International Economics and Economic Policy (2025) 22:25
https://doi.org/10.1007/s10368-024-00651-7

ORIGINAL PAPER

Germany's macroeconomic drivers during the pandemic and inflation surge

Stefan Hohberger[1,2]

Accepted: 23 December 2024 / Published online: 15 January 2025
© The Author(s) 2025

Abstract
This paper estimates a three-region macroeconomic model to analyse the key drivers of Germany's GDP, inflation, and wage growth during the COVID-19 pandemic and inflation surge. Incorporating COVID-related demand and supply shocks, trade in commodities, and endogenous ELB periods, the results highlight that (i) the 2020–2021 downturn was primarily driven by domestic and global lockdown shocks, (ii) the 2021–2022 inflation surge resulted from rising commodity prices, recovering global demand, and supply-side pressures, and (iii) wage growth per hour was shaped by opposing demand and supply forces. The model's estimated shocks closely align with external indicators, supporting its empirical plausibility.

Keywords COVID-19 · Inflation · Open-economy DSGE model · Bayesian estimation · Germany

JEL Classification C51 · E32 · E52 · F41 · F45

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 2021–2022 has amplified the surge in inflation, leading to a strong tightening of monetary policy.

✉ Stefan Hohberger
stefan.hohberger@hm.edu

1 HM Business School, Munich University of Applied Sciences, Munich, Bavaria, Germany

2 Centre for Applied Macroeconomic Analysis (CAMA), Australian National University, Canberra, Australia

This paper analyses the main drivers of the COVID-19 pandemic and subsequent inflation period for Germany through the lens of an estimated structural macroeconomic model. The model is a three-region monetary union DSGE model, consisting of Germany (DE), the rest of the euro area (REA), and the rest of the world (RoW). Following the approach of Cardani et al. (2022a), the model incorporates several COVID-related demand and supply shocks to account for the lockdown-imposed drop in consumption, fiscal stimulus packages, or short-time work arrangements. Additionally, the model extends the use of commodities to account for the impact of rising commodity prices during 2021–2022 along the lines of Giovannini et al. (2019).

The model is estimated using a parallelised slice sampling algorithm with data over the period 1999q1–2023q4. 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. Additionally, the model allows for endogenous occasionally binding constraints to account for effective lower bound (ELB) periods during the COVID-19 pandemic.

The estimation results highlight the pivotal role of transitory lockdown shocks in driving Germany's economic contraction and recovery during 2020–2021, with fiscal policy measures providing significant stabilisation. The GDP recovery in 2021–2023 shows offsetting effects between domestic and foreign demand normalisation and a slowdown in international trade, alongside growing supply chain bottlenecks. The surge in CPI inflation in 2021–2022 is largely driven by domestic and global supply-side disruptions and rising commodity prices. Adverse productivity and supply shocks reflect global supply chain and capacity constraints. The estimated shocks closely align with off-model indicators, reinforcing the empirical credibility of the findings.

The remainder of the paper is organised as follows: Section 2 reviews recent studies related to modelling COVID-specific developments and the empirical literature on the post-pandemic inflation surge. Section 3 presents stylised macroeconomic facts for the German economy since 2008. Section 4 presents the model's structure. Section 5 details the model solution, data, estimation methodology, and discusses the posterior estimates. Section 6 examines 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-based results with off-model evidence. Section 9 conducts a sensitivity analysis without COVID-specific shocks. Section 10 provides a summary and concludes the paper.

2 Related literature

The analysis relates broadly to two strands of literature. The first strand relates to studies that have explored the impact of COVID-19 on economic dynamics, using structural macroeconomic models. For the US, for example, Chen et al. (2020) extend the New York Fed DSGE model, finding the pandemic recession primarily driven by demand shocks, while (Corrado et al. 2021) attribute it to a combination of large demand and supply shocks. Ferroni et al. (2024) propose a framework to estimate a general 'Covid shock', which loads onto model wedges to capture the pandemic's

unique macroeconomic dynamics, using data from professional forecasts to update agents' beliefs. In the Euro Area (EA), Cardani et al. (2022a) enhance the European Commission's DSGE model with COVID-specific shocks and financially-constrained investors, highlighting the importance of 'forced savings' in explaining GDP growth during the 2020 recession. Cardani et al. (2023) offer a model-based comparison of the pandemic's economic impact in the US and EA. Regarding German-specific studies, Funke and Terasa (2022) examines the temporary VAT rate cut during 2020q3–2020q4 in a calibrated DSGE model for Germany, while (Hinterlang et al. 2023) simulate the German fiscal stimulus packages.

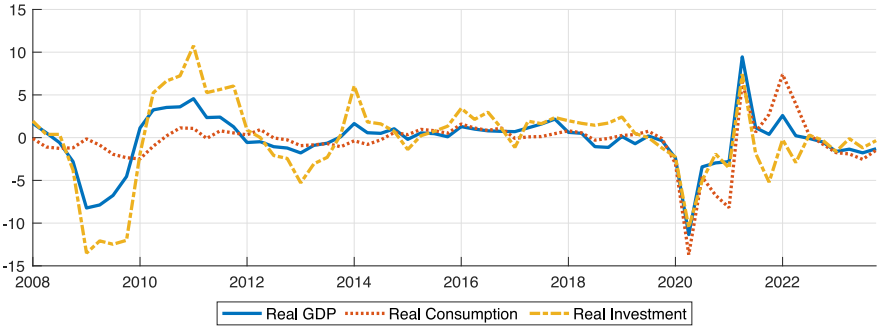
The second strand relates to the growing number of studies with a focus on the (global) inflation dynamics.[1] For the EA, studies such as Neri et al. (2023) and Pasimeni (2022) identify rising commodity prices as key drivers, contributing to over half of the post-COVID headline inflation. Pasimeni (2022) also highlights price pressures in sectors with high import content, pointing to international supply chain disruptions. Similarly, Hansen et al. (2023) attributes 40% of the EA's change in the consumption deflator in 2022 to import prices. Cardani et al. (2023) finds demand factors more influential for US inflation, while supply factors dominate in the EA. However, Giannone and Primiceri (2024) find unexpectedly strong demand forces in the Post-covid inflation, not only in the US, but also in the EA. Blanchard and Bernanke (2023) explore US inflation during the pandemic, identifying commodity prices, sectoral demand shifts, and supply constraints as key sources. This approach is applied to the EA and its member states by Menz (2024) (Germany), Pisani and Tagliabracci (2024) (Italy), Ghomi et al. (2024) (Spain), and Arce et al. (2024) (EA), all of whom find that commodity price shocks and supply bottlenecks were the primary inflation drivers.

This paper contributes to this discussion along several dimensions: (i) It develops and estimates a state-of-the-art multi-country DSGE model for the German economy (DE-REA-RoW) using data from 1999q1 to 2023q4; (ii) it applies the methodological approach of Cardani et al. (2022a) and incorporates heteroscedastic domestic and foreign COVID-19 shocks, such as a domestic consumption- and investment-specific lockdown shock, a shock to labour demand (labour hoarding) to account for the wedge between hours worked and employees (intensive margin) due to short-time work arrangements in Germany, and foreign risk shocks to account for spillover effects; (iii) it extends the use of commodities in production and final consumption demand to account for rising commodity prices; (iv) it allows for endogenous, occasionally binding constraints to account for ELB periods; and (v) it provides off-model evidence for the fit of the model-implied estimated shock pattern.

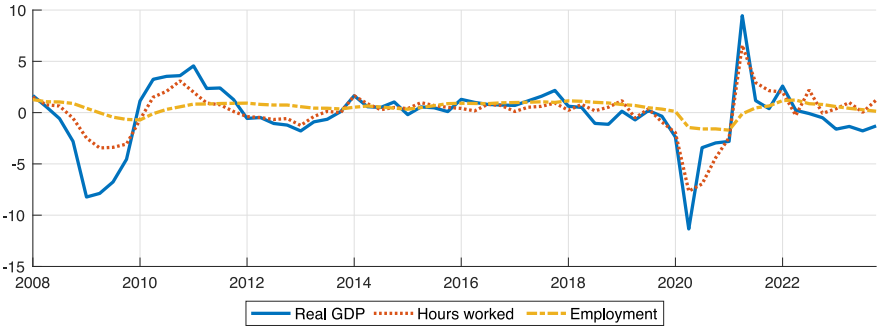
[1] Given the focus on Germany and the EA, I provide only a brief summary of the growing body of studies on US inflation dynamics, where the main drivers during the 2021–2022 US inflation surge are attributed to a combination of binding supply chain constraints (Comin et al. 2023; di Giovanni 2022; Blanchard 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).

3 Stylised facts

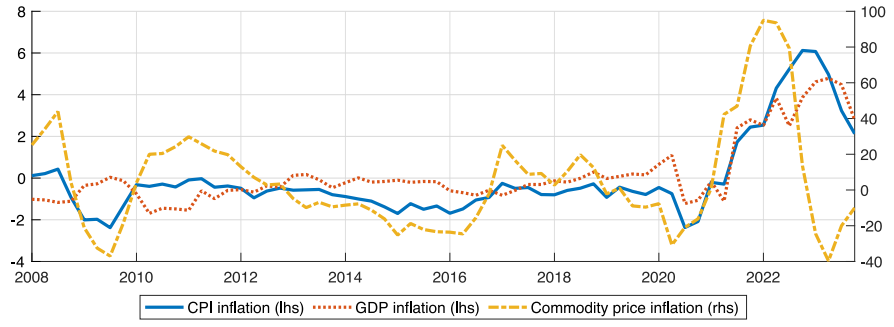
Figure 1 presents stylised facts about selected macroeconomic variables in Germany during the Global Financial Crisis (GFC) and the COVID-19 pandemic. First, the V-shaped contraction of economic activity in 2020q2 was sharper than the more



(a) Domestic demand components (yoy in %)



(b) Labour market (yoy in %)



(c) Price indices (yoy in %)

Fig. 1 Stylised facts of the pandemic and recovery period in Germany. 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

prolonged U-shaped recession of the GFC (Fig. 1a). Unlike the 2008–2009 recession, both private consumption and investment declined simultaneously during the 2020 pandemic. The model accounts for these patterns by incorporating transitory consumption- and investment-specific lockdown shocks during 2020.

Second, despite a significant decline in hours worked, the number of employees remained relatively stable during the onset of the pandemic (Fig. 1b). The gap between hours worked and employment during can be attributed to the introduction of job retention schemes (short-time work), which were designed to mitigate employment losses despite the sharp drop in GDP. The model addresses the wedge by introducing a labour hoarding shock that reduces effective hours worked.

Third, Fig. 1c illustrates that CPI and GDP inflation (left axis) rose significantly from 2021 onward, peaking at 8% and 6.8% in 2022q3 and 2023q2, respectively, when accounting for the 2% steady state. The co-movement between GDP and inflation during the 2020 lockdown, similar to the 2008–2009 recession, indicates a stronger initial demand-side driver (positive correlation). Commodity prices (right axis) fell at the onset of the pandemic, but surged in 2021–2022 due to the pandemic recovery, global supply chain bottlenecks, geopolitical tensions, and, ultimately, Russia's war against Ukraine. By 2023, oil and energy prices had dropped significantly to pre-crisis levels, contributing to the decline in CPI inflation. The model incorporates the most relevant time series, including commodity prices, GDP deflator, CPI inflation, sector-specific goods prices, and import/export prices, to capture supply-side disruptions through various disturbances.

4 The model

The structural setup builds upon the model used in Hohberger et al. (2020) and Cardani et al. (2022b). 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 are two types of households: Ricardian and liquidity-constrained (LC). The former have access to financial markets, smooth their consumption, and own the firms through equity. LC households do not have 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.

