Monetary Policy under Network-Level Bottlenecks*

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December 5, 2025

Abstract

This paper examines monetary policy under temporary, sector-level supply bottlenecks using a rich production-network framework. We first show that binding sectoral constraints steepen the aggregate supply curve and introduce novel trade-offs when interacting with demand shifts. We then embed this mechanism in a calibrated two-region, multi-sector New Keynesian model with occasionally binding constraints. First, we use the model to generate policy lessons when some sectors in the economy face supply constraints while others may face deficient demand. Second, we fit the model to 2020–24 and quantify how bottlenecks amplified inflation and output volatility during COVID-19. Unlike standard supply shocks, temporary sectoral constraints create a trade-off between economic stability when constrained and economic stability afterwards—so that crisis-period focus can worsen later aggregate adjustments. We also show that coordinated tightening across regions mitigates inflation spillovers through the production network, indicating that the global slack is an important independent determinant of domestic inflation.

Keywords: Production Networks, Monetary Policy, Supply Constraints, Open Economy Macroeconomics.
JEL classification: C67, E23, E52 F41.

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*We are grateful to Emine Boz, Benjamin Carton, Gita Gopinath, Pierre-Olivier Gourinchas, Jean-Marc Natal, Rafael Portillo, Elisa Rubbo, Silvana Tenreyro (discussant) for helpful comments. We thank Canran Zhang for excellent research assistance. A subset of the results in this paper was an input for the analysis in Chapter 2 of October 2024 issue of the World Economic Outlook. The views expressed in this paper are those of the authors and do not necessarily represent the views of the IMF, its Executive Board, or IMF management.

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1 Introduction

Central banks faced an unprecedented challenge in the wake of the COVID-19 pandemic: simultaneous, extreme sectoral supply bottlenecks and demand shifts led to a sharp output contraction followed by powerful inflationary pressures.[1] These developments stretched existing monetary-policy frameworks to their limits, initially prompting unprecedented stimulus and subsequently triggering a global tightening cycle. The speed of the switch from easing to tightening underscores the dynamic shift in the output–inflation trade-off as sectoral constraints bind and subsequently ease. This study contributes to understanding this changing macroeconomic environment faced by central banks and subsequent reaction during the entire period of 2020-2024 by developing a quantitative model that captures interactions between temporary supply bottlenecks and shifting relative prices across production networks.

Central to our analysis are supply bottlenecks and the possible impacts they might continue to have on the economy once resolved. To showcase the role of these constraints, we first incorporate them into a stylized model with roundabout production to illustrate the changes in the inflation–output trade-off. We embed this mechanism in a calibrated multi-sector, two-region quantitative production-network framework—tailored for central-bank policy guidance. We develop a novel estimation method to fit the model to 2020-2024 data and use the model to quantify the impact of supply bottlenecks. With this, we further investigate how they affect monetary policy transmission and the impact of different policy choices.

Our stylized model adopts a two-stage production structure: an upstream phase governed by binding labor caps and a downstream phase that captures input–output network amplification. In the upstream stage, two sectors employ workers to perform a variety of tasks. For some tasks, each sector may each face a binding labor cap–regardless of the prevailing wage–to capture pandemic-era bottlenecks. When these caps bind, sectoral supply curves steepen: output rises one-for-one with labor until capacity is reached, beyond which marginal costs–and thus prices–escalate sharply, reshaping the inflation–output trade-off. The downstream stage features a roundabout production technology that is representative of input–output linkages, amplifying the propagation of upstream constraints.

Intuitively, when a supply-constraint shock binds, the economy moves into the steep portion of the convex supply curve, so that any monetary expansion delivers only modest

[1] Among others, see the narrative in Bernanke and Blanchard (2023), Dao et al. (2024), Guerrieri et al. (2023), and Guerrieri et al. (2021).

output gains while generating large price increases. Even after the shock subsides, a demand stimulus that has pushed equilibrium into the steep segment leaves prices elevated relative to output. By contrast, a policy that responds forcefully to rising prices can bring the economy to the flatter, unconstrained region once bottlenecks ease—achieving substantial disinflation at limited output cost and preserving price stability in recovery. Next, we explore these insights further in a rich, quantitative framework which we fit to data on the 2020-2024 experience and use to conduct a variety of policy experiments.

Our quantitative framework features eleven production sectors and two regions – the United States and the Rest-of-the-World (RoW)– calibrated to match OECD Inter-Country Input-Output (ICIO) data.[2] Within each sector, output is generated by a multiple CES-nest aggregation of intermediate goods from all eleven sectors, which also captures limited substitutability. Sectoral prices evolve under Calvo (1983) rigidities, with distinct adjustment probabilities across sectors. Following the stylized model, we introduce supply constraints in the form of exogenously time-varying maximum level of labor that firms can hire. When combined with price stickiness we have two regimes per sector: labor demand in that sector is sufficiently low that the constraint does not bind and the firm sets prices according to its Philips curve. Alternatively, if labor demand is sufficiently high, then the constraint binds and firms must sharply curtail production and raise prices.

By embedding production-network interdependencies, production complementarities, and heterogeneous price stickiness, this model provides a controlled laboratory for evaluating the trade-offs that central banks face when sectoral shocks and relative-price shifts interact under imperfect adjustment dynamics. In some special cases, the shape of the network in production network models can be irrelevant as shown in a theorem known as Hulten's theorem.[3] In this model however, we show that the network is an important moderator of sectoral shocks. This is primarily because this model has both complementarities in production and sticky prices. We find that sticky prices lowers the aggregate GDP impact that productivity shocks in sticky price sectors but amplifies the impact productivity shocks in flexible price sectors have.

In addition, we verify with impulse response analysis that supply constraints have important effects on the propagation of shocks. For instance, supply constraints can flip the sign of the aggregate impact from a sectoral relative demand shock and in response to monetary policy shocks, when constraints are present, the positive GDP response is dampened

[2] In some exercises we consider a "quantitatively closed economy" setup where we calibrate to a small country vs. the Rest-of-the-World (RoW) and focus on the RoW region.

[3] See network irrelevance in Baqaee and Farhi (2019)

while the inflation response is amplified. We then show in an exercise with ascending supply constraints in multiple sectors how supply constraints can shift and steepen the Phillips curve.

We then use the quantitative model to conduct two sets of analysis relevant for understanding the trade-offs with respect to monetary policy. In the first set, we investigate policy lessons when some sectors in the economy face supply constraints while others may face deficient demand. In the second set, we fit the model to 2020-2024 data and investigate how widespread supply constraints affected inflation and monetary policy during that period.

For clarity on the policy lessons with some sectors facing supply constraints, we specialize the model to an environment where divine coincidence (henceforth, DC) in the form Rubbo (2023) studies may hold.[4] In this environment, stabilizing a weighted average of inflation with carefully chosen weights (which is called DC index) can deliver zero output gap which Rubbo (2023) shows is also optimal. The weights needed to achieve this are a simple ratio of two components: the "influence" (or Domar weight)[5] of the sector divided by the slope of that sector's Phillips curve. Then, we put this rule to the test in the face of a binding supply constraint for four quarters in the sector with the highest weight in the DC index (i.e., professional, scientific and technical services sector).

When we impose supply constraints in the sector facing a positive demand shift, we observe that following a DC index with weights that ignore the supply constraint weights delivers a negative output gap while the supply constraint binds, but successfully stabilizes the output gap after the constraints end. The intuition for this is that when a sector is supply constrained, its Phillips curve (in terms of the sectoral output gap) is steeper and as such it deserves a lower weight in any DC index utilized while the supply constraint binds. Since the constrained sector is over-weighted, the inflation caused by the supply constraint binding leads to tighter policy than necessary and a negative output gap on average. Once the constraint disappears, the over-weighting issue disappears as well and the rule continues to deliver inflation at target.

We compare this to a rule that takes the opposite approach: this rule stabilizes a DC index that assumes that the constraint binds *continuously* for the full simulation. Thus, while policy with this rule is appropriate during the period when the constraint binds, it risks being highly inappropriate in the period following. We choose this rule because in practice central

[4]This specialized model is a closed economy with flexible wages, frictionless labor reallocation with labor as the only factor of production.

[5]A Domar weight is the ratio of a sector's gross output to total value-added, capturing both its direct and indirect (spillover) contribution to aggregate productivity growth.

banks may not have fully up-to-date information on each supply constraint and whether it continues to bind. This rule focuses on the worst possible example of this; where the central bank never learns that the constraint is gone; and imposes an upper bound on the long term costs of optimizing for policy periods like 2020. This leads to a *lower* weight on the constrained sector in the DC index than if ignoring the constraint.

