easing) monetary policy shocks, implying that the model would have suggested raising interest rates more aggressively or starting earlier.[16] However, monetary policy contributes negatively to GDP growth in 2023.

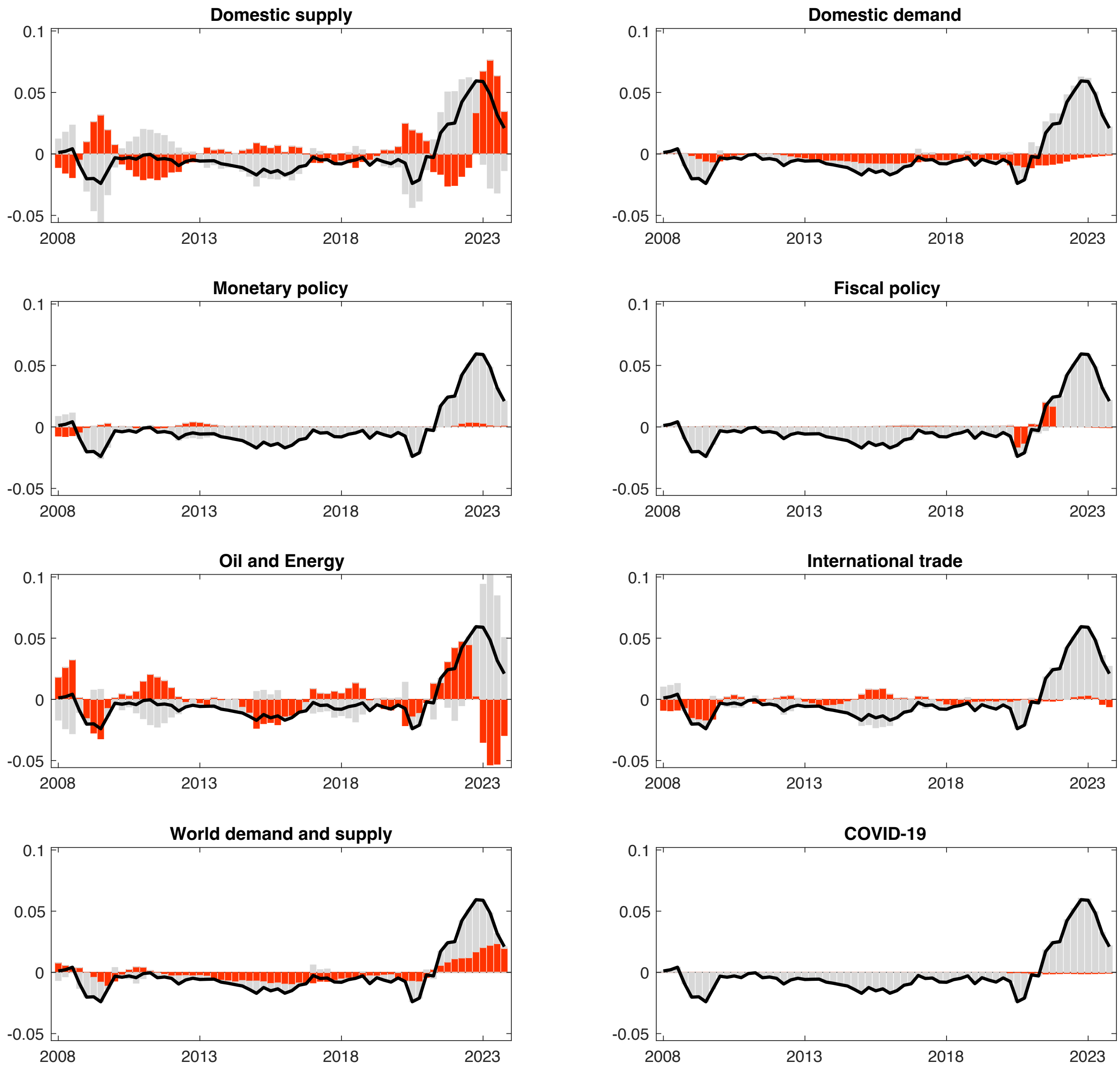
CPI inflation

The drivers of Germany's consumer price inflation (CPI) differ markedly from those influencing real GDP growth, particularly during the COVID-19 pandemic. Figure 7 illustrates that transitory lockdown shocks (within the COVID-19 shock group) have a very marginal impact on current inflation during the pandemic and the subsequent recovery. Despite their significant negative effects on GDP, these shocks do not affect inflation expectations.

The inflation dip during the GFC in 2008-09 was primarily driven by demand-side factors,

[16] It should be noted that 'monetary policy' refers only to Taylor-rule shocks and excludes the tapering and reversal of unconventional measures.

Figure 7: Historical decomposition of CPI inflation (yoy)



Note: CPI inflation is shown in percentage-point deviations from steady state, which is calibrated to 2% per year. 0.01 on the y-axis corresponds to 1 pp.

including domestic and world demand as well as financial shocks such as increased investment risk, and the appreciation of the euro (international trade). In contrast, Figure 7 highlights that the surge in CPI inflation in 2021-22 was significantly influenced by rising commodity prices and supply-side factors. The increase in energy prices alone contributed up to 4.5 pp to CPI inflation in 2022, accounting for roughly two-thirds of the inflation surge. The reversal of persistent negative global demand shocks indicates a recovery from their pre-COVID trends. Expansionary fiscal policy has played a moderately positive role in driving inflation. However, the VAT reduction during the third and fourth quarters of 2020 had a significant impact on the inflation dip, accounting for around 1.5 pp.

In 2023, decreasing commodity prices provided a downward pressure on inflation by lowering production and consumption costs. However, this effect has been counterbalanced by consumption-specific price markup shocks imposed by retailers (see Section 6). These markup shocks in the retail sector, manifesting as increased import price markups, reflect binding capacity constraints and increasing supply chain disruptions for the German economy.[17] This markup shock contributed up to 4 pp to above-trend inflation in 2023. The moderate positive contributions from monetary policy to CPI inflation in 2022 once again reflect the cautious approach to monetary tightening compared to our model-implied policy rule.

Overall, and in contrast to the GFC, the SDs of CPI inflation align with the findings of Menz (2024), which indicate that the inflation surge during 2021-22 was predominantly driven by supply-side factors.