In the DE 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 (import retailers), perfectly competitive firms purchase goods from foreign regions and assemble them into a final import good, which is then combined with domestic output by final good packagers to create final aggregate demand-component goods.

The DE government purchases final goods and provides lump-sum transfers to households. To finance its expenditure, the government issues debt and imposes distortionary taxes on labour, capital, and consumption, along with non-distortionary lump-sum taxes. Monetary authorities set short-term nominal interest rates by following a Taylor rule, which reacts to inflation and the output gap.

Following the methodological approach in Cardani et al. (2022a), the model incorporates the following COVID-specific demand and supply disturbances: (1) A transitory consumption-specific lockdown shock in DE and REA, 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 investment-specific lockdown shock, 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 (risk shock). The following description highlights the primary aspects of the model, with further details available in Appendix 1.

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, $B_{j,t}^{rf}$, domestic government bonds, $B_{j,t}^{G}$, one internationally traded bond, $B_{j,t}^{W}$, and internationally traded shares, $P_t^S S_{j,t}$:

$$A_{j,t} = B_{j,t}^{rf} + B_{j,t}^{G} + e_{RoW,t} B_{j,t}^{W} + P_t^S S_{j,t} \tag{2}$$

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

where P_t^S 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, $C_{j,t}^s$, and experience disutility from labour, $N_{j,t}^s$, as well as from holding risky financial assets, $U_{j,t-1}^A$. The instantaneous utility function of savers, $u^s(.)$, is defined as:

$$\begin{aligned} u_{j,t}^s(C_{j,t}^s, N_{j,t}^s, \frac{U_{j,t-1}^A}{P_t^{C,vat}}) = & \frac{(C_{j,t}^s - \varepsilon_t^{tC} - h(C_{t-1}^s - \varepsilon_{t-1}^{tC}))^{1-\theta}}{1-\theta} \\ & - \frac{\omega^N \varepsilon_t^U (C_t)^{1-\theta} (N_{j,t}^s + \varepsilon_t^{tN})^{1+\theta^N}}{1+\theta^N} \\ & - (C_{j,t}^s - \varepsilon_t^{tC} - h(C_{t-1}^s - \varepsilon_{t-1}^{tC}))^{-\theta} \frac{U_{j,t-1}^A}{P_t^{C,vat}}, \end{aligned} \tag{3}$$

where $C_t^s = \int_0^1 C_{j,t}^s dj$, h measures the strength of external habits in consumption, and ω^N is the stochastic weight of the disutility of labour. ε_t^U captures a labour supply shock. ε_t^{tC} captures the non-persistent lockdown shock (forced saving) that constrains consumption outside of habit persistence, ε_t^{tN} captures a labour hoarding shock.[3] The disutility of holding risky financial assets, $U_{j,t-1}^A$, takes the following form:

$$\begin{aligned} U_{j,t-1}^A = & \left(\alpha^{b_0} + \varepsilon_{t-1}^B\right) B_{j,t-1}^G + \left(\alpha^{bw_0} + \varepsilon_{t-1}^{bw}\right) e_{RoW,t} B_{j,t-1}^W \\ & + \frac{\alpha^{bw_1}}{2} \frac{(e_{RoW,t-1} NFA_{t-1})^2}{P_{t-1}^Y Y_{t-1}} + \left(\alpha^{S_0} + \varepsilon_{t-1}^S\right) P_{t-1}^S S_{j,t-1}. \end{aligned} \tag{4}$$

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, $x \in \{b_0, S_0, bw_0\}$. 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:

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

[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.

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 the 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.

4.1.2 Liquidity-constrained households

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

$$\begin{aligned} u_{j,t}^c(C_{j,t}^c, N_{j,t}^c) = & \frac{(C_{j,t}^c - \varepsilon_t^{tC} - h(C_{t-1}^c - \varepsilon_{t-1}^{tC}))^{1-\theta}}{1-\theta} \\ & - \frac{\omega^N \varepsilon_t^U (C_t)^{1-\theta}}{1+\theta^N} (N_{j,t}^c + \varepsilon_t^{tN})^{1+\theta^N}. \end{aligned} \tag{9}$$

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:

$$P_t^{C,vat} C_{j,t}^c = (1-\tau^N) W_t (N_{j,t}^c + \varepsilon_t^{tN}) + T_{j,t}^c - tax_{j,t}^c + P^{C,vat} \left(\varepsilon_t^{tC} - \frac{1}{6} \sum_{i=8}^{13} \varepsilon_{t-i}^{tC} \right). \tag{10}$$

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

[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.

4.1.3 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^w_t is the cyclical gross wage markup:

$$\mu^w_t = \gamma^w \left[\frac{\partial adj^w_t}{\partial W_t} - \beta E_t \frac{\lambda_{t+1}}{\lambda_t} \frac{1}{\pi^{C,vat}_{t+1} + 1} \frac{\partial adj^w_{t+1}}{\partial W_t} + \varepsilon^U_t \right]. \tag{12}$$

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^U_t captures a labour supply shock (wage markup). The marginal utility of leisure is defined as: $U^N_t = \omega^N (C_t)^{1-\theta} (N_t)^{-\theta^N}$, 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:

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

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

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

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

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:

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

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

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. Specifically, 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 with 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:

$$M_{l,t} = s_{l,t}^M\left(\frac{P_{l,t}^M}{P_t^M}\right)^{-\sigma^{FM}}M_t\frac{size}{size_l}, \tag{28}$$

and the import prices deflator is:

$$P_t^M = \left[\sum_l s_{l,t}^M(P_{l,t}^M)^{1-\sigma^{FM}}\right]^{\frac{1}{1-\sigma^{FM}}}. \tag{29}$$

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

$$P_{l,t}^M = e_{l,t}P_{l,t}^X. \tag{30}$$

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_t^N. ε_t^{tVAT} is the COVID-related shock to VAT

during 2020q3–2020q4. 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:

$$B_t^G = (1 + i_t^G)B_{t-1}^G - R_t^G + P_t G_t + P_t IG_t + P_t T_t, \tag{31}$$

where R_t^G are the nominal government revenues:

$$R_t^G = (\tau^C + \varepsilon_t^{tVAT})P_t C_t + \tau^K \Big(P_t Y_t - W_t(N_t + \varepsilon_t^{tN}) - \delta P_t K_{t-1} \Big) \tag{32}$$

$$+ \tau_t^N (N_t + \varepsilon_t^{tN}) W_t + \tau^{CO} P_t^{CO} CO_t + \tau^{FN} W_t \Big((N_t + \varepsilon_t^{tN}) - N_t \Big) + tax_t. \tag{33}$$

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

$$tax_t = \rho^{tax} tax_{t-1} + \eta^{deft} \left(\frac{\Delta B_{t-1}^G}{Y_{t-1} P_{t-1}^Y} - DEFTAR \right) + \eta^{BT} \left(\frac{B_{t-1}^G}{Y_{t-1} P_{t-1}^Y} - BTAR \right) + \varepsilon_t^{tax}, \tag{34}$$

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]:

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

$\bar{i} = \bar{r} + \bar{\pi}^{Yobs}$ 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})

[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.

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:

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

where $\varepsilon^{i}_{EA,t}$ captures a monetary policy shock. More details on the ELB treatment will be explained in Section 5.5.

4.6 Commodities

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^E_t, and the demand for industrial supplies in final goods production, IS_t. Following (Cardani et al. 2023), final household consumption is represented as a CES aggregate of commodities used for consumption and final manufactured goods C^{FG}_t:

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

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

4.7 Closing the economy

The resource constraint of the DE economy is:

$$Y_t P^Y_t + \tau^{CO} CO_t P^{Y0}_t = P^C_t C_t + P^I_t I_t + P^{IG}_t IG_t + P^G_t G_t + TB_t, \tag{38}$$

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

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

Domestic holding of the internationally traded bond, B^W_t, evolves according to:

$$e_{RoW,t} B^W_t = (1 + i^{bw}_{t-1}) e_{RoW,t} B^W_{t-1} + TB_t + ITRP^Y_t Y_t. \tag{40}$$

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

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 the 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:

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

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

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

$$C_{k,t} = A^{p}_{k,t}\left[(1-\varepsilon^{M}_{k,t} s^{M}_{k})^{\frac{1}{\sigma^{c}_{k}}} (Y^{C}_{k,t})^{\frac{\sigma^{c}_{k}-1}{\sigma^{c}_{k}}} + (\varepsilon^{M}_{k,t} s^{M}_{k})^{\frac{1}{\sigma^{c}_{k}}} (M^{C}_{k,t})^{\frac{\sigma^{c}_{k}-1}{\sigma^{c}_{k}}}\right]^{\frac{\sigma^{c}_{k}}{\sigma^{c}_{k}-1}}. \tag{43}$$

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

$$Y^{C}_{k,t} = (A^{p^{C}}_{k,t})^{\sigma^{c}_{k}-1}\left(1-\varepsilon^{M}_{k,t} s^{M}_{k}\right)\left(\frac{P^{Y}_{k,t}}{P^{C}_{k,t}}\right)^{-\sigma^{c}_{k}} C_{k,t}, \tag{44}$$

$$M^{C}_{k,t} = (A^{p^{C}}_{k,t})^{\sigma^{c}-1}\varepsilon^{M}_{k,t} s^{M}_{k}\left(\frac{P^{M}_{k,t}}{P^{C}_{k,t}}\right)^{-\sigma^{c}_{k}} C_{k,t}, \tag{45}$$

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

$$P^{C}_{k,t} = (A^{p^{C}}_{k,t})^{-1}\left[(1-\varepsilon^{M}_{k,t} s^{M}_{k})(P^{Y}_{k,t})^{1-\sigma^{c}_{k}} + \varepsilon^{M}_{k,t} s^{M}_{k} (P^{M}_{k,t})^{1-\sigma^{c}_{k}}\right]^{\frac{1}{1-\sigma^{c}_{k}}}. \tag{46}$$

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

curve:

$$\pi^{Y}_{k,t} - \bar{\pi}^{Y}_{k} = \beta \frac{\lambda_{k,t+1}}{\lambda_{k,t}} (\pi^{Y}_{k,t+1} - \bar{\pi}^{Y}_{k}) + \phi^{Y}_{k} log(\frac{Y_{k,t}}{\bar{Y}_{k}}) + \varepsilon^{Y}_{k,t}, \tag{47}$$

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

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

Combining the two regions' FOCs with respect to international bonds derives the uncovered interest parity (UIP) condition:

$$E_t \left[\frac{e_{RoW,EA,t+1}}{e_{RoW,EA,t}} \right] (1 + i_{RoW,t}) = (1 + i_{EA,t}) + \varepsilon^{bw}_{EA,t} + \alpha^{bw0}_{EA} + \alpha^{bw1}_{EA} \frac{e_{RoW,EA,t} B^{w}_{EA,t}}{P^{Y}_{EA,t} Y_{EA,t}}, \tag{48}$$

where $\varepsilon^{bw}_{EA,t}$ captures a euro exchange rate shock (shock to the bond premium between EA and RoW), and α^{bw1}_{EA} 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^{CO}_{t} 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, $\varepsilon^{P,CO}_{l,t}$, where $l = (DE, REA)$, aiming to reflect price variations due to differing commodity baskets. Therefore:

$$P^{CO}_{l,t} = \varepsilon^{P^{CO}}_{l,t} \left[s^{Oil}_{l} \left(P^{Oil}_{t} \right)^{1-\sigma^{CO}} + (1 - s^{Oil}_{l}) \left(P^{IS}_{t} \right)^{1-\sigma^{CO}} \right]^{\frac{1}{1-\sigma^{CO}}}, \tag{49}$$

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

Commodity prices are exogenous and follow:

$$P^{CO}_{t} = \frac{P_t}{A^{CO}_{t}}, \quad \text{where CO=(Oil, IS)} \tag{51}$$

where A^{CO}_{t} is the exogenous commodity-specific productivity technology.