We find that this alternative approach delivers a zero output gap while the constraint binds but delivers a negative output gap after the constraint disappears. The negative output gap occurs because the policy in the constrained period required considerable monetary stimulus to keep the output gap closed. However, the constrained sector cannot accommodated more demand without large price increases. After the constraints ease, prices in this sector ease relative to other sectors. But the DC index weight on inflation movements in this sector is lower than optimal given that the sector now is no-longer constrained. As this sector's price rises are the lowest, under-weighting this sector makes overall inflation appear too high and prompts a monetary policy response that is too contractionary. That delivers a prolonged negative output gap while this relative price gap resolves itself.

These exercises suggest that the trade-offs associated with temporary supply constraints are fundamentally different than those associated with more traditional supply shocks. Instead of there being an inflation-output trade off, supply constraints impose a trade-off between economic stability when constrained and economic stability afterwards. This gives some insight into the experiences in the 2020-2024 period – focusing on economic stability early in the pandemic may have had the consequence of requiring considerable aggregate adjustments once economies reopened.

In the second set of results we bring the model to the data to assess the role of supply constraints in driving inflation during the 2020–2024 period, and to evaluate the extent to which alternative monetary policy could have mitigated the inflation surge. We linearize the model but employ a novel approach to identify supply bottlenecks in the data where in some cases we explain fluctuations with supply constraints and in other cases with productivity shocks. Essentially, when we observe that there is a supply contraction in a sector needed to explain the sectoral price and quantity data, we assume that this contraction is due to the presence of a supply constraint. In cases where we require a supply expansion to fit the data, we assume that this is due to a positive sectoral productivity shock.[6] A limitation of our approach is that some sectors may have faced both productivity and supply constraints;

[6]Note that with this approach, we can still identify constraints in sectors facing large demand increases. Supply constraints will be inferred in any rising demand situation where prices rise by more than expected given the sector's Phillips curve and quantities by less.

but, provided negative productivity shocks are rare, our assumption will deliver less strict supply constraints than methods that allow for mixtures of both shocks. When conducting counterfactuals with supply constraints, we impose that labor cannot increase beyond from the levels estimated in our data matching exercise.

We find that supply bottlenecks were extremely widespread even after reopening. These contributed approximately 2–3 percentage points to U.S. inflation during 2020–2022. These constraints also became a persistent drag on output beginning in 2021. We simulate a counterfactual scenario in which monetary policy tightens three quarters earlier than observed, with and without supply bottlenecks. When supply constriants are accounted for, peak inflation is reduced by about 2 percentage points relative to actual data, while real GDP declines by 0.8 percentage points. Without supply constraints, we estimate that inflation would have instead been reduced by only 1 percent while GDP would have been 1.8 percent lower. These counterfactuals reinforce key lessons about monetary policy under binding supply constraints. Specifically, when binding supply constraints are widespread, monetary tightening faces a favorable trade-off: in this case the impact on inflation is roughly twice as large, while the impact on GDP is about half compared to a scenario without binding constraints.

We further confirm this by conducting a counterfactual with respect to coordinated tightening in our two regions vs. uncoordinated tightening in a single region. We confirm that when the RoW delays its tightening, this raises inflation in the U.S. through 2 channels: raising demand for US goods that may be supply constrained and raising the price of supply constrained global inputs.

Overall our analysis suggests that supply bottlenecks introduce novel temporal trade-offs for central banks to consider. If supply constraints are widespread, then there is no trade-off: very few sectors are likely to have insufficient demand and monetary policy can focus on keeping inflation low and stable. However, if supply constraints are focused on some parts of the economy, then there is a risk that other sectors may also face deficient demand. In that case, monetary policy faces a choice between focusing on stimulating demand in low-demand sectors or keeping inflation coming from supply constrained sectors contained. The costs to letting inflation rise in supply constrained sectors is that it introduces relative price gaps that must be unwound after the supply constraints ease. When the previously constrained sectors face sticky prices, unwinding these relative prices can be difficult and cause prolonged inflation.

The paper proceeds as follows: Section 1.1 overviews the literature. Section 2 introduces a stylized model with supply constraints and roundabout production to showcase the trade-offs introduced by shifts in supply schedule. Section 3 describes the quantitative model and its calibration. Section 4 discusses how the model is brought to data to estimate shocks. Section 5 presents model properties by showcasing an impulse response analysis and the shape of the Phillips curve. Section 6 present our results on monetary policy and Section 7 concludes.

1.1 Literature Review

Our paper contributes to several strands of literature. First, it contributes to the literature that focuses on inflation in production networks. Early work by Basu (1995) establish that productivity is procyclical in an input-output production structure and Nakamura and Steinsson (2010) study a multi-sector menu-cost model with intermediate inputs and show that heterogeneity in price-change frequencies triples the degree of monetary non-neutrality; Ghassibe (2021) provide econometric evidence on the contribution of production networks to the real macroeconomic effects of monetary policy; Ghassibe (2024) develop a dynamic, sticky-price network model that shows the strength of real effects of monetary policy is related to the number of suppliers firms have and Baqaee et al. (2024) show that demand shocks have effects on productivity.

On optimal policy La'O and Tahbaz-Salehi (2022) and Rubbo (2023) build on Pasten et al. (2020)'s finding that heterogeneity in price stickiness across sectors is the central driver of real effects. The former establishes that optimal policy should assign higher weight to stickier price sectors and the latter extends this and establishes that the optimal policy stabilizes a sectorally weighted inflation-gap index.

In addition, there is extensive research on the recent pandemic inflation: Di Giovanni et al. (2022) and Di Giovanni et al. (2023) develop a multi-country, multi-sector New Keynesian model and find that the interaction of sectoral supply and aggregate demand shocks is the key to matching the inflation experience of several countries; Afrouzi and Bhattarai (2023) highlight the importance of production networks in amplification of shocks and the conduct of monetary policy by providing closed-form solutions; Ferrante et al. (2023) show the inflationary effects of demand shifts with hiring costs; Luo and Villar (2023) evaluate cross-sectional price changes induced by sticky-price input–output models; Minton and Wheaton (2023) study how supply chains transmit commodity-price movements to inflation; Rubbo (2025) shows how to isolate the effects that relative price dynamics in certain sectors may affect aggregate inflation and Woodford (2022) argue that fiscal transfers can be more effective than monetary policy in responding to sectoral shocks.

Second, our framework relates to the literature on monetary policy with a nonlinear Phillips curves and convex supply schedules. Karadi et al. (2025) and Blanco et al. (2024) study this feature in closed-economy models with menu costs. In the literature that focuses on COVID-19-era dynamics, Baqaee and Farhi (2020a) and Baqaee and Farhi (2021) were among the first to introduce supply constraints on labor in a production network model along with Çakmaklı et al. (2021a), Gourinchas et al. (2020), Gourinchas et al. (2021a), and Gourinchas et al. (2021b). More recently, Fornaro and Romei (2022) studies optimal policy analytically in a setup with convex supply curves, Guerrieri et al. (2022) show that, in a multi-sector New Keynesian model, the optimal monetary policy response to asymmetric shocks may let inflation exceed its target; Gudmundsson et al. (2024) provide evidence that the aggregate Phillips curve both shifted and steepened in the post-pandemic period; and Comin et al. (2023) and Comin et al. (2024), in a concurrent work, investigates the impact of supply constraints on the pandemic inflation. We distinguish from the latter on multiple fronts, including the type of constraints that we focus on (labor vs. output) and our analysis on the conduct of monetary policy during the pandemic and post-pandemic episodes.

Finally, our paper also contributes to the literature on the conduct of monetary policy in open economies. We contribute to the New Keynesian open economy literature (among others, see Benigno (2004), Benigno and Benigno (2003), Clarida et al. (1999), Gali and Monacelli (2005), and, more recently, Ghironi and Ozhan (2020)). A recently emerging subbranch of this literature started to integrate production networks. For instance, Yang (2023) studies the relationship between invoicing currency and input-output (I-O) linkages in global trade. Closest to our setup are Qiu et al. (2025) and Kalemli-Özcan et al. (2025). The former studies optimal policy in a small open economy with production networks; they show that the closed-economy results of Rubbo (2023) carry over under certain parameter restrictions. Whereas the latter studies the monetary policy response to a tariff shock in a model with nominal rigidities and production network.

2 The Stylized Model

In this section, we present our stylized model with capacity constraints and roundabout production. We assume a continuum of identical households that consume a single homogeneous final good. There is perfect foresight.

2.1 Households

Each representative household derives instantaneous utility from consumption according to

$$u(C_t) = \log C_t, \tag{1}$$

where C_t denotes consumption. The budget constraint can be written as

$$P_t C_t + B_{t+1} \;=\; W_t L_t + D_t + (1 + i_{t-1})\, B_t, \tag{2}$$

with P_t the nominal price of the final good, B_t one-period bonds, W_t the nominal wage, L_t employment, D_t dividend income, and i_t the nominal interest rate.