Nominal wage growth (compensation per hour)

Regarding wage developments in Germany, pandemic-related support measures created a significant disparity between compensation per employee (CPE) and compensation per hour (CPH).[18] The volatility in hours worked, driven by job retention schemes - particularly short-time work (STW) schemes in Germany - significantly contributed to this disparity. Since the government's compensation for wage losses is paid directly to employees as social transfers, while wages and salaries decrease in proportion to the reduced hours worked, STW schemes cause a substantial downward shift in CPE. Consequently, as CPE growth declined significantly at the start of the pandemic in 2020, CPH increased due to the substantial reduction in hours worked.[19]

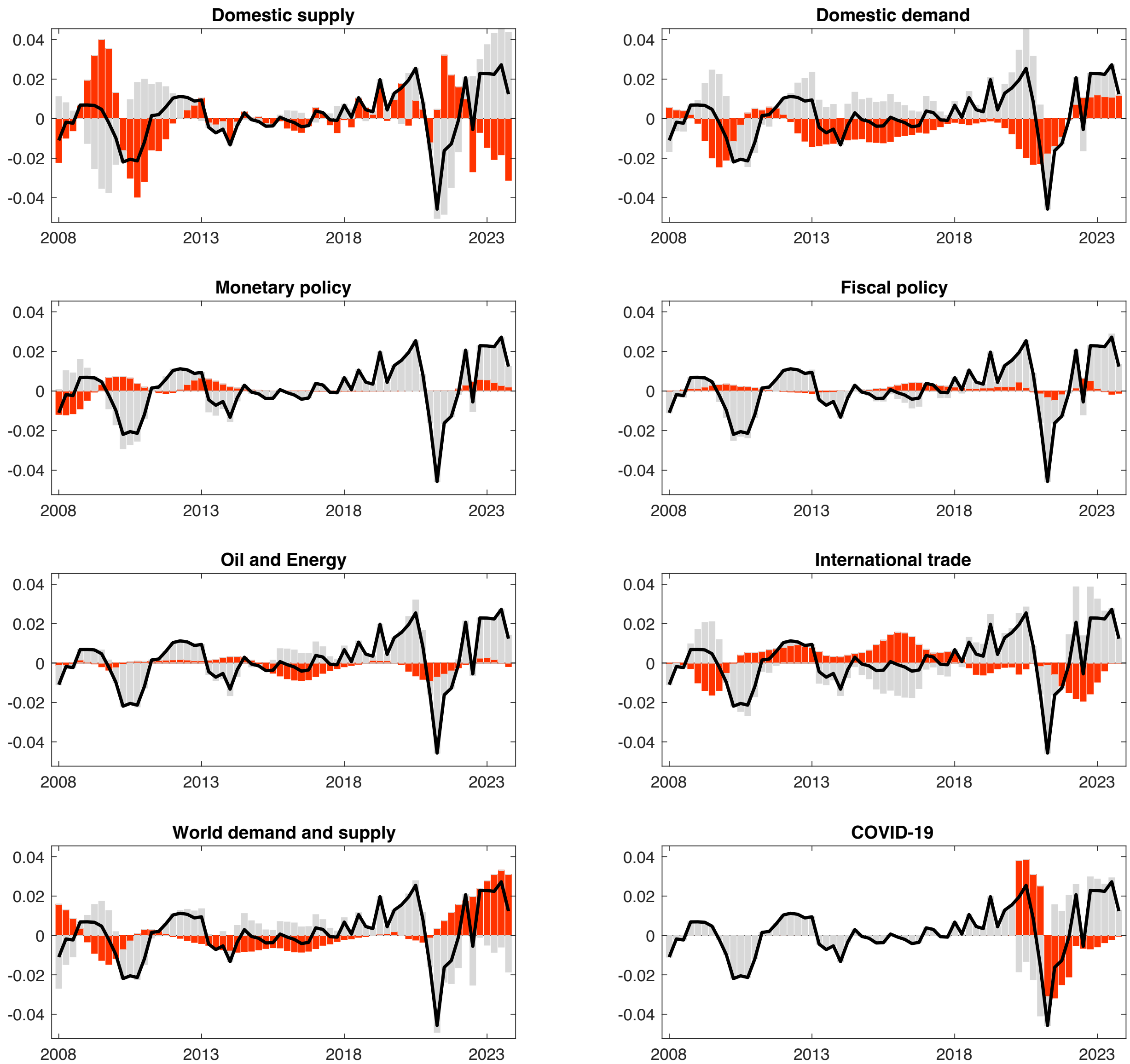
Figure 8 visualises the effects of STW schemes through the COVID-specific labour hoarding shock. The reduction in hours worked contributed positively to wage growth (per hour) in 2020 by around 4 pp (COVID-19 shock group), with adverse effects in 2021, partly due to base effects from 2020. Since the model does not include labour hoarding shocks during the GFC period in 2009, the wedge between CPE and CPH during that time is explained by

[17] Section 8 discusses and compares estimated shocks to off-model indicators, such as the Global Supply Chain Pressure Index by Benigno et al. (2022).

[18] The negative correlation between hours worked and compensation per hour due to job retention schemes was also observed during the GFC recession, though to a much lesser extent than during the pandemic.

[19] Bodnár et al. (2023) and Da Silva et al. (2020) provide detailed discussions on wage developments in the euro area and short-time work schemes, respectively, during the pandemic.

Figure 8: Historical decomposition of wage growth (compensation per hour) (yoy)



Note: Nominal wage growth, measured as compensation per hour, is shown in percentage-point deviations from steady state, which is calibrated to 2.9% per year. 0.01 on the y-axis corresponds to 1 pp.

labour demand and wage-markup shocks (domestic supply).[20] The main drivers of below-trend wage growth in Germany during the period from 2012 to 2019 were primarily low domestic and world demand, whereas euro depreciation and international trade components contributed positively. The lockdown-related drop in domestic demand was the main

[20]The estimated labour hoarding shock during the COVID-19 period can also serve as a proxy for labour market tightness, which is typically measured as the ratio of vacancies (v) to unemployed individuals (u). The contribution of labour market tightness as discussed in Menz (2024) is similar to this finding.

negative driver during 2020. In contrast, the normalisation and recovery of domestic and foreign demand contributed positively to wage growth during the pandemic recovery period from 2022 to 2023. These positive drivers during the recovery period were partly offset by domestic supply-side components, such as retail import price markups, and capacity constraints, which were captured by export price shocks and international trade components.

8. Comparison of shocks to off-model indicators

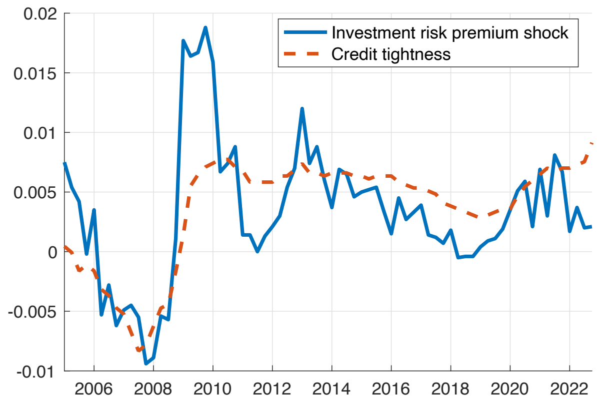
This section compares the pattern of estimated shocks to off-model indicators that are not included in the observed data, in order to assess the empirical plausibility of the identified shocks. Figure 9 illustrates the comparison between the estimated shocks to the investment risk premium, the COVID-specific lockdown shock, and the retail import price markup shock to their real-world counterparts. All the shocks are central to the historical decomposition of real GDP growth and inflation dynamics in Germany during the COVID-19 pandemic period.

The shock to investment risk in the model represents a wedge between actual investment and the investment demand compatible with average financing costs and expected future returns to investment. This can be interpreted, for example, as an increase in corporate financing costs over safe interest rates or quantitative restrictions on credit volumes. Figure 9a shows that the profile of the estimated shocks to the investment risk premium closely tracks the indicator of credit tightness in the German economy.[21] The investment risk premium (solid line) fell prior to 2008 and rose sharply during the GFC. It then dropped significantly after the financial crisis but increased again during the sovereign debt crisis starting in 2012. It has steadily but slowly declined towards pre-GFC levels, before rising once more during the COVID-19 pandemic. Figure 9a illustrates that the estimated investment risk premia align well with periods of sharp credit tightening during the financial crisis. The estimated premium also matches the easing of credit conditions after the sovereign debt crisis and the subsequent tightening during the pandemic.