5 Model solution and econometric approach

5.1 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 Eq. 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 Eq. 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 Eq. 53 incorporates deterministic heteroscedasticity:

$$Q_t = \begin{cases} Q^{COVID} & \text{for } t \in \{2020q1 : 2021q4\}, \\ Q & \text{otherwise.} \end{cases} \tag{54}$$

For the pandemic period 2020q1–2021q4, $Q_t = Q^{COVID}$ incorporates temporary COVID-specific shocks, whereas prior to COVID-19, $Q_t = Q$, implies zero standard deviations (and zero expectations) for these shocks.

5.2 Data

The model is estimated quarterly, using data for Germany and the Euro Area (EA19) from Eurostat. Bilateral trade flows are based on GTAP trade matrices, covering goods and services. Annual data for the rest of the world (RoW) are sourced from the IMF's International Financial Statistics (IFS) and World Economic Outlook (WEO) databases. The model includes 41 observed series and 41 exogenous shocks. Details on the time series are provided in Appendix 4.

5.3 Estimation procedure and filtering

The estimation proceeds in three steps:
1. A subset of parameters is calibrated to align with historical long-run properties, such as steady-state ratios. The heteroscedastic filter enables the ex-ante specification of shock standard errors for each period between 2020q1 and 2021q4. The timing of the COVID-related shocks is calibrated to reflect the imposed lockdown periods and policy-induced VAT reductions, as detailed in Table 2. Section 9 includes a sensitivity analysis examining the model's fit and economic narrative in the absence of COVID-specific shocks.

2. The remaining parameters and shocks are estimated using data over the sample period 1999q1–2023q4. The full-sample estimation procedure incorporates the estimation of heteroscedastic COVID-specific variances during the period 2020q1–2021q4, thereby allowing for time-varying shock disturbances Q_t.[7] The likelihood function (evaluated by implementing the Kalman filter) and the prior distribution of the parameters are combined to calculate the posterior distribution. The posterior Kernel is then simulated numerically using the slice sampler algorithm as proposed by Planas et al. (2015).[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.

5.4 Calibrated parameters and posterior estimates

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 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 steady-state share of Ricardian households is calibrated at 61%, based on Dolls et al. (2012). Table 3 in Appendix 2 provides an overview of calibrated parameters.

Table 1 reports prior and posterior estimates for selected model parameters. The estimated EA monetary policy parameters suggest a strong response to EA inflation (1.78) compared to the EA output gap (0.05), together with relatively high interest rate inertia (0.91). Estimated habit persistence is 0.90, implying a slow adjustment of consumption to changes in income. Risk aversion and the inverse labour supply elasticity are 1.33 and 3.72, 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 1.93, and the price elasticity of commodity demand is 0.40. The posterior estimates also suggest sticky prices (40.8), wages (17.3), and investments (38.2). The estimated parameters for REA and RoW can be found in

[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 the second step, they estimate the variances of heteroscedastic COVID-specific shocks using data for the pandemic period (2020q1–2021q4), 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).

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

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

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

		Prior distribution			Posterior distribution
		Distr	Mean St.Dev	Time	
DE COVID-specific shocks (standard deviations in %)					
Consumption-specific lockdown shock	ε^{tC}	G	5	[20q1 - 21q3]	4.75
			2		(4.03, 7.36)
Investment-specific lockdown shock	ε^{tS}	G	5	[20q1 - 20q2]	2.27
			2		(1.10, 5.80)
labour hoarding shock	ε^{tN}	G	5	[20q2 - 21q1]	2.57
			2		(1.85, 4.77)
VAT-tax shock	ε^{tVAT}	G	2	[20q3 - 20q4]	1.70
			0.8		(0.91, 3.03)
REA COVID-specific shocks (standard deviations in %)					
Consumption-specific lockdown shock	ε^{tC}	G	5	[20q1 - 20q2]	6.97
			2		(4.99, 9.78)
Risk shock	$\varepsilon^{t\beta}$	G	5	[20q1 - 21q4]	8.30
			2		(3.91, 10.13)
RoW COVID-specific shocks (standard deviations in %)					
Risk shock	$\varepsilon^{t\beta}$	**G**	5	[20q1 - 21q4]	13.76
			2		(12.63, 17.44)

Note: The table reports the mode and the standard deviation (in %) of the posterior distributions of DE, REA, and RoW COVID-specific shock innovations. Time refers to the ex-ante assumed periods of the heteroscedastic shock

Table 4 in Appendix 2. Tables 5 and 6 in Appendix 2 report the main estimated shock processes for DE, and REA and RoW, respectively.

Table 2 provides the posterior estimates of pandemic-specific shocks, revealing a mix of demand-side (lockdown) and supply-side shocks (labour market).[9] Specifically, it shows a significant incidence of consumption-specific lockdown shocks (4.75%) and substantial labour hoarding shocks (2.57%), reflecting Germany's adopted labour market policies. The estimated VAT cut in 2020q3–2020q4 is 1.7%. The simplified REA and RoW structure suggests persistent saving shocks (risk shocks) to capture the COVID-19 pattern during 2020 and the recovery from 2021 to 2022. Figure 12 in

[9] For robustness, I incorporated additional domestic and foreign heteroscedastic productivity shocks for the pandemic period (2020q1–2021q4) and the inflationary period (2022q1–2023q4) to assess whether the model might be missing key supply-side drivers not captured by the standard shocks. The analysis indicates that these additional shocks are weakly identified and have only a marginal impact on GDP and inflation compared to the standard incorporated and estimated supply shocks. This result suggests that the model effectively captures the dynamics of both the pandemic and the inflationary surge using the observed supply-side series and shocks.

Appendix 2 provides the prior and posterior distributions of the estimated COVID-specific shocks.

5.5 ELB environment—non-linear smoothing

The model accounts for binding ELB periods using the piecewise linear Kalman filter algorithm from Giovannini et al. (2021). Based on the model's parameter estimates, it identifies structural shocks that account for endogenous ELB periods using the OccBin approach of Guerrieri and Iacoviello (2015), generating a sequence of smoothed variables and shocks consistent with the occasionally binding constraint.[10] The sequence of regimes for Germany, indicating whether the ELB is binding or not, is shown in Table 7 in Appendix 2.

6 Dynamic transmission of shocks

This section examines the estimated dynamic effects of shocks characteristic of the COVID-19 pandemic and the subsequent inflation surge. For the pandemic period, it compares the COVID-specific shocks with their standard counterparts in a scenario where the ELB on the short-term nominal interest rate is binding.[11] Specifically, it presents generalised impulse response functions (GIRFs), which are simulated as follows: The starting point of the simulations is set to 2020q2. Based on the regime sequence in Table 7, a period where the ELB is binding for 5 more quarters. Remove the specific shock (e.g., the consumption-specific lockdown shock) and simulate the model with all remaining shocks. Then, reintroduce this shock and rerun the simulation. The difference between the two scenarios yields the GIRFs under the ELB (shown as dashed lines in the Figures).

All shocks are simulated using one estimated standard deviation. Each panel illustrates 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 shown as percent deviations from their steady states, while the policy rate (annualised), CPI inflation (annualised), and the trade balance-to-GDP ratio are expressed as deviations in basis points and percentage points, respectively.

6.1 Pandemic-related responses

This subsection presents the dynamic responses to the estimated COVID-specific disturbances, namely (i) the transitory consumption-specific lockdown shock (forced

[10] Similar ELB implementations are found in Hohberger et al. (2019) and Croitorov et al. (2020).

[11] When the ELB is binding, the economic contraction during the COVID-19 period, marked by declining output and inflation, is not mitigated by expansionary monetary policy. In contrast, during 2022–2023, negative supply-side shocks driving up inflation and slowing economic activity are compounded by monetary tightening aimed at reducing inflation.

saving, (ii) the shock to labour hoarding, (iii) the investment-specific lockdown shock, and (iv) foreign risk shocks in REA and RoW.

Transitory forced saving shock (consumption-specific lockdown)

Figure 2 compares the estimated dynamic responses to the transitory consumption-specific lockdown shock (forced saving) and the standard persistent savings shock. The transitory lockdown shock (dashed), combined with a binding ELB on interest rates, leads to an 8.5% drop in private consumption and a 3.6% drop in real GDP, both lasting for one quarter (2020q2). The fall in GDP causes a temporary dip in employment (hours worked), although the decline is mitigated by labour adjustment costs. In the short term, the trade balance improves due to lower domestic demand and reduced imports. It is important to note that this transitory lockdown shock captures both demand-side effects, such as precautionary household behaviour, and supply-side effects, such as forced business closures. The relatively modest impact on CPI inflation reflects the shock's temporary nature and the presence of sticky prices. Unlike persistent savings shocks, transitory shocks do not influence medium-term inflation expectations, which play a crucial role in determining actual inflation.

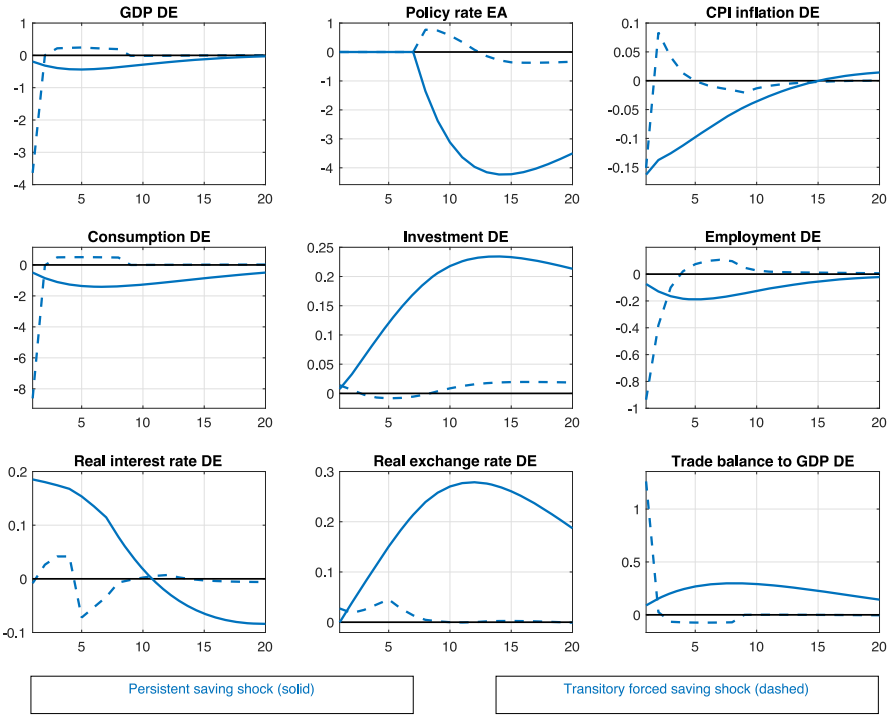


Fig. 2 Dynamic responses to saving shocks. Note: The trade balance (normalised by GDP), inflation (p.a.), and real interest rate (p.a.) responses are expressed as percentage point, the policy rate (p.a.) as basis point, deviations from steady state. All other responses are percent deviations from steady state. The size of the shock corresponds to one estimated standard deviation. Periods correspond to quarters