Each period, households allocate their disposable resources between consumption and bond holdings. The optimal intertemporal choice yields the Euler equation

$$C_t \;=\; \frac{C_{t+1}}{\beta}\,\frac{P_{t+1}}{(1 + i_t)\, P_t} \;=\; \frac{C_{t+1}}{\beta\,(1 + r_t)}, \tag{3}$$

where r_t is the real interest rate.

Although households would like to supply $\bar{L}$ units of labor each period, nominal wage rigidity implies that actual employment $L_t \leq \bar{L}$ is set by firms' demand. For simplicity, we henceforth assume

$$W_t = W \quad \text{for all } t.$$

2.2 Firms

2.2.1 Upstream production

There are two sectors—manufacturing (g) and services (s). Evidence shows that sectoral supply curves are convex—price responses intensify as firms near capacity (Boehm and Pandalai-Nayar (2022)). We capture this by introducing a technological ceiling on one of the tasks required in production similar to Fornaro and Romei (2022).

A continuum of identical, perfectly competitive firms each split labor between two tasks, A and B. Let $L^j_{A,t}$ and $L^j_{B,t}$ be the labor inputs to these tasks in sector $j \in \{g, s\}$; output in each sector is then

$$Y^j_t \;=\; \left(\frac{L^j_{A,t}}{\alpha}\right)^{\alpha} \left(\frac{L^j_{B,t}}{1-\alpha}\right)^{1-\alpha}, \tag{4}$$

where $0 < \alpha < 1$ governs each task's weight. Since labor is mobile, the wage does not vary by task.

To reflect capacity limits, tasks of type B cannot exceed

$$L^j_{B,t} \;\leq\; (1-\alpha)\,\bar{Y}^j_t, \tag{5}$$

where $\bar{Y}^j_t$ is an exogenous production limit in sector j, which might differ across sectors.

As the economy approaches its production frontier—due to input shortages, bottlenecks, or other supply shocks—the exogenous limit $\bar{Y}^j_t$ tightens, and the permissible allocation $L^j_{B,t}$ must shrink in lockstep. In other words, when a sector's capacity is constrained, firms are forced to reallocate labor away from type B activities so as not to exceed their feasible production. To keep the notation simple, we drop j superscript in the rest of the text unless the distinction between the sectors is needed.

Defining total labor in any sector, $L_t = L_{A,t} + L_{B,t}$, it follows that when the constraint is slack, firms set

$$L_{A,t} = \alpha\, L_t, \quad L_{B,t} = (1-\alpha)\, L_t.$$

Therefore, $Y_t = L_t$ provided $Y_t \leq \bar{Y}_t$. If instead $Y_t > \bar{Y}_t$, the binding constraint implies

$$L_{B,t} = (1-\alpha)\,\bar{Y}_t, \quad L_{A,t} \;=\; L_t - (1-\alpha)\,\bar{Y}_t.$$

Hence, the relationship between output and labor is thus given by

$$Y_t = \begin{cases} L_t, & \text{if } Y_t \leq \bar{Y}_t, \\ \left(\dfrac{L_t - (1-\alpha)\,\bar{Y}_t}{\alpha\,\bar{Y}_t}\right)^{\alpha} \bar{Y}_t, & \text{if } Y_t > \bar{Y}_t. \end{cases} \tag{6}$$

Output is linear in labor up to the threshold $\bar{Y}_t$. Until output reaches the capacity threshold $\bar{Y}_t$, it increases one-for-one with labor. Once Y_t exceeds $\bar{Y}_t$, the supply constraint binds and marginal labor productivity falls as output expands.

Under perfect competition, firms set the price of the final good equal to its marginal cost. When $Y_t \leq \bar{Y}_t$ the capacity constraint is slack, so marginal cost stays constant at the fixed wage and prices remain unchanged. Once output exceeds $\bar{Y}_t$, however, the constraint binds and marginal cost—and hence price—rises with Y_t. Consequently, the supply curve—i.e. the mapping from output to price—takes the form

$$P_t = \begin{cases} W, & Y_t \leq \bar{Y}_t, \\ W\,(Y_t/\bar{Y}_t)^{\frac{1-\alpha}{\alpha}}, & Y_t > \bar{Y}_t. \end{cases} \tag{7}$$

By letting the capacity limit $\bar{Y}_t$ vary over time, we allow firms' supply schedules to shift in response to shocks that restrict essential inputs.

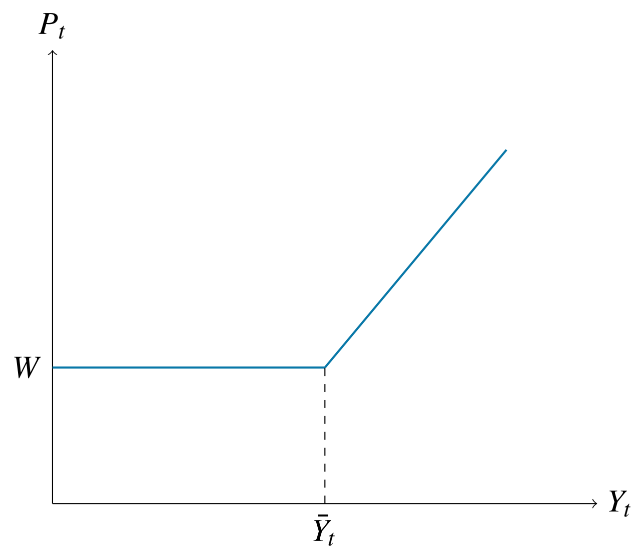


Figure 1: Sectoral supply curve with capacity constraint

Figure 1 plots the sectoral curve defined above. A convex sectoral supply curve captures the idea that marginal production costs rise as firms expand output. In the flat region, small increases in demand are met with no price pressures, reflecting underutilized capacity; beyond a kink point—where key inputs become scarce or bottlenecks bind—the curve steepens sharply, so that further output expansion requires disproportionately larger price increases. When a negative supply shock occurs (for example, a sudden disruption in intermediate-goods shipments or a labor shortage), the entire convex schedule shifts to the left: the economy's maximum feasible output falls, and the steep region of the curve begins at a lower level of production. In this constrained regime, any policy-induced lift in demand generates pronounced inflationary pressures, since firms must pay much higher marginal costs to increase output. As the shock dissipates and inputs are restored, the supply curve shifts back downward and to the right, returning the economy to the flatter portion of the schedule; in this recovery phase, demand expansions again yield more output with relatively muted price responses.

2.2.2 Downstream production

To capture network linkages between firms tractably, we model final-good production as a simple roundabout process that incorporates additional inputs from upstream sectors.

$$Y_{i,t}^{f} = \left(\frac{Y_{i,t}^{g}}{\kappa_1}\right)^{\kappa_1} \left(\frac{Y_{i,t}^{s}}{\kappa_2}\right)^{\kappa_2} \left(\frac{X_{i,t}}{1-\kappa_1-\kappa_2}\right)^{1-\kappa_1-\kappa_2}. \tag{8}$$

Here, $Y_{i,t}^{g}$ and $Y_{i,t}^{s}$ denote goods- and services-sector outputs in firm i, respectively, while $X_{i,t}$ represents the final good used as input. Each input is normalized by its corresponding share parameter (κ_1 for goods, κ_2 for services, and $1-\kappa_1-\kappa_2$ for the intermediate input). The technology exhibits constant returns to scale.

If neither the goods nor the services sector is capacity-constrained, the production technology exhibits constant returns in all three inputs. Under perfect competition, firms set price equal to marginal cost:

$$P_t^{f} \;=\; MC_t \;=\; W^{\kappa_1+\kappa_2}\,(P_t^{f})^{1-\kappa_1-\kappa_2}. \tag{9}$$

Because the exponents sum to unity, this condition reduces to

$$P_t^{f} = W. \tag{10}$$

Intuitively, when inputs are plentiful, the marginal cost of the final good is constant and coincides with the nominal wage, so the equilibrium price is flat at W.

Cost-minimization then delivers

$$\frac{P_t^{f}\,\kappa_1\,Y_{i,t}^{f}}{Y_{i,t}^{g}} = W, \tag{11}$$

$$\frac{P_t^{f}\,\kappa_2\,Y_{i,t}^{f}}{Y_{i,t}^{s}} = W, \tag{12}$$

$$\frac{P_t^{f}\,(1-\kappa_1-\kappa_2)\,Y_{i,t}^{f}}{X_{i,t}} = P_t^{f}. \tag{13}$$

Each equation equates the value of an input's marginal product to its unit cost—wage for goods and services inputs, and the final-good price for the intermediate input, which in turn is equal to the wage under the equilibrium in which production is not constrained. Firms allocate expenditure across inputs exactly in proportion to their share parameters κ_1, κ_2 and $1 - \kappa_1 - \kappa_2$.