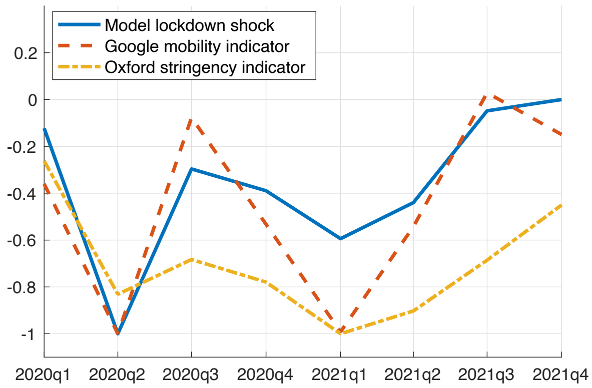
Figure 9b compares the pattern of the estimated lockdown shock to alternative pandemic-related restriction indicators for Germany: Google's mobility indicator and the Oxford COVID-19 Government Response Tracker (Hale et al., 2021). The latter captures government policies concerning closures, containment, and health and economic measures. The estimated lockdown shock shows a strong correspondence with both indicators. The slight

[21] Credit tightening as a performance indicator is based on the ECB bank survey on the tightening in bank lending standards (the percentage of banks reporting a tightening of lending standards minus the percentage of banks reporting a loosening of standards). Credit tightness at a given date is measured by the cumulative net tightening in preceding periods.

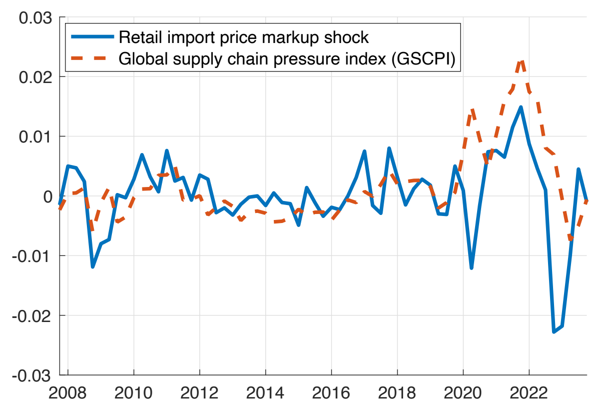
Figure 9: Off-model indicators and estimated model shocks.



(a) Investment risk and credit tightness



(b) COVID-specific lockdown measures



(c) Retail import price markup and GSCPI

Note: In Panel a), the model shock (blue solid line) corresponds to the estimated investment risk premium as described in Equation A.4. The data on credit tightening are sourced from the ECB's bank lending survey. In Panel b), the model shock (blue solid line) represents the estimated lockdown shock as described in Equation 3. The data used are time series for Google's mobility indicator (red dotted line) and the Oxford stringency index (Hale et al., 2021) (yellow dashed line), both of which are scaled to their maximum absolute values. In Panel c), the model shock (blue solid line) represents the estimated price markup shock by import retailers. The data for the Global Supply Chain Pressure Index (GSCPI) are taken from the NY Fed website based on Benigno et al. (2022). Data on credit tightness and the GSCPI have been adjusted using a linear transformation to align the mean and standard deviation of the adjusted series with the corresponding moments of the estimated model shocks.

decoupling from the stringency indicator after the first lockdown (2020q2) suggests that private consumption recovered more quickly than the relaxation of restrictions, potentially due to the increased adoption of online retail. Both the alternative indicators and the estimated lockdown shock also align during the subsequent improvement in the epidemiological situation in 2021.

Figure 9c compares the pattern of the estimated retail import price markup shock to the Global Supply Chain Pressure Index (GSCPI) by Benigno et al. (2022), an indicator that measures pressures within the global supply chain and provides a metric for potential supply chain disruptions, such as increasing global transportation costs or delivery times. The estimated price markup by retailers closely matches the pattern of the GSCPI indicator. Notably, during the pandemic in 2020-22, the estimated price markup rose sharply in tandem with increasing global supply constraints, before both indicated reduced pressures at the supply chain towards the end of 2022 and the beginning of 2023. Figure 9c also shows that the estimated retail price markup shocks were well-aligned in the aftermath of the GFC.

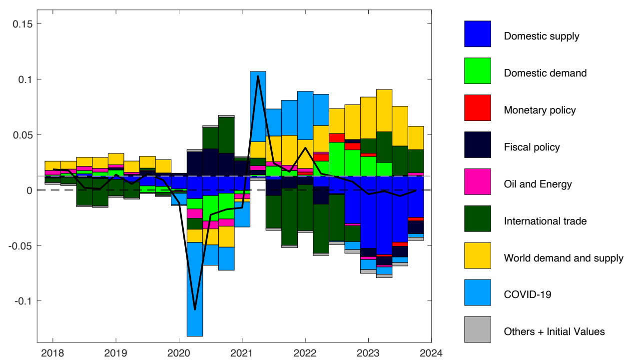
9. Counterfactual analysis without COVID-specific shocks

This section provides a counterfactual analysis to evaluate the benefits of incorporating COVID-specific shocks during the pandemic period. Specifically, it illustrates how these heteroskedastic shocks impact the model fit and the economic interpretation of the COVID-19 period. Figure 10 compares the shock decomposition of real GDP growth, CPI inflation, and wage growth during 2018q1 - 2023q4 between two model variants: (i) the model with COVID-specific shocks and (ii) a version without these shocks. The latter is generated by running a smoother with identical estimated parameters, but with all COVID-specific shocks deactivated. The groups of exogenous shocks are similar, except that the former model variant visualises all COVID-related shocks in a separate group (light blue). Note that Figures 10a, 10c, and 10e provide the identical historical decomposition as in Figures 6-8, respectively.

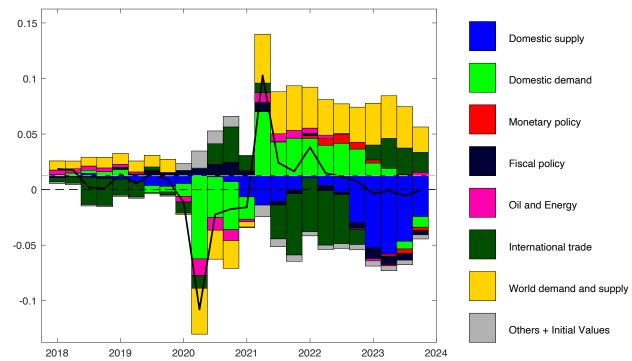
The corresponding Figures without COVID-specific shocks (10b, 10d, 10f) highlight significant differences during the 2020-21 period. As discussed in Section 7, the real GDP drop in 2020q2 in the baseline model primarily attributes the decline to a transitory (forced) savings shock, as it can better fit the large contraction and subsequent recovery implied by the lockdown measures (10a). In contrast, the counterfactual model, which excludes COVID-specific shocks, attributes the drop to standard (persistent) savings shocks (10b). However, the more sluggish consumption response in this model affects the path of future expectations, resulting in: (i) a stronger negative demand impact on CPI inflation in 2020 (d), and (ii) more pronounced offsetting supply-side factors, such as price and wage markup shocks, to match the observed time series. For nominal wage growth (compensation per hour), positive wage markup shocks (negative supply shocks) are needed in 2020 to reconcile the decline of hours worked in the absence of COVID-related labour hoarding shocks (10f).[22]