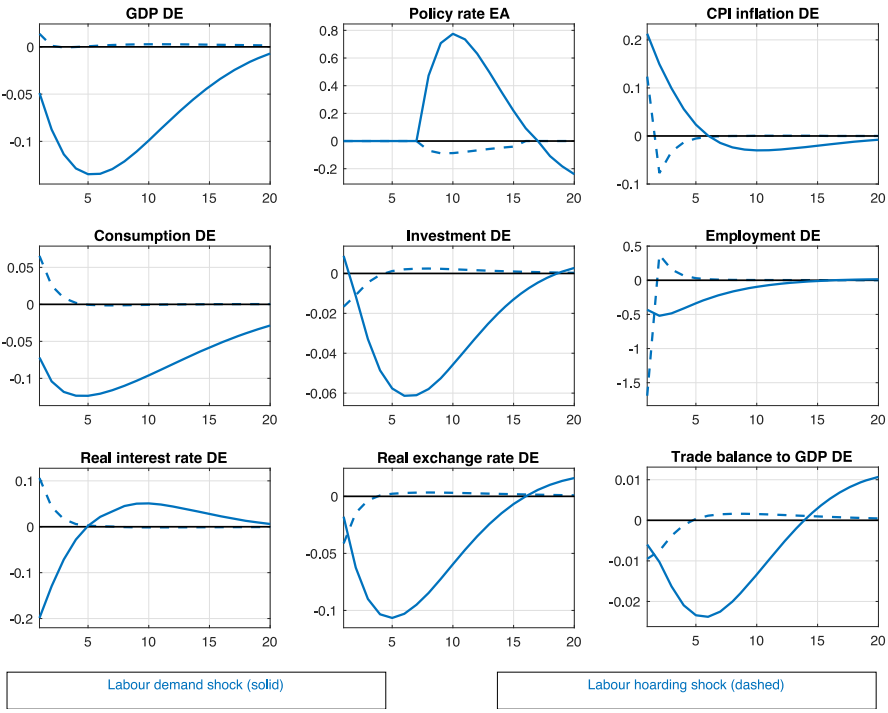


Fig. 3 Dynamic responses to labour shocks. Note: The trade balance (normalised by GDP), inflation (p.a.), and real interest rate (p.a.) responses are expressed as percentage point, the policy rate (p.a.) as basis point, deviations from steady state. All other responses are percent deviations from steady state. The size of the shock corresponds to one estimated standard deviation. Periods correspond to quarters

The economy's response to the standard savings shock (solid line) is qualitatively similar, characterised by a hump-shaped pattern in domestic demand driven by habit persistence. Moreover, the persistent savings shock remains deflationary when the economy exits the ELB environment after seven quarters, prompting the central bank to lower interest rates in the medium term relative to the no-shock baseline.[12] This policy response boosts investment, stabilises private demand and output, and leads to domestic currency depreciation, which in turn improves the trade balance.

Labour hoarding shock

Figure 3 compares the estimated responses to the standard labour demand shock (solid line) and the COVID-specific labour hoarding shock (dashed line). Labour hoarding represents a shock to labour demand that accounts for the wedge between hours worked and employment. This transitory shock reduces effective hours worked by 1.5% on impact. As the capital-labour ratio increases, the marginal return to capital

[12] Note that the starting point of the simulations is 2020q2, a period during which the ELB is initially expected to bind for seven more quarters (see Table 7). Afterward, the policy rate transitions to the (unconstrained) Taylor rule, responding to the negative shocks by decreasing the rate.

declines, leading to a fall in investment. However, households maintain real consumption levels, keeping overall income (GDP) and inflation relatively stable. The economy's estimated response to the standard labour demand shock (solid line) differs notably, as the persistent decline in employment reduces real wages and weakens domestic demand components. The accompanying real exchange rate appreciation worsens the trade balance, resulting in a much sharper and more prolonged contraction in output. Inflation rises due to higher import prices, prompting an increase in interest rates once the economy exits the ELB environment.

Transitory investment shock (investment-specific lockdown)

Figure 13 in Appendix 2 compares the estimated dynamic responses to the transitory investment-specific lockdown shock (dashed line) and the standard persistent shock to the investment risk premium. The economy's reaction to the lockdown shock closely resembles that of the consumption-specific lockdown shock, reflecting its one-off nature. Private investment drops by 11%, and real GDP falls by 1.4% in 2020q2, with only a marginal effect on CPI inflation. In contrast, the response to the investment risk shock (solid line) is characterised by a persistent decline in domestic demand components, exerting downward pressure on CPI inflation. This leads to lower interest rates in the medium term (after exiting the ELB), which in turn boosts consumption by reducing savings, stabilises private demand and output, and improves the trade balance.

Foreign demand shocks

Figure 4 compares the dynamic effects of a negative foreign demand shock in REA (solid line) and RoW (dashed line) on the German economy, modelled as a temporary increase in foreign household savings during the COVID-19 pandemic. This shock reduces foreign consumption, output, and prices. For Germany, the REA shock generates significantly larger spillovers, causing a 0.4% drop in real GDP without monetary support. This is primarily due to an appreciation of the real effective exchange rate (REER), which negatively impacts the trade balance by reducing foreign demand. The resulting decline in economic activity lowers employment, real wages, and domestic consumption. With the ELB constraint in place in 2020, these spillovers resemble the effects of an additional risk shock, characterised by the co-movement of consumption and investment, for Germany.

In summary, the dynamic responses to the COVID-specific shocks capture qualitative patterns that help explain key features of the pandemic period (see Fig. 1). Consumption- and investment-specific lockdown shocks lead to sharp declines in consumption, investment, and output, followed by a swift recovery. Labour hoarding accounts for the discrepancy between reduced hours worked and relatively stable employment during the pandemic. Neither transitory savings and investment shocks nor labour hoarding result in a significant change in inflation. Spillovers from REA and RoW provide insights into the global impact of the pandemic and the associated decline in Germany's trade balance. Consequently, incorporating additional pandemic-related shocks is necessary to fully capture the information from our comprehensive data set.

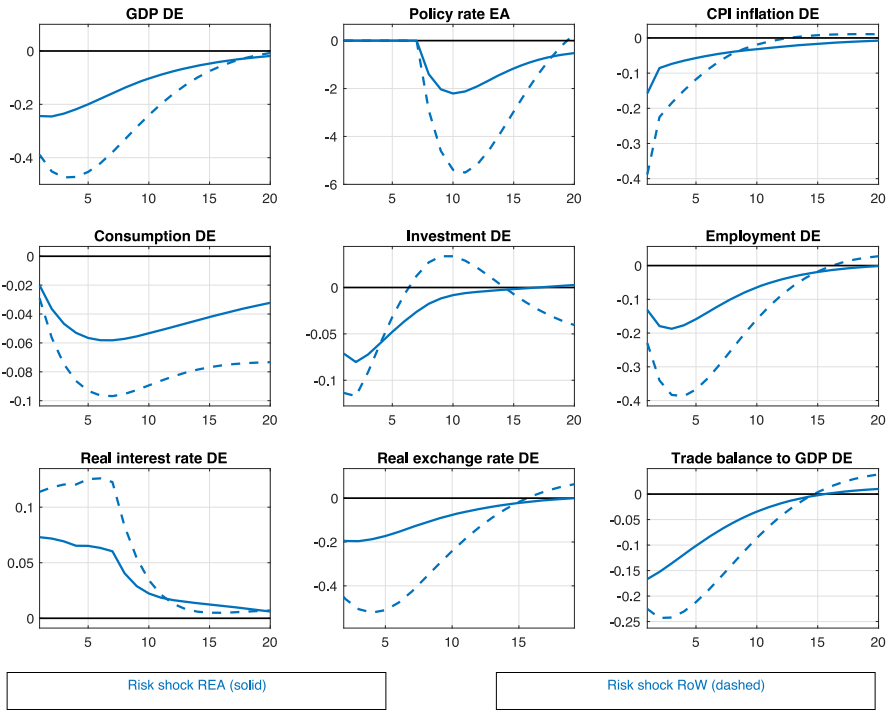


Fig. 4 Dynamic responses to foreign risk shocks. Note: The trade balance (normalised by GDP), inflation (p.a.), and real interest rate (p.a.) responses are expressed as percentage point, the policy rate (p.a.) as basis point, deviations from steady state. All other responses are percent deviations from steady state. The size of the shock corresponds to one estimated standard deviation. Periods correspond to quarters

6.2 Inflation-related responses

Figure 5 presents the dynamic responses to two key supply-side shocks characteristic of the inflationary period from 2022 to 2023: A retail price markup shock (solid lines), and a permanent increase in DE export prices (dashed lines). The retail price markup shock acts as a wedge between production costs and consumer prices, which can be interpreted as a consumption-specific price markup by retailers.[13] Note that the IRFs in Fig. 5 display linear responses since both shocks significantly contributed to GDP and CPI inflation dynamics in 2022–2023, during which the ECB began raising interest rates away from the ELB.

Both shocks can be viewed as proxies for binding capacity constraints, reflecting dynamics captured by the Global Supply Chain Pressure Index (GSCPI) developed by Benigno et al. (2022) and simulating the effects of supply chain disruptions. They both suppress domestic economic activity (consumption and investment), but only the retail price markup shock notably drives up CPI inflation. As a result, these shocks present different inflation-output trade-offs: the retail markup shock increases CPI inflation

[13] The shock, $A_t^{p^{\mathcal{Z}}}$, is modelled as a negative productivity shock for the final consumption good, $\mathcal{C}$, as detailed in Eq. 23

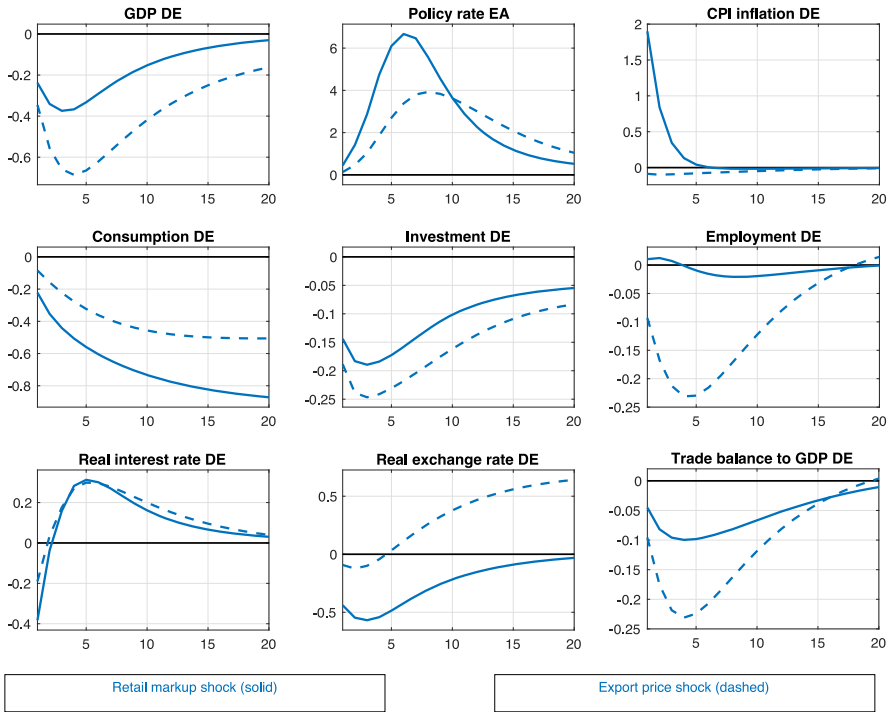


Fig. 5 Dynamic responses to supply-side shocks. Note: The trade balance (normalised by GDP), inflation (p.a.), and real interest rate (p.a.) responses are expressed as percentage point, the policy rate (p.a.) as basis point, deviations from steady state. All other responses are percent deviations from steady state. All other responses are percent deviations from steady state. The size of the shock corresponds to one estimated standard deviation. Periods correspond to quarters

by nearly 2 pp while causing a smaller drop in real GDP (up to 0.4%). In contrast, the export price shock leads to a larger decline in real GDP (up to 0.7% after one year) with less pronounced inflationary effects.