When the goods sector runs up against its capacity limit ($Y_t^g > \bar{Y}_t^g$) but the services sector remains slack, marginal cost and hence the final-good price satisfy

$$P_t^f \;=\; MC_t \;=\; W^{\kappa_1+\kappa_2} \left(\frac{Y_t^g}{\bar{Y}_t^g}\right)^{\kappa_2 \frac{1-\alpha}{\alpha}} \left(P_t^f\right)^{1-\kappa_1-\kappa_2}. \tag{14}$$

Solving for P_t^f yields

$$P_t^f = W \left(\frac{Y_t^g}{\bar{Y}_t^g}\right)^{\frac{\kappa_2}{\kappa_1+\kappa_2} \frac{1-\alpha}{\alpha}}. \tag{15}$$

Intuitively, once goods output exceeds its technological ceiling, producing the final good becomes increasingly costly in proportion to the goods-to-capacity ratio $Y_t^g/\bar{Y}_t^g$, while the wage component still anchors the baseline cost.

Cost minimization now implies three first-order conditions:

$$\frac{P_t^f\ \kappa_1\, Y_{i,t}^f}{Y_{i,t}^g} = W\frac{1}{\alpha}\left(\frac{Y_t^g}{\bar{Y}_t^g}\right)^{\frac{1-\alpha}{\alpha}}, \tag{16}$$

$$\frac{P_t^f\ \kappa_2\, Y_{i,t}^f}{Y_{i,t}^s} = W, \tag{17}$$

$$\frac{P_t^f\ (1-\kappa_1-\kappa_2)\, Y_{i,t}^f}{X_{i,t}} = P_t^f. \tag{18}$$

The first condition shows that, under a binding goods constraint, the marginal product of goods inputs—and hence their implied unit cost—rises above the fixed-wage benchmark, reflecting scarcity. Services inputs remain available at constant wage cost, while the intermediate input is priced at the final-good price itself.

The blue curve in Figure 2 represents the downstream sector's supply schedule, which naturally decomposes into three distinct segments. In the left-most segment, neither upstream constraint is binding and marginal costs—and hence prices—are flat. As output reaches the first kink, the goods-sector constraint becomes binding, steepening the slope in the middle segment. Finally, once output exceeds the second kink, both upstream constraints bind simultaneously, driving a sharp uptick in marginal cost and producing the steepest portion of the curve.

2.3 Market clearing and monetary policy

Market clearing The equilibrium condition

$$Y_t^f = X_t + C_t$$

states that all final-good production is absorbed either as the intermediate input X_t in the next period's production or as household consumption C_t.

Monetary policy We assume a standard feedback rule:

$$i_t = \rho i^{ss} + (1-\rho)(\phi_\pi \pi_t + \phi_x x_t).$$

where ρ is the interest rate inertia. By raising (or lowering) i_t when inflation is above (or below) its target, the policymaker can stabilize price dynamics.

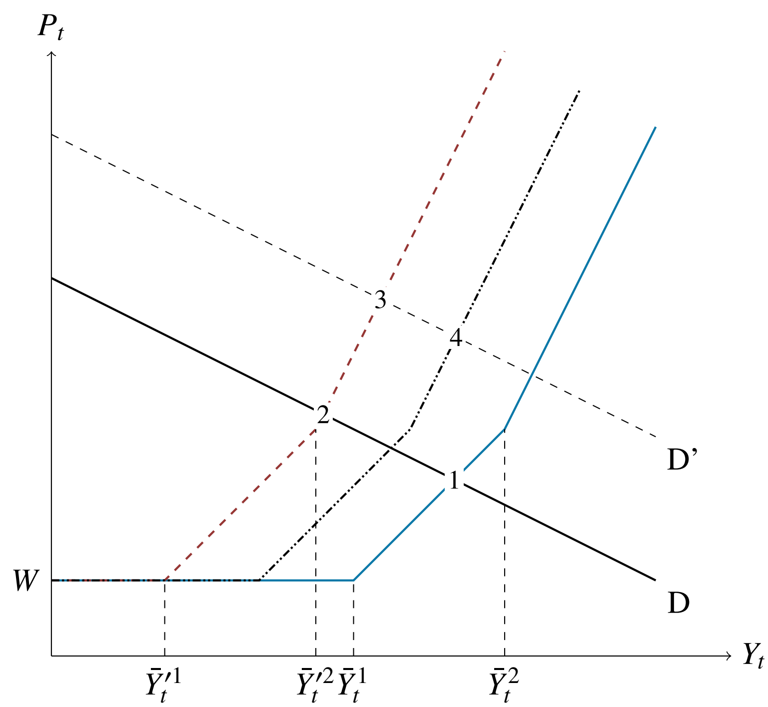


Figure 2: Downstream supply and demand curves with intersection points labeled 1–4.

Monetary policy faces a fundamental dilemma when supply shocks raise inflation and decrease output (transition from "1" to "2" in Figure 2). An accommodative stance that boosts aggregate demand may help push the output up, but it does so at the expense of even higher inflation. Because the downstream supply curve is steep—reflecting roundabout production and input bottlenecks—a monetary expansion yields only modest output gains for each increment of inflation (transition from "2" to "3").

The trade-off remains being on the steep end of the supply curve even if the shock is temporary. Suppose the shock eases and the supply schedule reverts to the dashed black curve. Under the new demand schedule, the new equilibrium features substantially higher inflation and no significant output gains than before the shock, because the policy has pushed demand into the steepest segment of the curve (transition from "3" to "4"). By contrast, a rule that responds aggressively to emerging price pressures can exploit the low sacrifice ratio after the shock, delivering significant disinflation at modest output cost—and, crucially, preserve price stability once bottlenecks lift. This channel lies at the heart of our quantitative model, whose implications we explore in the following sections.

3 The Quantitative Model

To analyze the monetary policy implications of supply bottlenecks quantitatively, we develop a 2 region, multi-sector model with sticky prices and rich input-output linkages. We use the index c and c^* for each region and within each region, S denotes the number of sectors, indexed by $i \in \{1, 2, .., S\}$.

3.1 Households

3.1.1 Inter-temporal choices

In each region, there are two types of households denoted by $z \in \{R, HtM\}$: Ricardian households (with population share μ_c) who can access financial markets and consume with exogenous consumption habits; and hand-to-mouth (HtM) households, with population share $1-\mu_c$, who consume their labor income. We model the Ricardian households as a continuum of agents with a constant probability of death as in Blanchard (1985) and Yaari (1965). Full details of this are included in Appendix 7.1 and given that agents have a probability of dying, their full discount rate is given by $\beta_c\theta_c$ where β_c is the typical discount factor and $1 - \theta_c$ is the probability of dying.

Both types of households have per-period utility functions as in King et al. (1988).

$$u(c_{c,z,t}, h_{c,z,t}) = \frac{\kappa(\bar{c}_{c,z,t-1})^{\sigma_c}}{1-\sigma_c}\left[\left(c_{c,z,t}\right)^{\eta_c}\left(\bar{h}_{c,t} - h_{c,z,t}\right)^{1-\eta_c}\right]^{1-\sigma_c}$$

where $\kappa(\bar{c}_{c,z,t-1})$ is a non-decision variable governing consumption habits, $\bar{h}_{c,z,t}$ is endowment of work hours. σ_c is the coefficient of relative risk aversion and η_c weights the utility of consumption relative to the utility of leisure in utility.

Hand to mouth households must consume their income and Ricardian households have access to two globally traded risk free bonds in local and foreign currency respectively.

$$\begin{aligned} P^{CPI}_{c,t} c_{c,R,t} + b^{\$c}_{c,R,t+1} + \mathcal{E}_{c,t} b^{\$c^*}_{c,R,t+1} &= W_{c,t} h_{c,R,t} + \Pi_{c,R,t} - T_{c,R,t} \\ &\quad + (1 + i_{c,t-1}) b^{\$c}_{c,R,t} + (1 + i_{c^*,t-1}) \mathcal{E}_{c,t} b^{\$c^*}_{c,R,t} - T_{c,t} \\ P^{CPI}_{c,t} c_{c,HtM,t} &= W_{c,t} h_{c,H2M,t} + \Pi_{c,HtM,t} - T_{c,H2M,t} \end{aligned}$$

where $P^{CPI}_{c,t}$ is aggregate consumer price level in domestic currency, $\mathcal{E}_{c,t}$ is the exchange rate in units of currency c per unit of currency c^* (so that a rise in $\mathcal{E}_{c,t}$ is a depreciation of currency c), $b^{\$c}_{c,t}$ and $b^{\$c^*}_{c,t}$ are risk free bond holdings in currencies c and c^* respectively with respective nominal interest rates $i_{c,t}$ and $i_{c^*,t}$. $W_{c,t}$ is nominal wage level in domestic currency and $\Pi_{c,z,t}$ are the profits paid to each type of household and $T_{c,t}$ represents lump-sum taxation by the government.