[22] In an early ex-ante assessment of the COVID-19 pandemic, Mckibbin and Fernando (2020) model the initial phase of the pandemic via preference and risk shocks to predict the adjustment without explicitly incorporating lockdown-related shocks. This approach is comparable to Figure 10b, which provides a reasonable economic interpretation. The added value of transitory (lockdown) shocks lies in their marginal impact

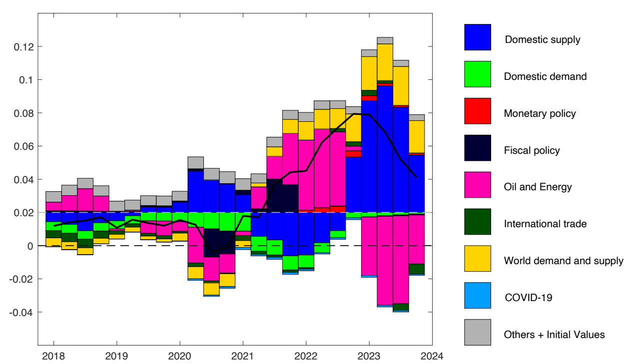
Figure 10: Counterfactual without COVID-specific shocks.



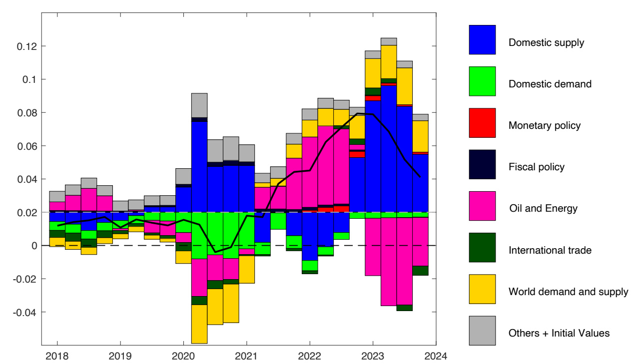
(a) GDP growth with COVID-shocks



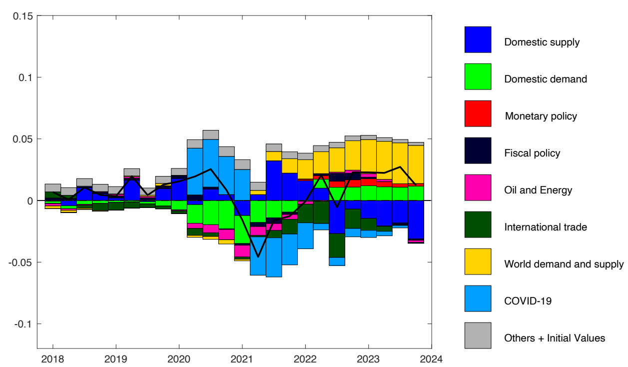
(b) GDP growth without COVID-shocks



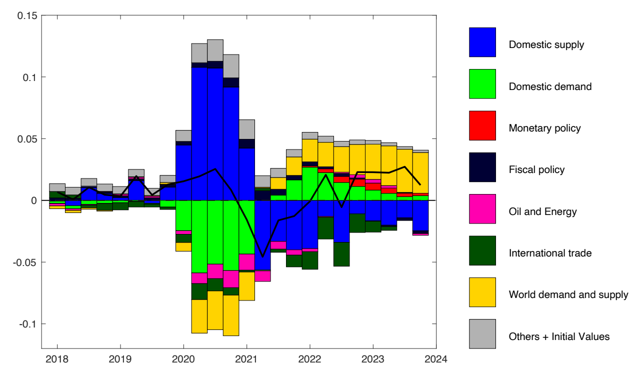
(c) CPI inflation with COVID-shocks



(d) CPI inflation without COVID-shocks



(e) Wage growth with COVID-shocks



(f) Wage growth without COVID-shocks

Note: CPI inflation is shown in percentage-point deviations from steady state, which is calibrated to 2% per year. 0.01 on the y-axis corresponds to 1 pp.

In summary, in the absence of COVID-specific shocks, the model requires higher shock variances to account for the observed data patterns, particularly during 2020. This suggests that the adjustment dynamics implied by the model with COVID-specific shocks more closely

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on the path of future expectations and, consequently, the improved fit of nominal variables.

align with the observed data during the COVID-19 period, indicating a superior model fit.

10. Conclusion

This paper estimates a state-of-the-art three-region DSGE model to analyse the macroeconomic drivers of the COVID-19 pandemic and recovery period in Germany. By incorporating COVID-specific shocks and the use of commodities in the model, the results suggest a central role for lockdown shocks via forced savings in explaining the contraction of economic activity in Germany during 2020, with significant stabilising effects from fiscal policy measures. Global demand and supply shocks also affected Germany's economic conditions during the pandemic.

The GDP recovery from 2021 to 2023 is characterised by the balancing effects of domestic and foreign demand normalisation against a slowdown in international trade and the exacerbation of supply-chain bottlenecks. The surge in CPI inflation during 2021-22 is primarily attributed to rising commodity prices and domestic and foreign supply-side factors, which mimic the effects of increasing supply chain disruptions. The increase in energy prices alone contributed up to 4.5 pp to CPI inflation in 2022, accounting for roughly two-thirds of the inflation surge. The normalisation of commodity prices in 2023 is counterbalanced by consumption-specific price markups by retailers, creating a wedge between production costs and consumer prices, and consequently slowing the decline in inflation rates in Germany in 2023. The analysis emphasises that supply-side factors were the predominant drivers of inflation during the pandemic recovery period.

The model's estimation results, including shocks to investment risk, consumption-specific lockdown shocks, and price markups by import retailers align closely with off-model indicators, validating the empirical robustness of the identified shocks. This comprehensive analysis provides a plausible narrative for the macroeconomic developments in Germany. It emphasises the importance of considering the variety of domestic and global factors, as well as demand and supply dynamics, in understanding the significant economic fluctuations and heightened volatility caused by the COVID-19 pandemic.