7 Estimated drivers of macroeconomic variables

Historical shock decompositions (SDs) offer a quantitative evaluation of the main estimated drivers of Germany's historical data pattern. Figures 6, 7, and 8 exhibit the SDs of real GDP growth, CPI inflation, and nominal wage growth from 2018q1 to 2023q4.[14] The assessment considers the endogenous ELB periods obtained from non-linear smoothing, as discussed in Subsection 5.5. The approach for extending standard linear (additive) historical shock decomposition to account for occasionally binding constraints is detailed in C.[15]

[14] Figs. 14 and 15 in Appendix 2 display the historical drivers of real GDP growth and inflation over the full-sample period.

[15] A similar methodology for adapted piecewise linear smoothed shock decomposition is presented in Croitorov et al. (2020) and Cardani et al. (2023).

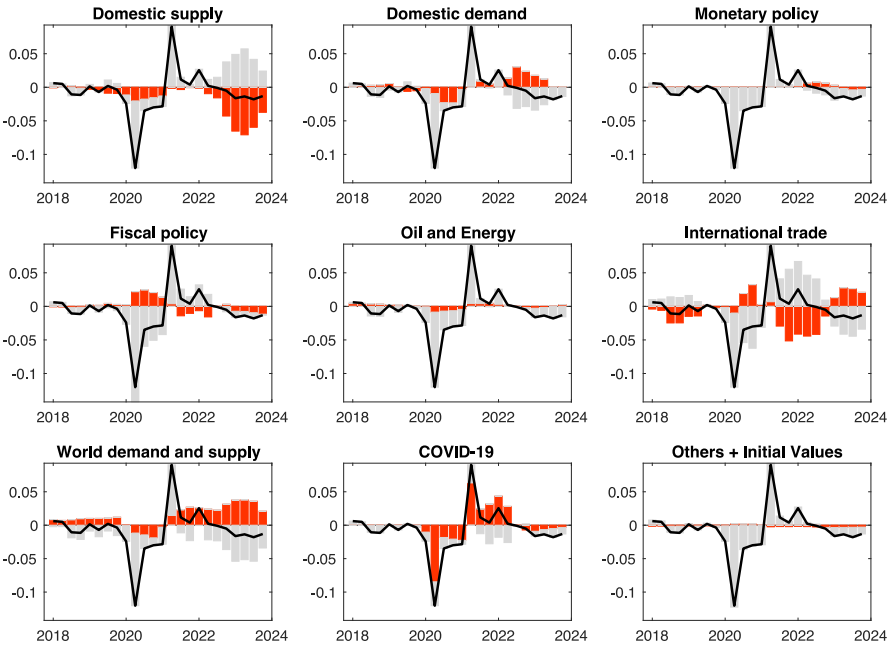


Fig. 6 Historical decomposition of real GDP growth (yoy) Note: Real GDP growth is shown in percentage-point deviations from steady state, which is calibrated to 1.25% per year. 0.01 on the *y*-axis corresponds to 1 pp. Continuous black lines represent the historical data. The vertical red bars illustrate the contribution of each respective (group of) exogenous shocks to the data, whereas stacked light grey bars summarise the contributions of all remaining shocks. The sum of the contributions equals the historical data

In each subplot in Figs. 6, 7, and 8, the continuous black line represents the historical data, from which the steady state (1.25% p.a. for GDP, 2.0% p.a. for inflation, and 2.9% p.a. for wage growth) has been subtracted. The vertical red bars illustrate the contribution of each respective (group of) exogenous shocks to the data, whereas stacked light grey bars summarise the contributions of all remaining shocks. Bars above the horizontal axis (steady state) represent positive shock contributions; bars below the horizontal axis show negative shock contributions. The sum of the contributions by all shocks equals the historical data in each period. The group of shocks are categorised as follows: (1) domestic supply, which includes productivity, price, labour supply and demand, and wage markup shocks; (2) domestic demand, encompassing private savings and investment risk premium; (3) monetary policy; (4) fiscal policy; (5) commodity prices, including oil and industrial supplies; (6) international trade, involving preferences for domestically produced versus foreign goods, export and import price markups, and exchange rate shocks; (7) world demand and supply, containing foreign (REA and RoW) demand and supply shocks; (8) COVID-19, covering lockdown and labour market shocks; and (9) initial values.

Real GDP growth

Figure 6 shows that the COVID-19 recession was driven by both demand and supply shocks. The model emphasises the significant impact of lockdowns in DE and REA,

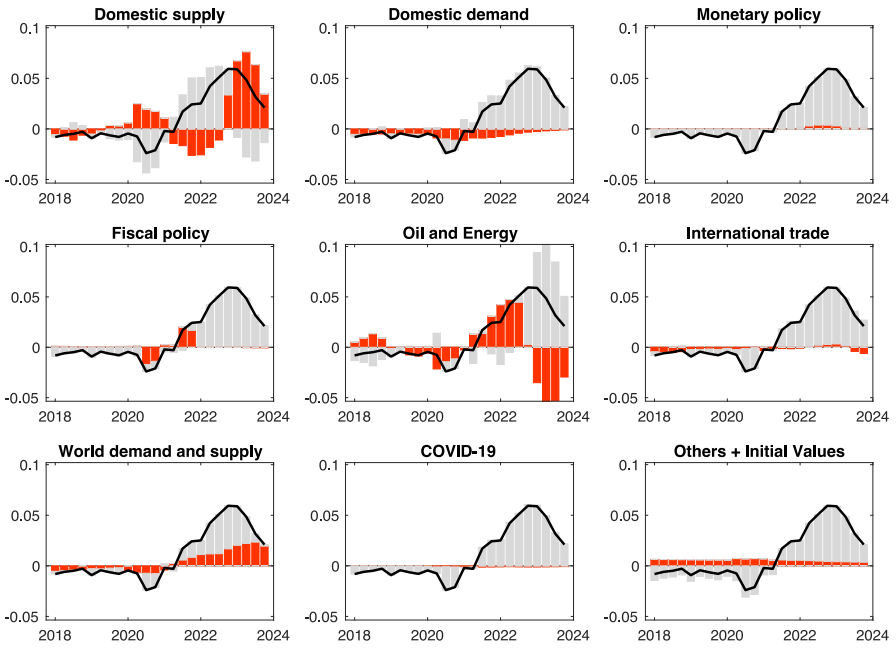


Fig. 7 Historical decomposition of CPI inflation (yoy) Note: CPI inflation is shown in percentage-point deviations from steady state, which is calibrated to 2% per year. 0.01 on the *y*-axis corresponds to 1 pp. Continuous black lines represent the historical data. The vertical red bars illustrate the contribution of each respective (group of) exogenous shocks to the data, whereas stacked light grey bars summarise the contributions of all remaining shocks. The sum of the contributions equals the historical data

notably through a transitory savings shock that reduced domestic consumption and increased investment risk, leading to an 8 percentage-point (pp) contraction in 2020q2 from trend. Global spillovers further contributed to the 2020 GDP decline, averaging 1 pp. However, international trade positively affected GDP growth due to reduced German import demand from REA and RoW, boosting net exports. Discretionary fiscal policy helped stabilise GDP, contributing up to 2 pp on average, consistent with findings by Funke and Terasa (2022) and Hinterlang et al. (2023).

The recovery phase during 2021–2023 was shaped by counterbalancing factors. The normalisation of domestic demand (as lockdowns eased) and recovering global demand supported real GDP growth. However, a slowdown in international trade and negative supply shocks exerted downward pressure, keeping growth rates modest. A significant export price shock, driven by supply chain bottlenecks, reduced economic activity in Germany by up to 4 pp in 2021–2022. Despite monetary tightening in 2022, moderate positive contributions from monetary policy arose because our model-implied rate was higher than the observed rate. This gap was offset by easing monetary policy shocks, suggesting the model would have advocated earlier or more aggressive rate hikes.[16]

[16] Monetary policy refers only to Taylor rule shocks, excluding the tapering of unconventional measures.

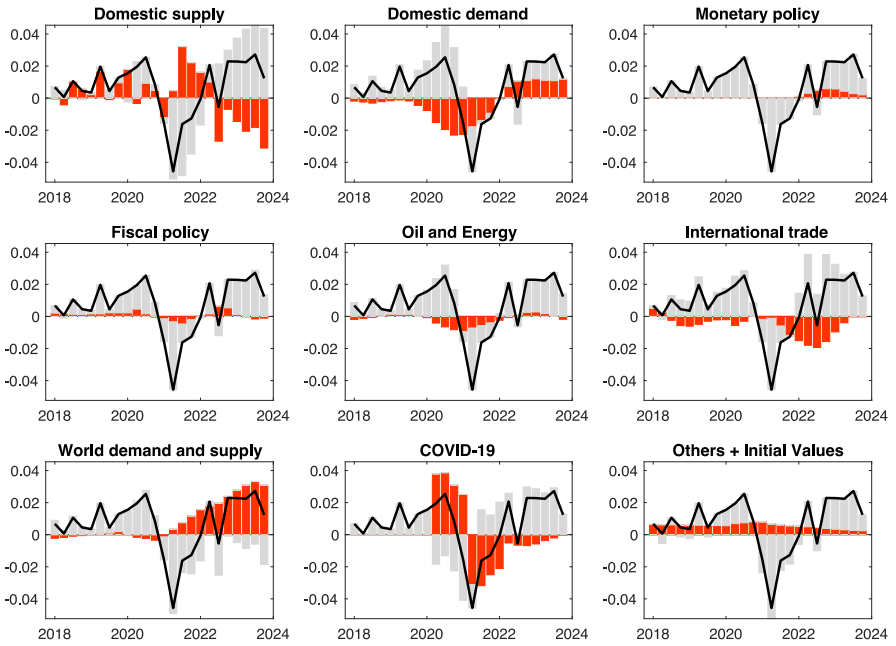


Fig. 8 Historical decomposition of wage growth (compensation per hour) (yoy) Note: Nominal wage growth, measured as compensation per hour, is shown in percentage-point deviations from steady state, which is calibrated to 2.9% per year. 0.01 on the *y*-axis corresponds to 1 pp. Continuous black lines represent the historical data. The vertical red bars illustrate the contribution of each respective (group of) exogenous shocks to the data, whereas stacked light grey bars summarise the contributions of all remaining shocks. The sum of the contributions equals the historical data

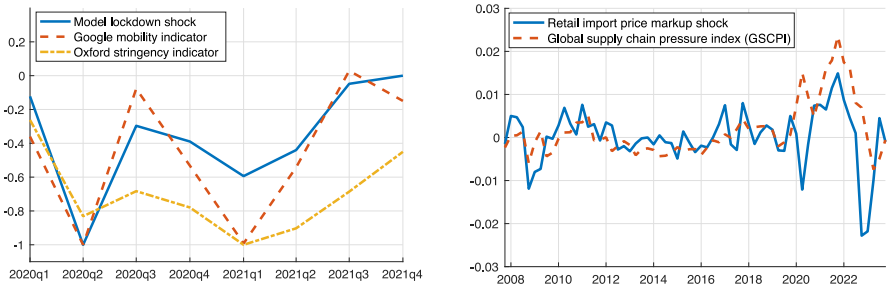
CPI inflation

Figure 7 shows that transitory lockdown shocks had a minimal impact on inflation during the pandemic, as they did not influence inflation expectations. The CPI inflation surge in 2021–2022 was primarily driven by rising commodity prices and supply-side factors, with energy prices contributing up to 4.5 pp in 2022. The reversal of persistent negative global demand shocks signals recovery from pre-COVID trends. Expansionary fiscal policy moderately boosted inflation, while the VAT reduction in late 2020 contributed to a 1.5 pp dip.