While we consider labor rigidities in a model extension, in our baseline model wages are flexible . This gives us the following Labor supply:

$$\frac{W_{c,t}}{P^{CPI}_{c,t}} = \frac{\eta_c}{1 - \eta_c} \frac{c_{c,z,t}}{\bar{h}_{c,t} - h_{c,z,t}}$$

The first-order conditions of domestic and dollar bonds imply uncovered interest rate parity (UIP) condition.

$$\ln(1 + i_{c,t}) = \ln(1 + i_{c^*,t}) + \ln\left(\frac{\mathcal{E}_{c,t+1}}{\mathcal{E}_{c,t}}\right)$$

It is shown in the appendix that Ricardian household consumption is determined by the following equation:

$$P^{CPI}_{c,t} C^{OLG}_{c,z,t} = \underbrace{\Omega_{c,z,t}}_{\text{Marginal propensity to consume}} \underbrace{\left\{ E_t \left[\sum_{s>0} \frac{1}{\prod_{j=1}^{s} (1 + i_{c,t+j})} \left(W_{c,t+s} h_{c,z,t+s} + \Pi_{c,z,t+s} - T_{c,z,t+s} \right) \right] + (1 + i_{c,t-1}) NFA_{c,t-1} \right\}}_{\text{Expected net present value of lifetime wealth}}$$

where $\Omega_{c,t}$ is the marginal propensity of consumption from lifetime wealth, $NFA_{c,t}$ is the local currency net foreign asset position given by the sum of each bond holding:$b^{\$c}_{c,t}$+$\mathcal{E}_{c,t} b^{\$c^*}_{c,t}$.

In a model with log-preferences we would have $\Omega_{c,z,t} = 1 - \beta_c$ and with CRRA preferences (and constant real rates) we would have

$$\Omega_{c,z,t}^{-1} = 1 + \frac{\beta_c^{\frac{1}{\sigma_c}}}{(1+i_{c,t})^{\frac{1}{\sigma_c}-1}} \Omega_{c,z,t+1}^{-1}$$

where the income effect and substitution effect no longer cancel. As we show in Appendix 7.1, the overlapping generation structure instead gives:

$$\Omega_{c,z,t}^{-1} = 1 + (\beta_c \theta_c)^{\sigma_c} E_t \left[\left(\frac{1}{i_{c,t}} \left(\frac{\kappa(\bar{c}_t)}{\kappa(\bar{c}_{t-1})} \right)^{\eta_c} \left(\frac{MRS_{c,z,t+1}}{MRS_{c,z,t}} \right)^{1-\eta_c} \right)^{1-\sigma_c} \Omega_{c,z,t+1}^{-1} \right]$$

where we choose a function for $\kappa(\cdot)$ to replicate the standard habit formation dynamics.[7] As $\sigma \rightarrow 1$ this expression collapses to the standard log-consumption expression and when $\sigma \neq 1$ the income and substitution effects of interest rates no longer cancel. In addition, we have mechanisms where labor and consumption are complements in a manner similar to Greenwood et al. (1988). As can be seen more work today raises the marginal rate of substitution between consumption and leisure which raises the current MPC out of lifetime income (if all else is unchanged).

3.1.2 Intra-temporal choices

Household consumption is determined by a two-layer nested-CES structure. Firstly different types of sectoral goods (e.g. Cars, food, shelter) are combined into a bundle. Then each sectoral good is comprised of a domestic variety and foreign variety (e.g. US cars combined with ROW cars). These bundles are identical for Ricardian and HtM agents in a given region so for simplicity of notation we omit the z subscript. These nests are given by:

$$c_{c,t} = \left[\sum_{i=1}^{N} (b_{i,t}^c)^{\frac{1}{\gamma_c}} c_{c,i,t}^{\frac{\gamma_c - 1}{\gamma_c}} \right]^{\frac{\gamma_c}{\gamma_c - 1}}, \quad c_{c,i,t} = \left[\sum_{o \in \{c, c^*\}} (b_{o,i}^c)^{\frac{1}{\gamma_i}} c_{o \rightarrow c,i,t}^{\frac{\gamma_i - 1}{\gamma_i}} \right]^{\frac{\gamma_i}{\gamma_i - 1}}$$

where γ_c is the elasticity of substitution between types of sectoral goods and γ_i is a sector-specific trade elasticity.

[7] This turns out to be: $\kappa(x) = x^{\frac{\gamma_h}{\eta}}$ to give a habit persistence parameter γ_c.

Household relative demand can vary both endogenously as relative prices change and exogenously based on household taste shocks for different types of goods over others. We implement these taste shocks into the demand shifter $b^{c}_{i,t}$ as follows:

$$b_{c,i,t} = \frac{b_{c,i}\hat{\xi}_{c,i,t}}{\sum_{c\in C}\sum_{i\in S} b_{c,i}\hat{\xi}_{c,i,t}}$$

where $b_{c,i}$ is the steady state value of household expenditure share. With this implementation we can choose any combination of fundamental shocks $\{\hat{\xi}_{c,i,t}\}_i$ and ensure that $\sum_i b_{c,i,t} = 1$.

Price indices are given by:

$$P^{CPI}_{c,t} = \left[\sum_i b_{c,i,t} P^{1-\gamma_c}_{c,i,t}\right]^{\frac{1}{1-\gamma_c}}, \quad P_{c,i,t} = \left[\sum_{o\in\{c,c^*\}} b^{c}_{o,i}(P^{\$c}_{o\to c,i,t})^{1-\gamma_i}\right]^{\frac{1}{1-\gamma_i}}$$

where $P_{o\to c,i,t}$ is the price of good i produced in country o when sold in country c in the currency of the purchaser c. This formulation of prices allows us to consider different currency pricing strategies by firms which we discuss in the next subsection.

Labor supply: We assume in our baseline model that labor is allocated between sectors in the same region frictionlessly and all firms pay the same wage $W_{c,t}$. Labor is restricted to be supplied to firms within the region only.

3.2 Firms

3.2.1 Production

Firms in each sector i combine labor and an intermediate bundle together to produce output $Z_{c,i,t}$ in constant elasticity of substitution (CES) production function with an elasticity of γ^z.

$$Z_{c,i,t} = \left[\left(\alpha^{L}_{c,i}\right)^{\frac{1}{\gamma^z}}\left(A^{L}_{c,i,t}L_{c,i,t}\right)^{\frac{\gamma^z-1}{\gamma^z}} + \left(\alpha^{M}_{c,i}\right)^{\frac{1}{\gamma^z}}\left(M_{c,i,t}\right)^{\frac{\gamma^z-1}{\gamma^z}}\right]^{\frac{\gamma^z}{\gamma^z-1}} \quad (19)$$

where $L_{c,i,t}$ is labor used by sector j, with labor productivity $A^{L}_{d,i,t}$, and $\alpha^{L}_{c,i}$ and $\alpha^{M}_{c,i}$ are country/sector-specific parameters we calibrate to match labor and intermediates use in this sector.

As for consumption, intermediates follows a 2-nest CES demand structure:

$$M_{c,i,t} = \left[\sum_{j=1}^{N} \omega_{j\to ci,t}^{\frac{1}{\gamma_m}} M_{j\to ci,t}^{\frac{\gamma_m-1}{\gamma_m}}\right]^{\frac{\gamma_m}{\gamma_m-1}} \quad , \quad M_{j\to ci,t} = \left[\sum_{o\in\{c,c^*\}} \omega_{oj\to ci}^{\frac{1}{\gamma_i}} M_{oj\to ci,t}^{\frac{\gamma_i-1}{\gamma_i}}\right]^{\frac{\gamma_i}{\gamma_i-1}}$$

where γ_m is a different elasticity to households between types of goods to capture the strong complementarities in production that firms face. γ_i by contrast is the same elasticity that consumers face.

We follow Baqaee and Farhi (2022), Çakmaklı et al. (2021b), Gourinchas et al. (2021b) and others by modeling supply constraints in terms of an exogenous time-varying maximum workforce limit imposed on firms:

$$L_{c,i,t} \leq \hat{x}_{c,i,t}\bar{L}_{c,i}$$

where $\hat{x}_{c,i,t}$ is an exogenous shock and $\bar{L}_{c,i}$ represents steady state labor in that sector.