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Appendix A. Model description

Appendix A.1. Households

The Ricardian households maximise the present value of the expected stream of future utility, subject to equation (5), by choosing the amount of consumption, $C^s_{j,t}$, and next period asset holdings, $B^{rf}_{j,t}$, $B^G_{j,t}$, $S_{j,t}$, $B^W_{j,t}$. The resulting FOCs are:

$$\lambda^s_{j,t} = \left[C^s_{j,t} - \varepsilon^{tC}_t - h(C^s_{t-1} - \varepsilon^{tC}_{t-1})\right]^{-\theta}, \tag{A.1}$$

$$1 = \tilde{\beta}_t E_t\left[\frac{\lambda^s_{j,t+1}}{\lambda^s_{j,t}} \frac{(1 + i^{rf}_t}{1 + \pi^{C,vat}_{t+1}}\right], \tag{A.2}$$

$$1 = \tilde{\beta}_t E_t\left[\frac{\lambda^s_{j,t+1}}{\lambda^s_{j,t}} \frac{(1 + i^G_t) - \left(\alpha^{b_0} + \varepsilon^B_t\right)}{1 + \pi^{C,vat}_{t+1}}\right], \tag{A.3}$$

$$1 = \tilde{\beta}_t E_t\left[\frac{\lambda^s_{j,t+1}}{\lambda^s_{j,t}} \frac{(1 + i^S_{t+1}) - \left(\alpha^{S_0} + \varepsilon^S_t\right)}{1 + \pi^{C,vat}_{l,t+1}}\right], \tag{A.4}$$

$$1 = \tilde{\beta}_t E_t\left[\frac{\lambda^s_{j,t+1}}{\lambda^s_{j,t}} \frac{(1 + i^W_t)\frac{e_{RoW,t+1}}{e_{RoW,t}} - \left(\varepsilon^{bw}_t + \alpha^{bw_0} + \alpha^{bw_1}\frac{e_{RoW,t}NFA_t}{P^Y_t Y_t}\right)}{1 + \pi^{C,vat}_{t+1}}\right], \tag{A.5}$$

where, $\alpha^{bw1}\frac{e_{RoW,t}NFA_t}{P^Y_t Y_t}$ captures a debt-dependent country risk premium on net foreign asset holdings as external closure to ensure long-run stability (see Schmitt-Grohe and Uribe, 2003; Adolfson et al., 2008).

The optimality conditions are similar to standard Euler equations, but incorporate asset-specific risk premia which depend on exogenous shocks ε^B_{kt}, ε^S_{kt}, $\varepsilon^b w_{kt}$. Combining the Euler equation for the risk-free bond (A.2) with (A.3), (A.4) and (A.5), we obtain the following approximated expressions:

$$i^G_t = i^{rf}_t + rprem^G_t, \tag{A.6}$$

$$i^S_t = i^{rf}_t + rprem^S_t, \tag{A.7}$$

$$E_t\left[\frac{e_{RoW,t+1}}{e_{RoW,t}}\right] i^W_t = i^{rf}_t + rprem^W_t, \tag{A.8}$$

where $rprem^G_t$ and $rprem^W_t$ are risk premia on domestic government bonds and foreign bonds, respectively, $rprem^S_{l,t}$ are the country-specific risk premia on domestic and foreign shares, and $rprem^{ra}_t$ a global financial shock to the risk appetite.

Appendix A.2. Firms

Following Rotemberg (1982), firms face quadratic adjustment costs, $adj_{i,t}$, measured in terms of production input factors. Specifically, the adjustment costs are associated with the output price, $P^Y_{i,t}$, labour input, $N_{i,t}$, capital stock and investment, $I_{i,t}$, as well as capacity utilisation variation, $CU_{i,t}$:

$$adj^{P^Y}_{i,t} = \sigma^Y \frac{\gamma^P}{2} Y_t \left[\frac{P^Y_{i,t}}{P^Y_{i,t-1}} - \exp(\bar{\pi}) \right]^2, \tag{A.9}$$

$$adj^N_{i,t} = \frac{\gamma^N}{2} Y_t \left[\frac{N_{i,t}}{N_{i,t-1}} - \exp(g^{pop}) \right]^2, \tag{A.10}$$

$$adj^I_{i,t} = \frac{P^I_t}{P^Y_t} \left[\frac{\gamma^{I,1}}{2} K_{t-1} \Big(\frac{I_{i,t}}{K_{t-1}} - \delta^K_t \Big)^2 + \frac{\gamma^{I,2}}{2} \frac{(I_{i,t} - I_{i,t-1} \exp(g^Y + g^{P^I}))^2}{K_{t-1}} \right], \tag{A.11}$$

$$adj^{CU}_{i,t} = \frac{P^I_t}{P^Y_t} K^{tot}_{i,t-1} \left[\gamma^{CU,1}(CU_{i,t} - 1) + \frac{\gamma^{CU,2}}{2} (CU_{i,t} - 1)^2 \right], \tag{A.12}$$

where γ-s capture the degree of adjustment costs, $\bar{\pi}$, g^{pop}, g^Y, g^{P^I} are the steady-state growth rates of inflation, population, and country-specific GDP and investment price deflator, respectively. $\delta^K_t \neq \delta$ is a function of the depreciation rate adjusted for the capital trend in order to have zero adjustment costs on the trend-path.[23]

Given the Lagrange multiplier associated with the technology constraint, μ^y, the FOCs with respect to labour, capital, investment, and capacity utilisation are given by:

$$(1-\tau^K) \frac{W_t}{P^Y_t} = \alpha \left(\mu^y_t - \varepsilon^{ND}_t \right) \frac{Y_t}{N_t - FN} - \frac{\partial adj^N_t}{\partial N_t} + E_t \Big[\frac{1+\pi^Y_{t+1}}{1+i^s_{t+1}} \frac{\partial adj^N_{t+1}}{\partial N_t} \Big], \tag{A.13}$$

$$\begin{aligned} Q_t \;=\; & E_t \Bigg[\frac{1+\pi^Y_{t+1}}{1+i^s_{t+1}} \frac{P^I_{t+1}}{P^Y_{t+1}} \frac{P^Y_t}{P^I_t} \\ & \left(\tau^K \delta - \frac{\partial adj^{CU}_t}{\partial K_{t-1}} + Q_{t+1}(1-\delta) + (1-\alpha) \mu^Y_{t+1} \frac{P^Y_{t+1}}{P^I_{t+1}} \frac{Y_{kt+1}}{K^{tot}_t} \right) \Bigg], \end{aligned} \tag{A.14}$$

[23] We specify $\delta^K_t = exp(g^{\bar{Y}} + GAPI0) - (1-\delta)$, where $g^{\bar{Y}}$ and $GAPI0$ are the global GDP trend and the investment-specific technology growth, respectively, so that $\frac{I}{K} - \delta^k \neq 0$ along the trend path.

$$
\begin{aligned}
Q_t &= \Big[1 + \gamma^{I,1}\Big(\frac{(I_t + \varepsilon_t^{tS})}{K_{t-1}} - \delta_t^K\Big) + \gamma^{I,2}\frac{((I_t + \varepsilon_t^{tS}) - (I_{t-1} + \varepsilon_{t-1}^{tS})\exp(g^Y + g^{PI}))}{K_{t-1}}\Big] \\
&- E_t\Big[\frac{1 + \pi_{t+1}^Y}{1 + i_{t+1}^s}\frac{P_{t+1}^I}{P_{t+1}^Y}\frac{P_t^Y}{P_t^I}\exp(g^Y + g^{PI}) \\
&\cdot \gamma^{I,2}\frac{((I_{t+1} + \varepsilon_{t+1}^{tS}) - (I_t + \varepsilon_t^{tS})\exp(g^Y + g^{PI}))}{K_t}\Big],
\end{aligned} \tag{A.15}
$$

$$
\mu_t^y(1-\alpha)\frac{Y_t}{CU_t}\frac{P_t^Y}{P_t^I} = K_{t-1}^{tot}\Big[\gamma^{u,1} + \gamma^{u,2}(CU_t - 1)\Big], \tag{A.16}
$$

where $Q_t = \mu_t / \frac{P_t^I}{P_t^Y}$ represents Tobin's Q and $Actr_t Pop_t$ is the active labour force of the domestic country. Equation (A.13) characterises the optimal level of labour input, taking into account labour overhead. Equation (A.14) and (A.15) define the Tobin's Q, which is equal to the replacement cost of capital (the relative price of capital). ε_t^{tS} is the investment-specific lockdown shock. Finally, (A.16) describes capacity utilisation, where the left-hand side indicates the additional output produced while the right-hand side captures the costs of higher utilisation rate.