In 2023, falling commodity prices put downward pressure on inflation, offset by consumption-specific price markup shocks from retailers. These increased import markups, due to capacity constraints and supply chain disruptions, added up to 4 pp to above-trend inflation. The moderate inflationary impact of monetary policy in 2022 reflects again a cautious approach to tightening relative to the model-implied policy rule.

Nominal wage growth (compensation per hour)

Pandemic-related support measures in Germany created a significant gap between compensation per employee (CPE) and compensation per hour (CPH). The volatility in hours worked, mainly due to job retention schemes like short-time work (STW), contributed to this disparity. Since the government's compensation for wage losses



(a) COVID-specific lockdown measures

(b) Retail import price markup and GSCPI

Fig. 9 Off-model indicators and estimated model shocks. Note: In Panel a), the model shock (blue solid line) represents the estimated lockdown shock as described in Eq. 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 b), 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 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

is paid as social transfers while wages decrease with reduced hours, STW schemes caused a marked drop in CPE. As CPE growth fell sharply in early 2020, CPH rose due to the significant reduction in hours worked.[17]

Figure 8 illustrates the effects of STW schemes through the COVID-specific labour hoarding shock. The reduction in hours worked positively impacted wage growth (per hour) by about 4 pp in 2020 (COVID-19 shock group), though it had negative effects in 2021, partly due to base effects from 2020.[18] The decline in domestic demand was a primary negative driver in 2020. In contrast, the normalisation and recovery of domestic and foreign demand boosted wage growth during the recovery phase from 2022 to 2023. However, these gains were partly offset by domestic supply-side factors, such as retail import price markups and capacity constraints, as reflected in export price shocks and international trade components.

8 Comparison of shocks to off-model indicators

To assess the empirical plausibility of two identified shocks, Fig. 9 compares the estimated COVID-specific lockdown shock and the retail import price markup shock with their real-world counterparts.

Figure 9a examines the estimated lockdown shock alongside two pandemic-related restriction indicators for Germany: Google's mobility indicator and the Oxford COVID-19 Government Response Tracker (Hale et al. 2021), which reflects government policies on closures, containment, and health measures. The estimated lockdown shock closely aligns with both indicators. The slight decoupling from the strin-

[17] Bodnár et al. (2023) and Da Silva et al. (2020) discuss wage developments and STW schemes during the pandemic in detail.

[18] The estimated labour hoarding shock during the COVID-19 period can also indicate labour market tightness, consistent with Menz (2024).

gency indicator after the first lockdown (2020q2) indicates that private consumption rebounded faster than the easing of restrictions, likely due to the increased adoption of online retail. Both the alternative indicators and the estimated lockdown shock also correspond during the subsequent improvement in the epidemiological situation in 2021.

Figure 9b compares the estimated retail import price markup shock with the Global Supply Chain Pressure Index (GSCPI) by Benigno et al. (2022), which measures pressures within the global supply chain and indicates potential disruptions. The estimated price markup closely follows the GSCPI pattern. Notably, during the pandemic from 2020 to 2022, the estimated price markup rose sharply alongside increasing global supply constraints, before both showed reduced pressures on the supply chain toward the end of 2022 and the beginning of 2023.

9 Sensitivity analysis

This section explores the sensitivity of the model's results through two counterfactual analyses: (i) the absence of heteroscedastic COVID-specific shocks, and (ii) the robustness of observing shadow rates instead of the short-term nominal interest rate to proxy for the effect of unconventional monetary policy (UMP).

9.1 Counterfactual without COVID-specific shocks

Figure 10 presents the shock decomposition of real GDP growth, CPI inflation, and wage growth for two model variants: (i) one including COVID-specific shocks and (ii) one excluding these shocks. The latter variant is generated by running a smoother with identical estimated parameters, but with all COVID-specific shocks deactivated. The exogenous shock groups are similar, except the former variant separately visualises all COVID-related shocks (light blue).

The counterfactual model without COVID-specific shocks attributes the 2020 GDP drop to persistent savings shocks (10b). This model's slower consumption response affects future expectations, leading to (i) a stronger negative demand impact on CPI inflation in 2020 and (ii) more pronounced offsetting supply-side factors, like price and wage markup shocks, to match observed data. For nominal wage growth, positive wage markup shocks (negative supply shocks) are needed in 2020 to reconcile the decline in hours worked without COVID-related labour hoarding shocks (10f).[19] In the absence of COVID-specific shocks, the model requires higher shock variances to match the observed data patterns, particularly during 2020. The implied adjustment dynamics with COVID-specific shocks are more closely aligned with the observed data during the pandemic period, indicating a better model fit.

From an empirical standpoint, data density serves as a valuable global criterion for model evaluation in the Bayesian context. It assesses the model fit, favouring

[19] In an early ex-ante assessment of the COVID-19 pandemic, Mckibbin and Fernando (2020) used preference and risk shocks to predict the initial phase of the pandemic without explicitly incorporating lockdown-related shocks. This approach is comparable to Fig. 10b, which provides a reasonable economic interpretation. However, the added value of transitory lockdown shocks lies in their marginal impact on future expectations and, consequently, the improved fit of nominal variables.

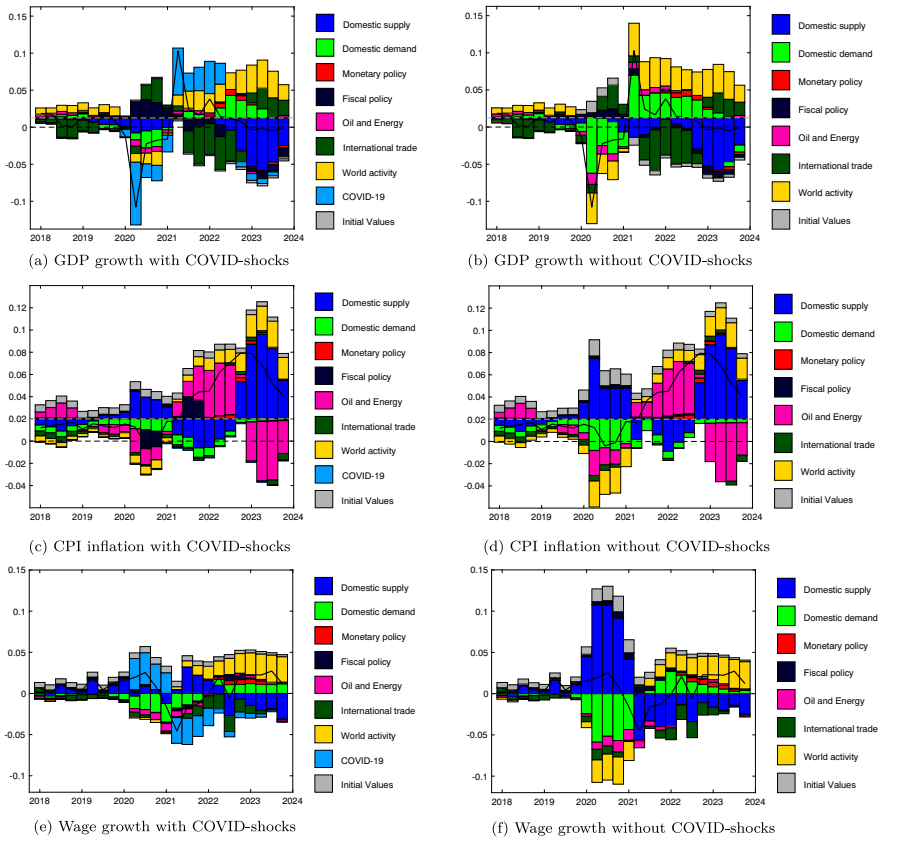


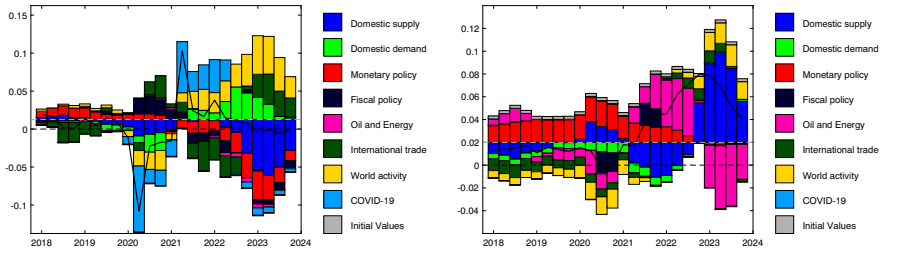
Fig. 10 Counterfactual without COVID-specific shocks. Note: Real GDP growth, CPI inflation, and nominal wage growth are shown as percentage-point deviations from their steady states, calibrated to 1.25%, 2%, and 2.9% per year, respectively. 0.01 on the *y*-axis corresponds to 1 pp. Figures 10a, c, and e present identical historical decompositions as Figs. 6, 7, and 8, respectively

simplicity by penalising models with more parameters, assuming an equal fit. In the baseline model, the data density (12.225) is significantly higher than that of the model excluding COVID-specific shocks (11.407), indicating that the estimation process supports the inclusion of heteroscedastic disturbances.[20]

9.2 Counterfactual with shadow rates

During the observed period, the European Central Bank (ECB) extensively employed unconventional monetary policy (UMP) measures. As the model uses a first-order approximation, it does not account for occasionally binding constraints during estimation but applies an ex-post evaluation of the ELB via the Occbin smoother. Given the rich set of observed time series and estimated shocks, UMP effects are, hence, implicitly captured through domestic demand shocks and exchange rate depreciation.

[20] The data density is reported in log points using a Laplace approximation.



(a) GDP growth (b) CPI inflation

Fig. 11 Counterfactual with shadow rates. Note: Real GDP growth and CPI inflation are shown as percentage-point deviations from their steady states, calibrated to 1.25% and 2% per year, respectively. 0.01 on the *y*-axis corresponds to 1 pp

To explicitly account for UMP, this robustness check introduces a counterfactual using shadow rates to proxy both conventional and unconventional interventions.

Following Hohberger et al. (2023), I use the estimated EA shadow rate from Wu and Xia (2017, 2016) as a measure of UMP, replacing the constrained short-term rate with the shadow rate when the economy operates at the ELB.[21] For simplicity, the estimated shadow rate is incorporated into the baseline model's estimated Taylor rule without re-estimating its coefficients.[22]

Figure 11 illustrates the decomposition of real GDP growth and CPI inflation from 2018 to 2023 under the shadow rate model. The results show that UMP measures positively contributed to GDP growth (until 2020) and CPI inflation (until 2022) in Germany, indicating a stronger stimulus than predicted by the estimated Taylor rule. From 2021 onward, UMP contributions shift toward monetary tightening, with a more pronounced effect compared to a short-term interest rate constrained by the ELB (see Fig. 6). This results in a sharper negative impact of monetary shocks on GDP growth during 2021–2022. The ECB's gradual phasing out of UMP measures in 2021 dampened their contribution to CPI inflation, though it remained positive. By 2022, as interest rates increased, monetary policy's contribution to CPI inflation approached zero, aligning with the model's estimated interest rate rule. Incorporating UMP shocks also alters the contributions of private savings, investment, and exchange rate shocks, which would otherwise absorb omitted UMP effects in a model with a binding ELB. Nonetheless, the differences in standard deviations between the two model variants are relatively minor.