These maximum limits are assumed to rarely bind in normal times allowing firms to choose their workforce size based on worker marginal products and the prevailing sectoral wage. In crisis times – such as the recent pandemic – these constraints may shift, or if demand is sufficiently high, they may bind. When they bind, firms' labor demand at the prevailing wage is curtailed to be consistent with the employment limit. This constraint effectively lowers their labor demand relative to the case without any employment limits.

Formally, when the constraint binds firms face a shadow wage in excess of the wage paid to workers. We define a wedge $\lambda_{c,i,t}$ to capture the effect on labor demand:

$$W_{c,t} + \lambda_{c,i,t} = \underbrace{MC_{c,i,t}\left(\alpha_{c,i}^{L}\frac{Z_{c,i,t}}{L_{c,i,t}}\right)^{\frac{1}{\gamma_z}}}_{\text{Sector } i \text{ marginal product of labor}} \quad ; \quad \underbrace{\lambda_{c,i,t}(\hat{x}_{c,i,t}\bar{L}_{c,i} - L_{c,i,t}) = 0}_{\text{Kuhn-Tucker condition on constraint}} \tag{20}$$

where $MC_{c,i,t}$ is equal to marginal cost. When the constraint does not bind, $\lambda_{c,i,t} = 0$ and the marginal product of labor equals the market wage. When the constraint binds, firms still pay the market wage, but the constraint forces them to value labor as if the wage were much higher.

We can calculate the value of $\lambda_{c,i,t}$ as the difference between the marginal product of labor at $L_{c,i,t} = \hat{x}_{c,i,t}\bar{L}_{c,i}$ and the prevailing wage if this difference is positive:

$$\lambda^L_{c,i,t} = \max\left(A^L_{c,i,t} PZ_{d,j,t}\left(\frac{\alpha^L_{c,i} Z_{c,i,t}}{A^L_{c,i,t}\hat{x}_{c,i,t}\bar{L}_{c,i}}\right)^{1/\gamma^Z} - W_{c,i,t}, 0\right). \tag{21}$$

Note that in this one input model, a labor constraint is identical to a value added constraint. Gross output may still rise if firms replace the labor they would hire if unconstrained with intermediates instead. However with $\gamma_z < 1$, this will be considerably inefficient.

3.2.2 Price Setting

Prices in each sector adjust sluggishly as in Calvo (1983), where the degree of sluggishness varies by sector. Slow price adjustment forces firms to absorb some of the cost changes into their margins and leaves their prices somewhat disconnected from costs of production. It also magnifies the effects of demand shocks on production and real GDP.

We also follow Goldberg and Tille (2008), Gopinath et al. (2020), Yang (2023) and others and assume that firms face a dominant currency pricing paradigm where all cross country trade is denominated in currency $\$d$ (where $\$d \in \{c, c^*\}$). For the country whose currency is $\$d$, it is as if we have a single Phillips curve in every sector; whereas for the non-dominant currency country, there are two Phillips curves: one for exports and another for domestic sales.

We assume linearized versions of these Phillips curves with sectoral price stickiness parameter $\delta_{c,i} \in [0,1]$ with 1 indicating completely flexible prices:

$$\ln(\pi^{Y,\$c}_{c,i,t}) = \ln(\pi^{e,Y,\$c}_{c,i,t+1}) + \frac{\delta_{c,i}(1-\beta_c\theta_c(1-\delta_{c,i}))}{1-\delta_{c,i}} \cdot \left(\ln\left(MC^{\$c}_{c,i,t}\right) - \ln\left(P^{Y,\$c}_{c,i,t}\right)\right)$$
$$\ln(\pi^{X,\$d}_{c,i,t}) = \ln(\pi^{e,X,\$d}_{c,i,t+1}) + \frac{\delta_{c,i}(1-\beta_c\theta_c(1-\delta_{c,i}))}{1-\delta_{c,i}} \cdot \left(\ln\left(MC^{\$c}_{c,i,t}/\mathcal{E}^{\$,d}_{c,t}\right) - \ln\left(P^{X,\$d}_{c,i,t}\right)\right)$$

where $\ln(\pi^{D,\$c}_{c,i,t})$ and $\pi^{e,D,\$c}_{c,i,t+1}$, $D \in \{Y, X\}$ denotes respectively inflation and inflation expectations in currency c and $MC^{\$c}_{c,i,t}$ is nominal marginal cost denominated in currency c. Y denotes domestic sales and X denotes exports. The key differences between the domestic and exports Phillips curve expressions are the currency of the inflation rates as well as the currency of the difference between marginal cost and price.

Next we allow departures from rational expectations in the determination of sectoral inflation expectations. This is to investigate possible consequences of not responding to persistent supply shocks – conventional wisdom says monetary policy should look through supply shocks unless they become embedded in inflation expectations – the formulation here allows us to investigate this.

$$\pi^{e,D}_{c,i,t+1} = \rho_{1,\pi}\pi^{e,D}_{c,i,t-1} + \rho_{2,\pi}\pi^{D}_{c,i,t-1} + (1 - \rho_{1,\pi} - \rho_{2,\pi})\mathbb{E}_t[\pi^{D}_{c,i,t+1}]; \quad D \in \{Y, X\}$$

where $\rho_{1,\pi}$ and $\rho_{2,\pi}$ are parameters and $\mathbb{E}_t\pi_{c,i,t+1}$ is the model consistent expectation of inflation. Setting $\rho_{1,\pi^D} = \rho_{2,\pi^D} = 0$ recovers rational expectations.

3.3 Monetary Policy

We will consider many different policy rules in various parts of the paper; however as a benchmark we will assume each central bank targets CPI in a standard Taylor rule:

$$\ln(i_{c,t}) = \rho^i_c \ln(i_{c,t-1}) + (1 - \rho^i_c)\left(\ln\left(\bar{\pi}_{c,t} r^*_c\right) + \alpha^i_c \ln\left(\frac{\pi^C_{c,t}}{\bar{\pi}_{c,t}}\right)\right) + \varepsilon^i_{c,t}$$

where ρ^i_c is the persistence of policy rate, α^i_c is policy rate sensitivity to CPI inflation, $\bar{\pi}_{c,t}$ is the inflation target, r^*_c is neutral interest rate, and $\varepsilon^i_{c,t}$ is a monetary policy shock.

3.4 Government

Government levies a transfer on households to subsidize firms to remove the steady state markup distortion introduced by monopolistic competition. Each sector's subsidy is given by:

which implies a per-unit subsidy $\tau_{c,i}$ of:

$$\tau_{c,i} = \frac{1}{\mu_{c,i}} - 1$$

where $\mu_{c,i}$ is the steady state markup of firms in sector i.

The total transfer from households is therefore

$$T_c = \sum_{i=1}^{S} \tau_{c,i} = \sum_{i=1}^{S} (\mu_{c,i} - 1) \cdot \bar{Z}_{c,i}$$

3.5 Market Clearing

Given our pricing assumptions we have the following relationships for the prices faced by consumers and firms purchasing intermediates:

$$P^{\$c}_{o\to c,i,t} = \begin{cases} P^{\$d}_{o,i,t}\mathcal{E}_{c,t} & \text{if } o \neq c \\ P^{\$o}_{o,i,t} & \text{if } o = c \end{cases}, \quad P^{\$c}_{oi\to cj,t} = \begin{cases} P^{\$d}_{o,i,t}\mathcal{E}_{c,t} & \text{if } o \neq c \\ P^{\$o}_{o,i,t} & \text{if } o = c \end{cases}$$

The market clearing conditions for goods produced in sector i in region c is divided into domestic and international markets:

$$\begin{aligned} Z_{c,i,t} &= Y_{c,i,t} + X_{c,i,t} \\ Y_{c,i,t} &= c_{c\to c,i,t} + \sum_{j\in S} M_{ci\to cj,t} \\ X_{c,i,t} &= c_{c\to c^*,i,t} + \sum_{j\in S} M_{ci\to c^*j,t} \end{aligned}$$

In asset markets we impose that only the bonds of the dominant currency country are held in equilibrium with asset market clearing condition:

$$b^{\$d}_{c,i,t} + b^{\$d}_{c^*,i,t} = 0$$

We assume the other bonds are not held in equilibrium by either agent:

$$b^{\$-d}_{o,i,t} = 0; \quad \forall o \in \{c, c^*\}$$

Labor market clearing is given by:

$$\mu_{c,i} h_{c,R,t} + (1-\mu_{c,i}) h_{c,HtM,t} = \sum_{i=1}^{S} L_{c,i,t} \tag{22}$$

3.6 Extensions

We consider 3 extensions to the baseline model to assist in fitting the data in the final section.