Given the Rotemberg set-up and imposing the price symmetry condition, $P_{i,t}^Y = P_t^Y$, the FOC with respect to $P_{i,t}^Y$ yields the New Keynesian Phillips curve:

$$
\begin{aligned}
\mu_t^y\sigma^Y &= (1-\tau^K)(\sigma^Y - 1) + \sigma^Y\gamma^P\frac{P_t^Y}{P_{t-1}^Y}\Big(\pi_t^Y - \bar{\pi}\Big) \\
&- \sigma^Y\gamma^P E_t\left[\frac{1 + \pi_{t+1}^Y}{1 + i_{t+1}^s}\frac{P_{t+1}^Y}{P_t^Y}\frac{Y_{t+1}}{Y_t}\Big(\pi_{t+1}^Y - \bar{\pi}\Big)\right] + \sigma^Y\varepsilon_t^{\mu Y},
\end{aligned} \tag{A.17}
$$

where $\varepsilon_t^{\mu Y}$ is the inverse of the markup shock.

Appendix B. Additional results

Table B.1: Selected calibrated structural parameters.

		DE	REA	RoW
Preferences				
Intertemporal discount factor	β	0.998	0.998	0.998
Savers share	ω^s	0.61	1.00	1.00
Weight of disutility of labour	ω^N	2.5	-	-
Degree of openness	s^M	0.36	0.28	0.06
Import share in consumption	$s^{M,C}$	0.22	0.17	0.05
Import share in investment	$s^{M,I}$	0.31	-	-
Import share in government expenditure	$s^{M,G}$	0.31	-	-
Import share in export	$s^{M,X}$	0.26	0.31	0.15
Preference for imports from REA	$s^{M,REA}$	0.33	-	0.67
Preference for imports from RoW	$s^{M,RoW}$	0.23	0.77	-
Preference for imports from DE	$s^{M,DE}$	-	0.52	0.48
Production				
Cobb-Douglas labour share	α	0.65	1.00	1.00
Depreciation of private capital stock	δ	0.014	-	-
Elasticity of substitution between differentiated goods	σ^Y	6.50	-	-
Share of commodities in total output	s^{CO}	0.06	0.04	0.05
Linear capacity utilisation adj. costs	$\gamma^{CU,1}$	0.03	-	-
Fiscal policy				
Consumption tax	τ^C	0.20	-	-
Corporate profit tax	τ^K	0.20	-	-
Labour tax	τ^N	0.41	-	-
Deficit target (in % of GDP)	Def^T	0.50	-	-
Debt target (in % of GDP)	$\bar{B}^G$	61.6	-	-
Steady-state ratios				
Private consumption share	C/Y	0.55	0.68	0.72
Private investment share	I/Y	0.19	-	-
Government consumption share	G/Y	0.19	-	-
Government investment share	IG/Y	0.02	-	-
Transfer share	T/Y	0.17	-	-
Trade balance share	TB/Y	0.04	-0.02	-0.02
Size of the country (% of world)	$size$	5.4	14.5	80.1

Table B.2: Prior and posterior distribution of estimated model parameters in REA and RoW.

		Prior distribution		Posterior distribution	
		Distr	Mean St.Dev	REA	RoW
Monetary Policy					
Interest rate persistence	ρ^i	G	0.85	0.91	0.95
			0.05	(0.88, 0.93)	(0.94, 0.96)
Response to inflation	$\eta^{i,\phi}$	G	2.00	1.78	1.77
			0.20	(1.56, 2.19)	(1.47, 1.91)
Response to GDP	$\eta^{i,y}$	G	0.10	0.05	0.07
			0.04	(0.03, 0.11)	(0.05, 0.15)
Preferences					
Consumption habit persistence	h	B	0.50	0.73	0.87
			0.20	(0.72, 0.83)	(0.85, 0.90)
Risk aversion	θ	G	1.50	1.50	1.29
			0.20	(1.19, 1.71)	(1.18, 1.72)
Phillips curve coefficient	ϕ^Y	G	0.025	0.04	0.06
			0.01	(0.02, 0.05)	(0.03, 0.07)
Import price elasticity	σ^z	G	2.00	3.13	1.28
			0.40	(2.62, 3.88)	(1.11, 1.43)
Oil price elasticity	σ^o	G	0.5	0.31	0.12
			0.1	(0.30, 0.35)	(0.01, 0.29)

Note: Cols. (1)-(2) list model parameters. Cols. (3)-(4) indicate the prior distribution function (B: Beta distribution; G: Gamma distribution). Col. (5)-(6) show the mode and the 90% HPD intervals of the posterior distributions of REA and RoW model parameters.

Table B.3: Selected estimated exogenous shock processes for DE.

		Prior distribution		Posterior distribution
		Distr	Mean St.Dev	DE
Autocorrelations of forcing variables				
Subjective discount factor	ρ^{UC}	Beta	0.50	0.83
			0.20	(0.75, 0.90)
Investment risk premium	ρ^{S}	Beta	0.85	0.94
			0.05	(0.88, 0.94)
Labour demand	ρ^{ND}	Beta	0.50	0.78
			0.20	(0.74, 0.83)
Trade share	ρ^{M}	Beta	0.50	0.91
			0.20	(0.88, 0.95)
Government consumption	ρ^{G}	Beta	0.50	0.97
			0.20	(0.95, 0.98)
Government transfers	ρ^{T}	Beta	0.50	0.94
			0.20	(0.90, 0.95)
Commodity imports	ρ^{CO}	Beta	0.50	0.82
			0.20	(0.76, 0.86)
Productivity growth	ρ^{GA}	Beta	0.50	0.82
			0.20	(0.94, 0.98)
International bond preference	ρ_{EA}^{BW}	Beta	0.50	0.87
			0.20	(0.71, 0.89)
Standard deviations (%) of innovations to forcing variables				
Subjective discount factor	ε^{UC}	Gamma	1.00	1.74
			0.40	(0.64, 2.50)
Investment risk premium	ε^{S}	Gamma	0.10	0.25
			0.04	(0.20, 0.44)
Price mark-up	ε^{MUY}	Gamma	2.00	8.77
			0.80	(5.39, 9.80)
Labour demand	ε^{ND}	Gamma	1.00	2.81
			0.40	(2.56, 2.94)
Trade share	ε^{M}	Gamma	1.00	1.94
			0.40	(1.74, 2.05)
International bond preference	ε_{EA}^{BW}	Gamma	1.00	0.21
			0.40	(0.15, 0.40)
Labour supply	ε^{U}	Gamma	1.00	2.73
			0.40	(1.94, 2.88)
Export price	ε^{PX}	Gamma	1.00	0.49
			0.40	(0.39, 0.59)
Government consumption	ε^{G}	Gamma	1.00	0.19
			0.40	(0.16, 0.22)
Government transfers	ε^{T}	Gamma	1.00	0.15
			0.40	(0.13, 0.17)
Commodity imports	ε^{CO}	Gamma	1.00	5.05
			0.40	(4.02, 5.86)
Productivity growth	ε^{GA}	Gamma	0.10	0.05
			0.04	(0.02, 0.06)
Productivity trend	ε^{A}	Gamma	0.10	0.02
			0.04	(0.01, 0.05)
Monetary policy	ε_{EA}^{i}	Gamma	1.00	0.10
			0.40	(0.08, 0.11)

Note: Cols. (1)-(2) list model parameters. Cols. (3)-(4) indicate the prior distribution function (B: Beta distribution; G: Gamma distribution). Cols. (5) shows the mode and the 90% HPD intervals of the posterior distributions.