10 Conclusion

This paper estimates a three-region DSGE model to analyse the macroeconomic drivers of the pandemic and inflation surge in Germany. The results suggest a central role for lockdown shocks via forced savings in explaining the contraction of economic activity

[21] Shadow rate data is available at: https://sites.google.com/view/jingcynthiawu/shadow-rates.

[22] Shadow rates, derived from term structure models, align with the short-term policy rate under normal conditions and turn negative when the ELB binds. For further discussion on the substitutability between policy rates and shadow rates, see, e.g., Hohberger et al. (2023).

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 reflects a balance between domestic and foreign demand normalisation and a slowdown in international trade, exacerbated by supply chain bottlenecks. The surge in CPI inflation during 2021–2022 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. In 2023, normalising commodity prices are offset by consumption-specific price markups from retailers, slowing the decline in inflation rates. The estimation results align well with off-model indicators, confirming the robustness of the identified shocks.

This analysis offers a plausible narrative for Germany's macroeconomic developments, highlighting the importance of accounting for various domestic and global factors, as well as demand and supply dynamics, in understanding the significant fluctuations driven by the COVID-19 pandemic and the subsequent inflation surge.

Appendix 1: Model description

A.1 Households

The Ricardian households maximise the present value of the expected stream of future utility, subject to Eq. 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.

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, $CU_{i,t}$:

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

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

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

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

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

[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.

by:

$$(1-\tau^K)\frac{W_t}{P_t^Y} = \alpha\left(\mu_t^y - \varepsilon_t^{ND}\right)\frac{Y_t}{N_t - FN} - \frac{\partial adj_t^N}{\partial N_t} + E_t\Big[\frac{1+\pi_{t+1}^Y}{1+i_{t+1}^s}\frac{\partial adj_{t+1}^N}{\partial N_t}\Big], \tag{A.13}$$

$$Q_t = E_t\Bigg[\frac{1+\pi_{t+1}^Y}{1+i_{t+1}^s}\frac{P_{t+1}^I}{P_{t+1}^Y}\frac{P_t^Y}{P_t^I} \left(\tau^K\delta - \frac{\partial adj_t^{CU}}{\partial K_{t-1}} + Q_{t+1}(1-\delta) + (1-\alpha)\mu_{t+1}^Y\frac{P_{t+1}^Y}{P_{t+1}^I}\frac{Y_{kt+1}}{K_t^{tot}}\right)\Bigg], \tag{A.14}$$

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

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

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. Equations 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, Eq. 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:

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

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

Appendix 2: Additional results

Table 3 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 4 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 5 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)

Table 5 continued

		Prior distribution		Posterior distribution
		Distr	Mean St.Dev	DE
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 6 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

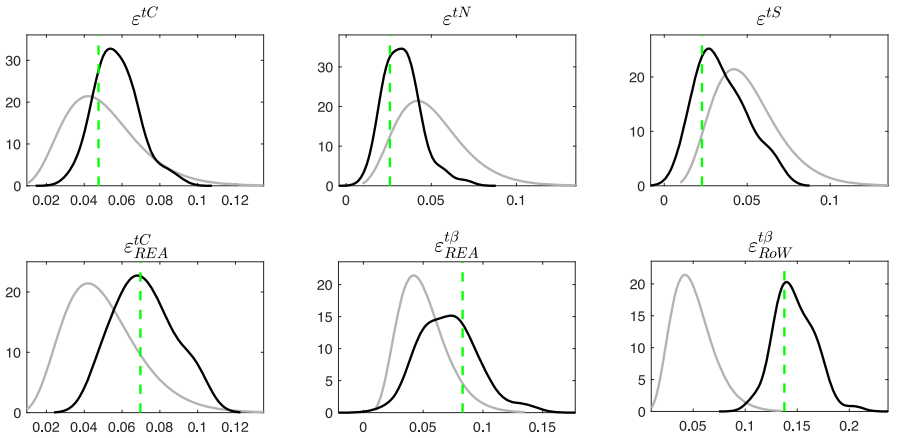


Fig. 12 Prior and posterior identification of COVID-specific shocks. Note: The light grey lines represent the prior distributions, while the black lines show the posterior distributions of the estimated COVID-specific disturbances. The green vertical lines indicate the posterior mode (see Table 2)

Table 7 Historical sequence of occasionally binding regimes

Time	Regime sequence	Starting period of regime
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

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 4 6] indicates an expected constrained regime starting in 4 periods ahead and last for additional 2 periods; [1 8] indicates a constrained regime with an expected duration of additional 7 periods

Table 7 continued

Time	Regime sequence	Starting period of regime
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 8
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 4 6] indicates an expected constrained regime starting in 4 periods ahead and last for additional 2 periods; [1 8] indicates a constrained regime with an expected duration of additional 7 periods

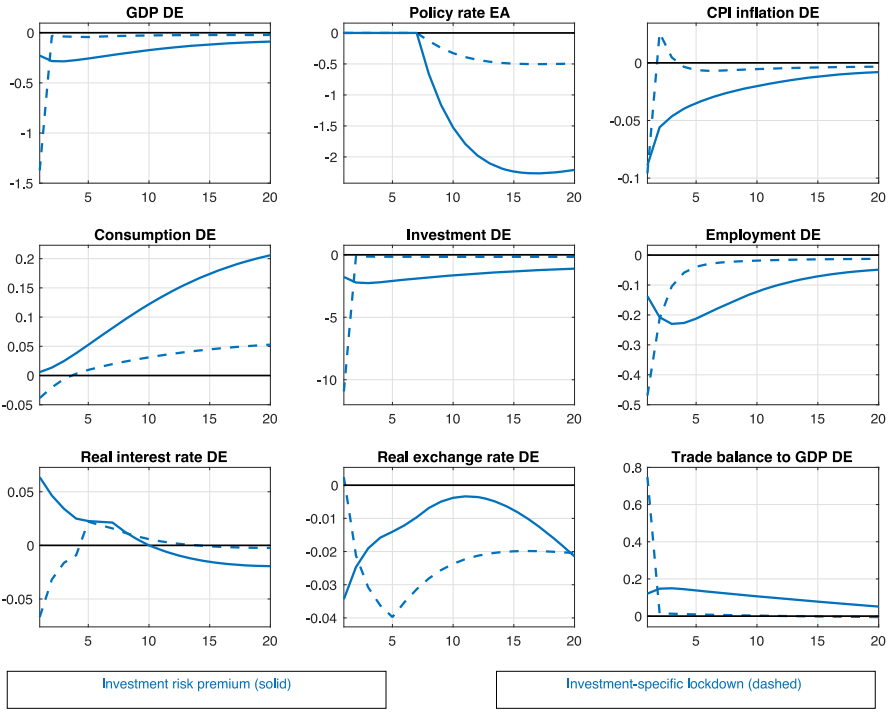


Fig. 13 Dynamic responses to investment shocks. Note: The trade balance (normalised by GDP), inflation (p.a.), and real interest rate (p.a.) responses are expressed as percentage point, the policy rate (p.a.) as basis point, deviations from steady state. All other responses are percent deviations from steady state. The size of the shock corresponds to one estimated standard deviation. Periods correspond to quarters

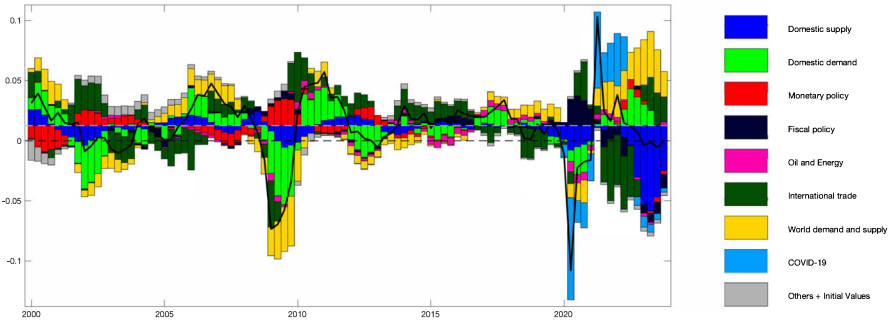


Fig. 14 Historical decomposition of real GDP growth (yoy). Note: Real GDP growth is shown in percentage-point deviations from steady state, which is calibrated to 1.25% per year. 0.01 on the *y*-axis corresponds to 1 pp

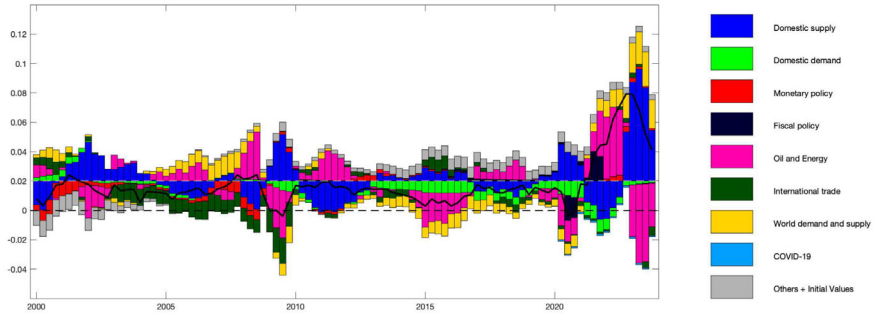


Fig. 15 Historical decomposition of CPI inflation (yoy). Note: CPI inflation is shown in percentage-point deviations from steady state, which is calibrated to 2% per year. 0.01 on the y-axis corresponds to 1 pp

Appendix 3: 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 7). 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 4: Data source and transformations

Table 8 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)	3-month interest rate (nominal)	3-month 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)		
Gov. investment (nominal)		
Government transfers (nominal)		
Gov. interest payments (nominal)		
Commodities import share (nominal)		
Price of commodity imports (from RoW)		
Active population rate		
Population		

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.