Firstly we allow for a labor union to set wages collectively subject to Calvo price stickiness. This gives rise to a wage Phillips curve of the following form:

$$\ln(\pi^W_{c,t}) = \ln(\mathbb{E}_t \pi^W_{c,i,t+1}) + \frac{\delta_{c,w}(1-\beta_c\theta_c(1-\delta_{c,w}))}{1-\delta_{c,w}} \cdot \left(\ln\left(P^{CPI}_{c,t} MRS_{c,i,t}\right) - \ln\left(W_{c,i,t}\right)\right)$$

where currency superscripts are omitted because all prices here are in local currency.

Second we allow for imperfect labor mobility between sectors. We implement this by assuming differentiated occupations by sector where jobs in the construction sector are assumed to be imperfect substitutes for each other according to the following CES function:

$$L_{c,t} = \left[\sum_{i=1}^{S} \omega_{L\to i}^{\frac{1}{\gamma_l}} L_{c,i,t}^{\frac{\gamma_l}{1+\gamma_l}}\right]^{\frac{1+\gamma_l}{\gamma_l}} \tag{23}$$

where γ_l is the elasticity of substitution between sectors.

Each sector pays a different wage $W_{i,t}$ which is connected to the aggregate wage by the following price index:

$$W_{c,t} = \left[\sum_{i=1}^{N} \omega_{L\to i} W_{c,i,t}^{1-\gamma_l}\right]^{\frac{1}{1+\gamma_l}]}$$

Every sector now has a sector-specific labor supply given by:

$$L_{c,i,t} = \omega_{L\to i}\left(\frac{W_{c,i,t}}{W_{c,t}}\right)^{\gamma_l} L_{c,t}$$

We replace Equation 22 with the following new market clearing condition:

$$\mu_{c,i} h_{c,R,t} + (1-\mu_{c,i}) h_{c,Z,t} = L_{c,t}$$

where the sectoral demand equations and wage index are added to the model.

The final extension we consider is to extend the production function to have a second factor of production – capital – which we assume to be fixed. We adjust Equation 19 to the following:

$$Z_{c,i,t} = \left[\left(\alpha^L_{c,i}\right)^{\frac{1}{\gamma^z}} \left(A^L_{c,i,t} L_{c,i,t}\right)^{\frac{\gamma^z-1}{\gamma^z}} + \left(\alpha^K_{c,i}\right)^{\frac{1}{\gamma^z}} \bar{K}_{c,i}^{\frac{\gamma^z-1}{\gamma^z}} + \left(\alpha^M_{c,i}\right)^{\frac{1}{\gamma^z}} \left(M_{c,i,t}\right)^{\frac{\gamma^z-1}{\gamma^z}}\right]^{\frac{\gamma^z}{\gamma^z-1}}$$

where $\bar{K}_{c,i}$ is fixed and makes production exhibit diminishing returns to scale. Even without labor constraints, this makes increasing production increasingly costly and all else unchanged tends to steepen the aggregate Phillips curve.

3.7 Calibration

To calibrate the share parameters of the household final expenditure $b^{d}_{o,i}$ and intermediate goods expenditure $\omega^{d,j}_{o,i}$, we use the Inter-Country Input-Output (ICIO) table in year 2018 from the OECD. The ICIO tables provide global input-output flows of production, value-added, and final expenditures for 76 countries and the rest of the world, and 45 sectors. For our analysis, we aggregate to 2-regions. We run some scenarios which we label as a "closed economy" which is calibrated to 2 regions: Philippines and the rest-of-the-world (ROW). Since the Philippines is 0.005% of world GDP, we focus our analysis on the rest of the world and quantitatively this model operates as if a one region model.[8] for details on this production network. When we wish to consider an open economy we calibrate to the US and ROW. In both calibrations there are 11 sectors based on the mapping in Table 1.[9] We make minor adjustments to overall consumption holding constant the "technical coefficients" of the input-output data (input-to-sales ratios) in order to close the trade imbalances we observe in the data for model stability.

Sector No.	Sector	ICIO Industry Code
S01	Agriculture	D01T02, D03
S02	Mining and Energy	D05T06, D07T08, D09, D35, D36T39
S03	Manufacturing	D10T12, D13T15, D16, D17T18, D19, D20, D21, D22, D23 D24, D25, D26, D27, D28, D29, D30, D31T33
S04	Construction	D41T43
S05	Wholesale and Retail	D45T47, D49, D50, D51, D52, D53, D55T56
S06	IT and Telecommunications	D58T60, D61, D62T63
S07	Finance and Insurance	D64T66
S08	Real Estate	D68
S09	Professional, Scientific and Technical	D69T75, D77T82
S10	Education, Health, and Government	D84, D85, D86T88
S11	Arts, Entertainment and Recreation	D90T93, D94T96, D97T98

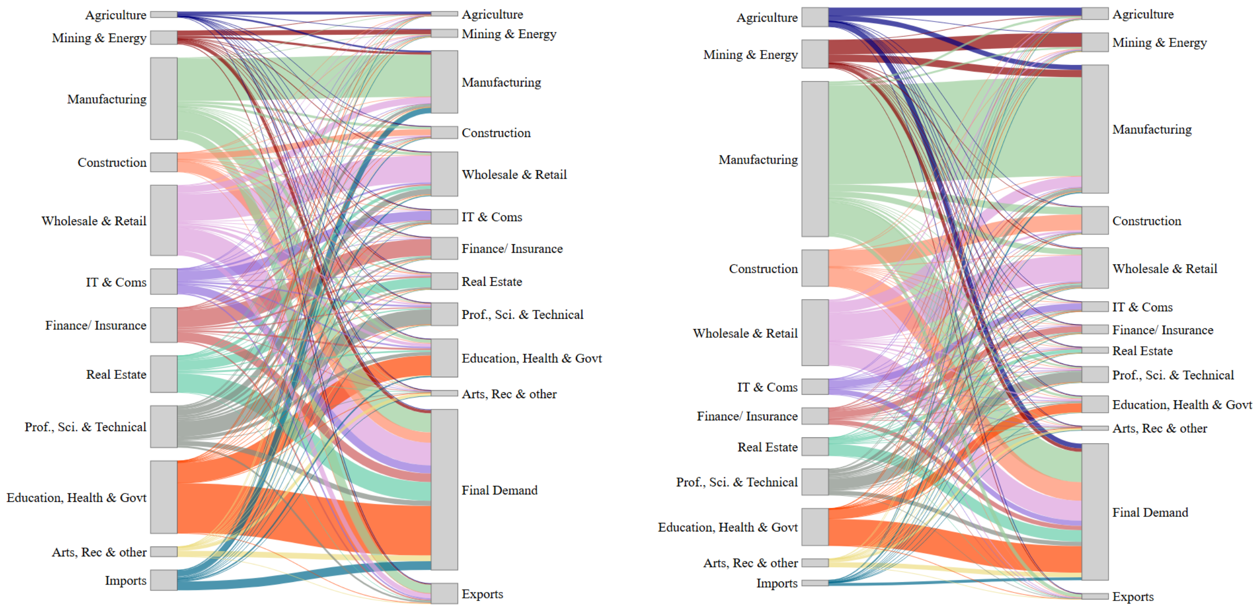
Table 1: Industry Code Mapping to Sectors

The full production network is shown in Figure 3. In each panel, sectors on the left sell goods to sectors and final demand on the right where each color indicates a flow from a

[8]See Figure 15 in Appendix B

[9]We choose a calibration with 11 sectors because of availability of time series deflators and activity at the sectoral level from the OECD. This is discussed later in Section 6.2.

Figure 3: Production network for USA and ROW calibration



(a) USA (b) Rest of the World

Notes: These diagrams showcase the production network for the USA and rest of the world regions. Sectors on the left sell to sectors and final demand on the right. To minimize the number of colors, we collapse all cross border trade into "Exports" and "Imports". In our calibration we have information on exactly who sells and who purchases each.

particular sector. The left panel shows the production network for the USA and the right panel shows the production network for the Rest of the World region. Notable differences between the two are that the service sectors are much larger in the USA than the rest of the world and agriculture, mining and manufacturing are much smaller.

Following Atalay (2017) and Baqaee and Farhi (2019), consumption and intermediate bundles are comprised of products from all 11 sectors in both economics with a CES elasticity of $\gamma_c = 0.8$ and $\gamma_m = 0.1$. The latter low elasticity captures the difficulty in substituting between different types of goods in production. Each good in sector i is a bundle comprised of two varieties from each region. We assume that agriculture, mining and energy goods are highly substitutable between countries, with an elasticity of $\gamma_i = 10$. Other goods are assumed to be less substitutable with an elasticity of $\gamma_i = 1.2$. Lastly, factors and composite intermediate good are combined with an elasticity of $\gamma^z = 0.5$.