Table B.4: Selected estimated exogenous shock processes for REA and RoW.

		Prior distribution		Posterior distribution	
		Distr	Mean St.Dev	REA	RoW
Autocorrelations of forcing variables					
Subjective discount factor	ρ^{UC}	Beta	0.50	0.69	0.79
			0.20	(0.59, 0.74)	(0.73, 0.87)
Price mark-up	ρ^{Y}	Beta	0.50	0.57	0.62
			0.20	(0.33, 0.63)	(0.52, 0.69)
Trade share	ρ^{M}	Beta	0.50	0.94	0.97
			0.20	(0.90, 0.96)	(0.95, 0.99)
Commodity imports	ρ^{CO}	Beta	0.50	0.90	-
			0.20	(0.85, 0.96)	
Productivity growth	ρ^{GA}	Beta	0.50	0.93	0.94
			0.20	(0.90, 0.95)	(0.91, 0.95)
Standard deviations (%) of innovations to forcing variables					
Subjective discount factor	ε^{UC}	Gamma	1.00	1.95	0.69
			0.40	(1.53, 2.69)	(0.46, 1.01)
Price mark-up	ε^{MUY}	Gamma	1.00	0.17	0.43
			0.40	(0.14, 0.28)	(0.34, 0.53)
Trade share	ε^{M}	Gamma	1.00	3.14	2.89
			0.40	(2.69, 3.42)	(2.53, 3.16)
Commodity imports	ε^{CO}	Gamma	1.00	4.86	-
			0.40	(4.02, 5.86)	
Productivity growth	ε^{GA}	Gamma	0.10	0.03	0.08
			0.04	(0.03, 0.04)	(0.07, 0.10)
Monetary policy	ε^{i}	Gamma	1.00	0.10	0.09
			0.40	(0.08, 0.11)	(0.08, 0.11)

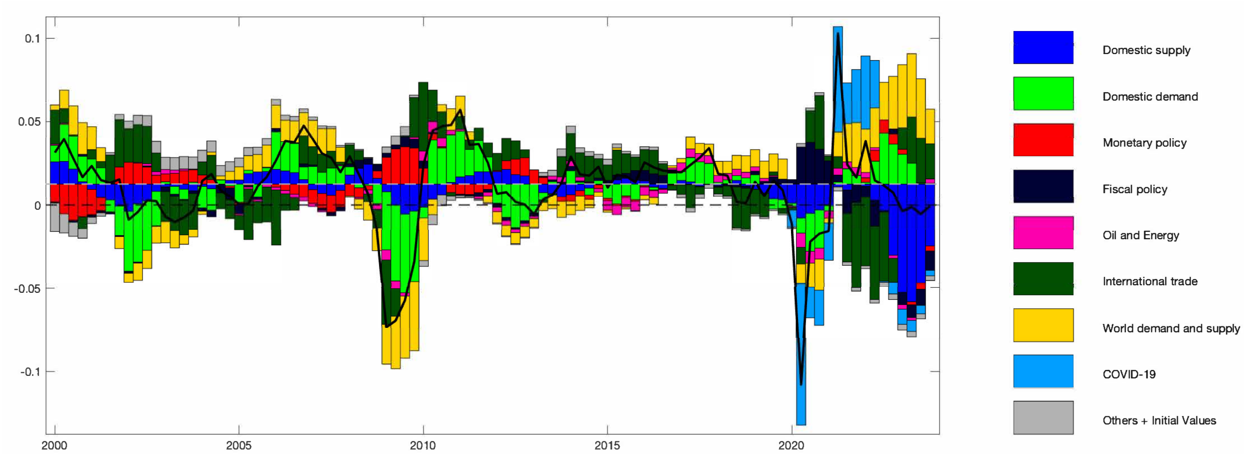
Note: Cols. (1)-(2) list model parameters. Cols. (3)-(4) indicate the prior distribution function (B: Beta distribution; G: Gamma distribution). Cols. (5) shows the mode and the 90% HPD intervals of the posterior distributions.

Table B.5: Historical sequence of occasionally binding regimes.

time	regime sequence	starting period of regime
2008Q1	0	1
2008Q2	0	1
2008Q3	0	1
2008Q4	0	1
2009Q1	0 1 0	1 8 11
2009Q2	0 1 0	1 5 9
2009Q3	0 1 0	1 4 7
2009Q4	0	1
2010Q1	0	1
2010Q2	0	1
2010Q3	0	1
2010Q4	0	1
2011Q1	0	1
2011Q2	0	1
2011Q3	0	1
2011Q4	0	1
2012Q1	0	1
2012Q2	0	1
2012Q3	0	1
2012Q4	0	1
2013Q1	0	1
2013Q2	0 1 0	1 4 6
2013Q3	0 1 0	1 4 6
2013Q4	0 1 0	1 3 6
2014Q1	0 1 0	1 4 5
2014Q2	0 1 0	1 3 6
2014Q3	0 1 0	1 2 6
2014Q4	1 0	1 6
2015Q1	1 0	1 6
2015Q2	1 0	1 5
2015Q3	1 0	1 5
2015Q4	1 0	1 6
2016Q1	1 0	1 7
2016Q2	1 0	1 6
2016Q3	1 0	1 5
2016Q4	1 0	1 4
2017Q1	1 0	1 3
2017Q2	1 0	1 3
2017Q3	1 0	1 3
2017Q4	1 0	1 3
2018Q1	1 0	1 3
2018Q2	1 0	1 3
2018Q3	1 0	1 3
2018Q4	1 0	1 3
2019Q1	1 0	1 3
2019Q2	1 0	1 3
2019Q3	1 0	1 3
2019Q4	1 0	1 3
2020Q1	1 0	1 3
2020Q2	1 0	1 6
2020Q3	1 0	1 5
2020Q4	1 0	1 5
2021Q1	1 0	1 3
2021Q2	1 0	1 3
2021Q3	1 0	1 3
2021Q4	1 0	1 3
2022Q1	1 0	1 2
2022Q2	0	1
2022Q3	0	1
2022Q4	0	1
2023Q1	0	1
2023Q2	0	1
2023Q3	0	1
2023Q4	0	1