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 8 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 16 plots

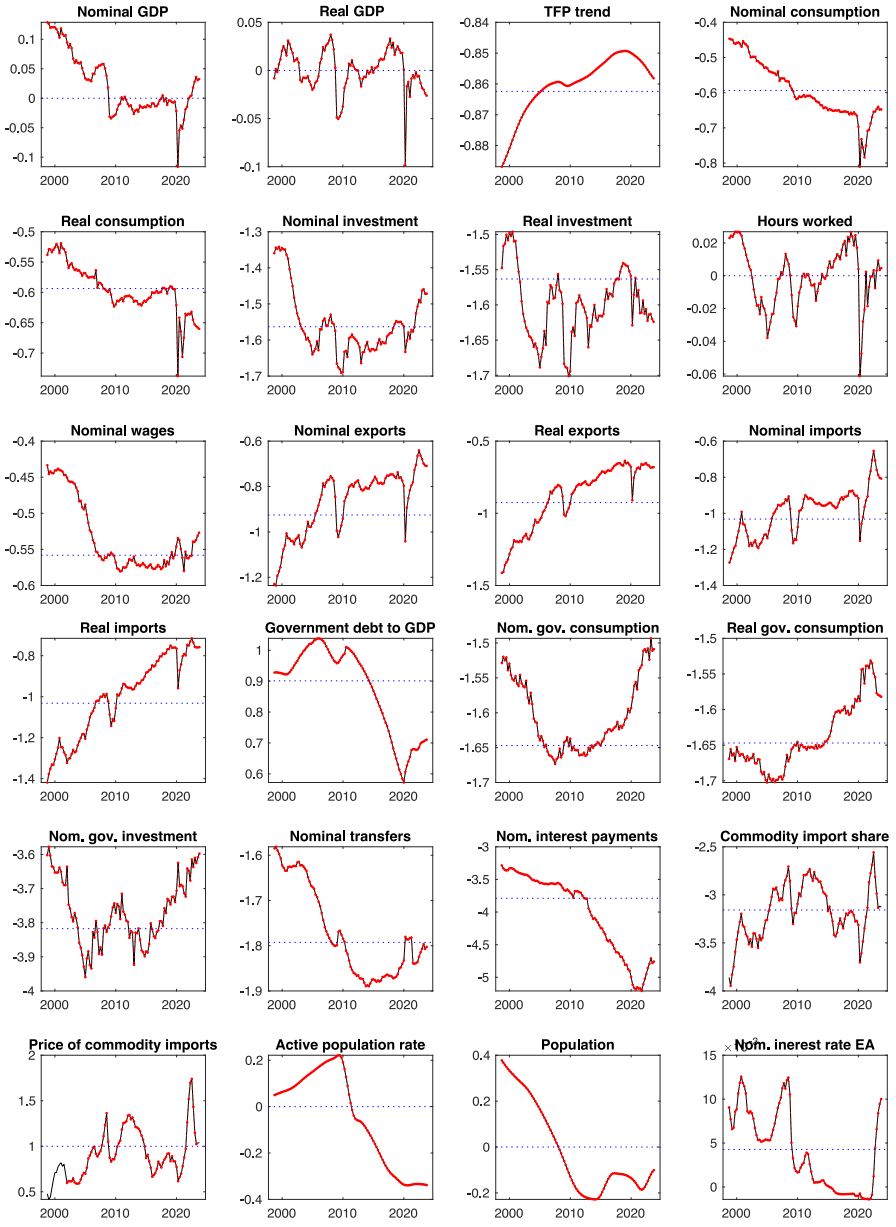


Fig. 16 Observed DE time series

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.

Acknowledgements I thank the Editor Joscha Beckmann as well as an anonymous referee for very helpful and constructive comments. I also thank Marco Ratto for the extensive discussions on the Global Multi-country (GM) model as well as Warwick McKibbin and research seminar participants at the Munich University of Applied Sciences for very helpful comments and discussions.

Funding Open Access funding enabled and organized by Projekt DEAL.

Data availability The data used for estimation are available on open-access databases. They are also available from the corresponding author upon request.

Declarations

Conflict of interest The author declares no competing interests.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by/4.0/.

References

Adjemian S, Juillard M, Karamé F, Mutschler W, Pfeifer J, Ratto M, Rion N, Villemot S (2024) Dynare: reference manual, version 6, Dynare Working Papers 80, CEPREMAP

Adolfson M, Laséen S, Lindé J, Villani M (2008) Evaluating an estimated new Keynesian small open economy model. J Econ Dyn Control 32:2690–2721

Albonico A, Calés L, Cardani R, Croitorov O, Ferroni F, Giovannini M, Hohberger S, Pataracchia B, Pericoli FM, Raciborski R (2019) Comparing post-crisis dynamics across Euro Area countries with the Global Multi-country model. Econ Model 81:242–273

Arce O, Ciccarelli M, Montes-Galdón C, Kornprobst A (2024) What caused the euro area post-pandemic inflation? Occasional Paper Series 343, European Central Bank

Ball LM, Leigh MD, Mishra MP (2022) Understanding U.S. inflation during the COVID era, IMF Working Papers 2022/208, International Monetary Fund

Bayer C, Born B, Luetticke R, Müller GJ (2023) The coronavirus stimulus package: how large is the transfer multiplier. Econ J 133:1318–1347

Benigno G, Giovanni JD, Groen JJ, Noble AI (2022) The GSCPI: a new barometer of global supply chain pressures, FRB of New York Staff Report

Benigno P, Eggertsson GB (2023) It's baaack: the surge in inflation in the 2020s and the return of the non-linear phillips curve, NBER Working Papers 31197, National Bureau of Economic Research, Inc

Benigno P, Eggertsson GB (2024) The slanted-L Phillips curve. AEA Papers and Proceedings 114:84–89

Blanchard O, Galí J (2007) Real wage rigidities and the new Keynesian model. J Money, Credit, Bank 39:35–65

Blanchard OJ, Bernanke BS (2023) What caused the US pandemic-era inflation? NBER Working Papers 31417, National Bureau of Economic Research, Inc

Bodnár K, Gonçalves E, Górnicka L, Koester G (2023) Wage developments and their determinants since the start of the pandemic. Econ Bull Artic 8
Bussière M, Callegari G, Ghironi F, Sestieri G, Yamano N (2013) Estimating trade elasticities: demand composition and the trade collapse of 2008–2009. Am Econ J Macroecon 5:118–151
Calés L, Pericoli F, Ratto M (2017) Rotated slice sampling: applications for the Bayesian estimation of DSGE models, mimeo, European Commission
Cardani R, Croitorov O, Giovannini M, Pfeiffer P, Ratto M, Vogel L (2022a) The euro area's pandemic recession: a DSGE-based interpretation. J Econ Dyn Control 143
Cardani R, Hohberger S, Pfeiffer P, Vogel L (2022b) Domestic versus foreign drivers of trade (im)balances: how robust is evidence from estimated DSGE models? J Int Money and Financ, 121
Cardani R, Pfeiffer P, Ratto M, Vogel L (2023) The COVID-19 recession on both sides of the Atlantic: a model-based comparison, European Econ Rev, 158
Chen W, Negro M, Goyal S, Johnson A (2020) The New York fed DSGE model forecast—December 2020, Liberty Street Economics December, 23
Comin DA, Johnson RC, Jones CJ (2023) Supply chain constraints and inflation, NBER Working Papers 31179, National Bureau of Economic Research, Inc
Corrado L, Grassi S, Paolillo A (2021) Modelling and estimating large macroeconomic shocks during the pandemic, CREATES Research Papers 2021–08. Aarhus University, Department of Economics and Business Economics
Croitorov O, Giovannini M, Hohberger S, Ratto M, Vogel L (2020) Financial spillover and global risk in a multi-region model of the world economy. J Econ Behav Organ 177:185–218
Da Silva AD, Dossche M, Dreher F, Foroni C, Koester G (2020) Short-time work schemes and their effects on wages and disposable income. Econ Bull Boxes 4
di Giovanni J (2022) How much did supply constraints boost U.S. Inflation? Liberty Street Economics 20220824, Federal Reserve Bank of New York
di Giovanni J, Kalemli-Özcan S, Silva A, Yıldırım MA (2023) Quantifying the inflationary impact of fiscal stimulus under supply constraints. AEA Papers and Proceedings 113:76–80
Dolls M, Fuest C, Peichl A (2012) Automatic stabilizers and economic crisis: US vs. Europe, J Public Econ 96:279–294
Ferroni F, Fisher JD, Melosi L (2024) Unusual shocks in our usual models. J Monet Econ 147
Funke M, Terasa R (2022) Has Germany's temporary VAT rates cut as part of the COVID-19 fiscal stimulus boosted growth? J Policy Model 44:450–473
Gagliardone L, Gertler M (2023) Oil prices, monetary policy and inflation surges, NBER Working Papers 31263, National Bureau of Economic Research, Inc
Ghomi M, Hurtado S, Montero JM (2024) Recent dynamics of inflation in Spain. An analysis based on the model by Blanchard and Beranke (2023), Occasional papers 2404, Bank of Spain
Giannone D, Primiceri G (2024) The drivers of post-pandemic inflation, NBER Working Papers 32859, National Bureau of Economic Research, Inc
Giovannini M, Hohberger S, Kollmann R, Ratto M, Roeger W, Vogel L (2019) Euro Area and U.S. External Adjustment: The Role of Commodity Prices and Emerging Market Shocks. J Int Money Financ 94:183–205
Giovannini M, Pfeiffer P, Ratto M (2021) Efficient and robust inference of models with occasionally binding constraints, Working Papers 2021–03. Joint Res Cent Eur Comm
Guerrieri L, Iacoviello M (2015) OccBin: a toolkit for solving dynamic models with occasionally binding constraints easily. J Monet Econ 70:22–38
Hale T, Angrist N, Goldszmidt R, Kira B, Petherick A, Phillips T, Webster S, Cameron-Blake E, Hallas L, Majumdar S, Tatlow H (2021) A global panel database of pandemic policies (Oxford COVID-19 Government Response Tracker). Nat Hum Behav 5:529–538
Hansen N-J, Toscani F, Zhou J (2023) Euro area inflation after the pandemic and energy shock: import prices, profits and wages, IMF Working Paper 2023/131, International Monetary Fund
Harding M, Lindé J, Trabandt M (2023) Understanding post-COVID inflation dynamics. J Monet Econ 140(Supplement):S101–S118
Hinterlang N, Moyen S, Röhe O, Stähler N (2023) Gauging the effects of the German COVID-19 fiscal stimulus package. Eur Econ Rev 154
Hohberger, S., R. Priftis, and L. Vogel (2019): The macroeconomic effects of quantitative easing in the euro area: evidence from an estimated DSGE model. J Econ Dyn Control 108

Hohberger S, Ratto M, Vogel L (2020) The euro exchange rate and Germany's trade surplus. Int Financ 23:85–103
Hohberger S, Ratto M, Vogel L (2023) The macroeconomic effects of unconventional monetary policy: comparing euro area and US models with shadow rates. Econ Modell 127
Jorda O, Nechio F (2023) Inflation and wage growth since the pandemic. Eur Econ Rev 156:104474
Mckibbin W, Fernando R (2020) Global macroeconomic scenarios of the COVID-19 pandemic, in COVID ECONOMICS 39, CEPR Press
Menz J-O (2024) Sources of post-pandemic inflation in Germany and the euro area: an application of Bernanke and Blanchard (2023), Technical Paper 02/2024, Deutsche Bundesbank, Frankfurt a. M
Neal R (2003) Slice sampling. Ann Stat 31:705–741
Neri S, Busetti F, Conflitti C, Corsello F, Monache DD, Tagliabracci A (2023) Energy price shocks and inflation in the euro area, Questioni di Economia e Finanza (Occasional Papers) 792. Bank of Italy. Econ Res Int Relat Area
Pasimeni P (2022) Supply or demand, that is the question: decomposing euro area inflation. Intereconomics: Rev Eur Econ Policy 57:384–393
Pisani M, Tagliabracci A (2024) What caused the post-pandemic inflation in Italy? An application of Bernanke and Blanchard (2023), Occasional papers (questioni di economia e finanza) 851, Bank of Italy
Planas C, Ratto M, Rossi A (2015) Slice sampling in Bayesian estimation of DSGE models, mimeo, European Commission
Reis R (2022) The burst of high inflation in 2021–22: how and why did we get here? BIS Working Papers 1060, Bank for International Settlements
Rotemberg JJ (1982) Monopolistic price adjustment and aggregate output. Rev Econ Stud 49:517–531
Schmitt-Grohe S, Uribe M (2003) Closing small open economy models. J Int Econ 61:163–185
Taylor JB (1993) Discretion versus policy rules in practice. Carn-Roch Conf Ser Public Policy 39:195–214
Wu JC, Xia FD (2016) Measuring the macroeconomic impact of monetary policy at the zero lower bound. J Money, Credit, Bank 48:253–291
Wu JC, Xia FD (2017) Time-varying lower bound of interest rates in Europe. Tech. rep, Chicago Booth Research Paper No, pp 17–06

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.