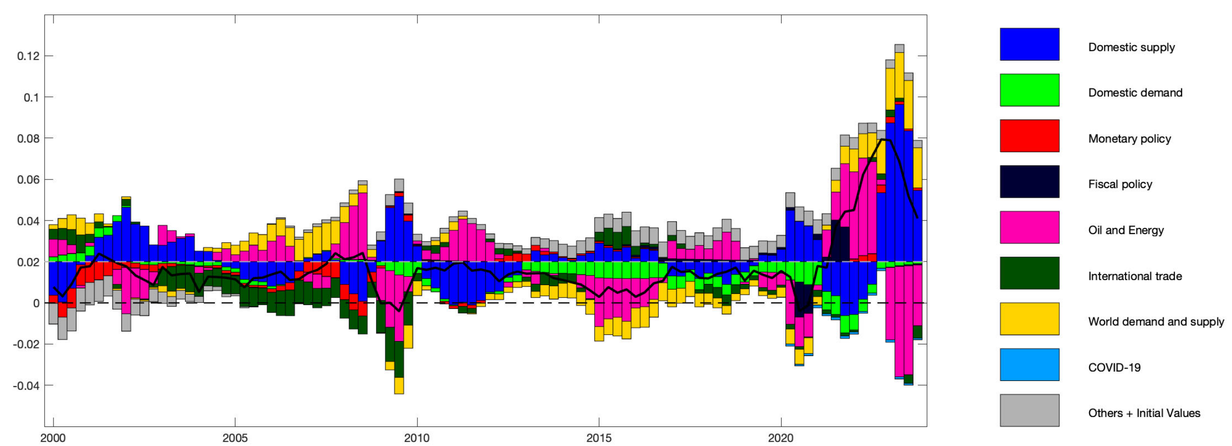
Note: First column: [0] unconstrained; [0 1 0] indicates an unconstrained regime, but agents expect to be binding in the future; [1 0] indicates a constrained regime. Second column: [1 8 11] indicates an expected constrained regime starting in 8 periods ahead and last for additional 3 periods; [1 6] indicates a constrained regime with an expected duration of additional 6 periods.

Figure B.1: Historical decomposition of real GDP growth (yoy)



Note: Real GDP growth is shown in percentage-point deviations from steady state, which is calibrated to 1.25% per year. 0.01 on the y-axis corresponds to 1 pp.

Figure B.2: Historical decomposition of CPI inflation (yoy)



Note: CPI inflation is shown in percentage-point deviations from steady state, which is calibrated to 2% per year. 0.01 on the y-axis corresponds to 1 pp.

Appendix C. Piecewise linear smoothed shock decomposition

This appendix describes the extension of the standard linear (additive) historical shock decomposition to occasionally binding constraints. The piecewise linear smoother provides an estimate of the historical sequence of regimes, i.e. identifies periods in which the ELB has been binding (Table B.5). The sequence of regimes triggers a sequence of state space matrices:

$$y_t = C(t) + T(t)y_{t-1} + R(t)\epsilon_t,$$

where y are endogenous variables in deviation from steady state, ε are the smoothed shocks, and $C(t)$ is a constant which is triggered by the ELB regime. While $C = 0$ in normal times, the constant is triggered by the fact that, under the ELB regime, the Taylor-rule becomes $i_{EA} = i_{EA}^{LB}$ and violates the steady state solution as $i_{EA}^{LB} < \bar{i}$.

The smoothed shock decomposition is performed similarly to the usual linear case: Given the smoothed series of regimes, the shocks are propagated individually through the sequence of state space matrices T and R. The array C is, instead, treated as an additional 'exogenous' process, the so-called ´regime effect'. The regime effect results from the interaction of all shocks hitting the system simultaneously, for all times $<= t$. Hence, we can assume that such a regime effect is also a function of the model shocks, which allows us to compute, at each time point and for each y_j of interest, the absolute value of the contribution of each shock ε_i onto variable y_j:

$$w_{j,i}(t) = |y_j(e_i, t)|,$$

which provides a set of weights that can be used to apportion the regime affect among all shocks in the model. The intuition behind this procedure is the following: If a shock is relevant for y at a given point in time t, it will also be relevant in triggering the regime effect. For example, if it is an expansionary shock, it would contribute to mitigate the duration of the constrained regime and vice versa. By doing so, we obtain a historical shock decomposition in terms of the usual model shocks, which also includes the regime effect.

Appendix D. Data source and transformations

Data sources

Data for the Germany and EA (quarterly national accounts, fiscal aggregates, quarterly interest and exchange rates) are taken from Eurostat. DE and EA imports of commodities from RoW are based on BEA data and on Eurostat Comext data. RoW series are constructed on the basis of the IMF International Financial Statistics (IFS) and World Economic Outlook (WEO) databases.

Data series for RoW variables

Series for GDP, investment, prices and interest rates in RoW starting in 1999 are constructed on the basis of data for the following 58 countries: Albania, Algeria, Argentina, Armenia, Australia, Azerbaijan, Belarus, Brazil, Bulgaria, Canada, Chile, China, Colombia, Croatia, Czech Republic, Denmark, Egypt, Georgia, Hong Kong, Hungary, Iceland, India, Indonesia, Iran, Israel, Japan, Jordan, Korea, Lebanon, Libya, FYR Macedonia, Malaysia, Mexico, Moldova, Montenegro, Morocco, New Zealand, Nigeria, Norway, Philippines, Poland, Romania, Russia, Saudi Arabia, Serbia, Singapore, South Africa, Sweden, Switzerland, Syria, Taiwan, Thailand, Tunisia, Turkey, Ukraine, United Arab Emirates, United Kingdom, and Venezuela. The RoW data are annual data from the IMF International Financial Statistics (IFS) and World Economic Outlook (WEO) databases.

List of observables

The estimation uses the time series information for 41 endogenous variables. We additionally observe the first quarter of the capital stock and the net international investment position to initialise the starting point. Table D.6 lists the observed time series. We apply logarithmic transformations to all observables, with the exception of the trade balance-to-GDP ratio, the oil price (Brent), the commodities import share to GDP, the price of commodities imports, and nominal interest rates. Figure D.3 plots the observed DE data pattern for the estimation. GDP deflators and relative prices of demand components are computed as the ratios of the current-price value to the chain-indexed volume series. Note that we observe EA aggregate variables and compute model-consistent REA variables given the size of Germany.

Table D.6: Observed times series.

DE	**EA**	**RoW**
GDP (nominal and real)	GDP (nominal and real)	GDP (nominal and real)
TFP trend	GDP trend	GDP trend
Private consumption (nominal and real)	Interest rate (nominal)	Interest rate (nominal)
Total investment (nominal and real)	Effective exchange rate (nominal)	Oil price (Brent) in USD
Hours worked	Exports (nominal and real)	Population
Wages (nominal)	Imports (nominal and real)	
Exports (nominal and real)	Commodities import share (nominal)	
Imports (nominal and real)	Price of commodity imports (from RoW)	
Government debt (nominal)	Population	
Gov. consumption (nominal and real)		
Gov. investment (nominal)		
Government transfers (nominal)		
Gov. interest payments (nominal)		
Commodities import share (nominal)		
Price of commodity imports (from RoW)		
Active population rate		
Population		

Figure D.3: Observed DE time series.