We follow Kumhof et al. (2010) to calibrate the household behavior. The average remaining time at work of the OLG households is assumed to be 20 periods, which suggests that survival rate $\theta_c = 0.95$. We target an intertemporal elasticity of substitution of 0.5, or $\sigma_c = 2$, the weight on consumption in utility of $\eta_c = 0.6$, and the habit formation parameter $\gamma_c^b = 0.5$. Share of OLG households is assumed to be $\mu_{US} = 0.7589$ for the US, and $\mu_{ROW} = 0.6887$ for the ROW. Lastly, discount factor β_c is implied by the steady state of the (quarterly) real interest rate $r_c = 1.005$.

Following Rubbo (2023) and Pasten et al. (2020), We use the sector-level estimates of frequency of price adjustment to calibrate the slope of sectoral Phillips curve. To be specific, if $\delta_{c,i}^m$ is the frequency of price adjustment of country-sector pair (c,i) in market $m \in \{X, Y\}$, corresponding slope of sectoral Phillips curve $\kappa_{c,i}^m$ is

$$\kappa_{c,i}^m = \frac{\delta_{c,i}^m \left(1 - \beta_c (1 - \delta_{c,i}^m)\right)}{1 - \delta_{c,i}^m}$$

When active, the slope of Wage Phillips curve is equal to $\kappa_w = 0.3$, in line with the literature. In regard to sectoral inflation expectations, we assume that forward-looking component is 0.4, backward-looking component is $\rho_{2,\pi} = 0.2$, with persistence of $\rho_{1,\pi} = 0.4$. WHen active, wage inflation expectations is purely forward-looking, i.e. $\rho_{1,\pi^W} = \rho_{2,\pi^W} = 0$.

Taylor rule coefficients are $\rho_c^i = 0.5$ for interest rate persistence, $\alpha_{US}^i = 3$ and $\alpha_{ROW}^i = 1.5$ for inflation rate sensitivity, and the (quarterly) neutral rate of interest $r_c^* = 1.005$.

When we make labor supply in each country is imperfectly substitutable between sectors, we use an elasticity of $\zeta^c = 0.76$. Lastly, log of labor-augmenting productivity $\ln(A_{c,i,t}^L)$, household demand shifter $\ln(\hat{\xi}_{o,i,t}^d)$, and export total factor productivity $\ln(A_{c,i,t}^X)$ are assumed to follow an AR(1) process with 0.8 persistence. These parameters are shown in Table 2.

4 Data, model simulation and fitting to data

The majority of the results in this paper are impulses responses simulated using Dynare's non-linear perfect foresight solver. However, the model is also taken to the data for the 2020Q1-2023Q4 period which both provides insight insight to the role of supply shock over the period, and allows counter-factual policy scenarios to be run. In both cases a quasi-nonlinear approach is utilized. This section describes the data to which the data is fitted, and how this data matching and counter factual scenario are simulated.

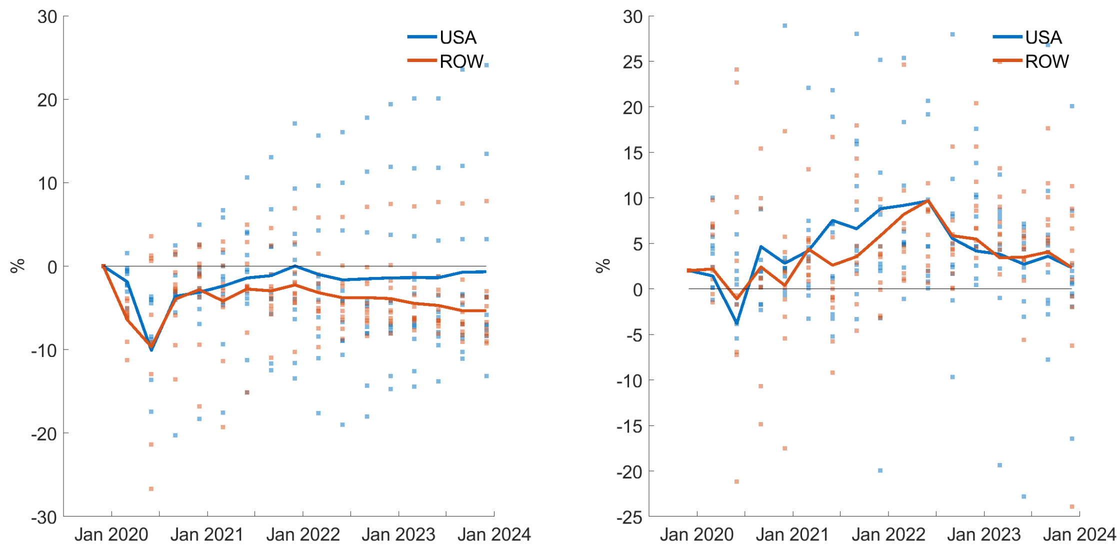
4.1 Data

Quarterly data was collected on sectoral value added, sectoral value-added deflators, aggregate CPI inflation, and interest rates for both the US and rest of the world. The sectoral

Table 2: Model Parameters

Parameter	**Symbol**	**Value**	**Source:**
Discount Factor	β_c	Ensures $1 + \bar{r} = 1.02$	
Household elasticity of substitution between sectoral goods	γ_c	0.8	
Agriculture & Mining sectors' trade elasticities	$\gamma_i,\ i \in \{1, 2\}$	10	
All other trade elasticities	$\gamma_i,\ i \in \{3, \ldots, 10\}$	1.2	
Intermediate elasticity of substitution between sectoral goods	γ_m	0.1	
Elasticity of substitution between input factors and intermediates	γ_z	0.5	
Survival probability	θ_c	0.95	
Intertemporal Elasticity of Subtitution	$\frac{1}{\sigma_c}$	2	
Habit persistence	$\gamma_{c,h}$	0.5	
Share of hand-to-mouth	$[\mu_{US}, \mu_{ROW}]$ $[\mu_{PHL}, \mu_{ROW}]$	[0.7589,0.6887] [0.7589,0.6887]	
Price stickiness parameters	$\delta_{c,i}$		Rubbo (2023) & Pasten et al. (2020)
Wage stickiness (when active)	$\delta_{c,w}$ 0.3		
Imperfect Labor mobility elasticity	γ_L	0.76	
Inflation expectations persistence	$\rho_{1,\pi}$	0.4	
Inflation expectations adaptiveness	$\rho_{2,\pi}$	0.2	
Taylor rule persistence	ρ_c	0.5	
Taylor rule inflation responsiveness	$\alpha_{c,\pi}$	1.5	
Sectoral demand persistence		0.8	
Productivity shock persistence		0.8	
Household demand weights	$\{b_{c,i}, b^c_{o,i}\}$	Calibrated	ICIO
Intermediate expenditure weights	$\{\omega_{j\rightarrow ci}, \omega_{oj\rightarrow, ci}\}$	Calibrated	ICIO
Labor share of production	$\{\alpha^L_{c,i}\}$	Calibrated	ICIO/TIM
Capital share of production (when used)	$\{\alpha^K_{c,i}\}$	Calibrated	ICIO/TIM
Intermediate share of production	$\{\alpha^M_{c,i}\}$	Calibrated	ICIO

data was for each of the 11 sector giving 48 observables in each quarter.[10] The data was de-trended and seasonally adjusted. The sectoral and headline data for both regions and for output and inflation is shown in Figure 4.[11] These were obtained from the Federal Reserve Economic Data, the OECD and Eurostat.



(a) Output (% deviation from trend)

(b) Inflation (% QoQ annualized)

Figure 4: Headline and sectoral observed sectoral output and inflation data.

4.2 Bringing the model to data – identification assumptions

A key challenge in estimating shocks consistent with data is identifying where the labor supply constraints bind. This section outlines the quasi-nonlinear shocks extraction used to fit the model to the data as it has novel elements and the required assumptions are important for understanding the results of the shock extraction.

To estimate the shocks that we assume that negative supply shocks are due to labor constraints binding, while positive supply shocks are due to increases in labor productivity. This

[10]The scope of the rest of world time-series data was limited by the need for quarterly sectoral activity and price data. As such, the rest of the world is a exchange weighted aggregation data for the Euro Area, UK, Japan, Korea, Australian and New Zealand. As such, the value add deflator for the rest of the world energy sector did not accurately capture global energy price movements. Hence, this was excluded from the observable data and US energy import prices are included as an observable instead.

[11]The energy sector value added deflator in the figure is the model estimated series as this series is not included as an observable.

allows us to apply an exactly identified shock extraction. Here we treat the shadow value of our (occasionally binding) labor constraints, λ^L in equation 20, as an exogenous shocks. We ensure that the shadow value of these shocks must always be positive, consistent with the assumption of the occasionally binding constraint. As such, the shadow labor constraint shocks only help explain the data when they bind. In periods and sectors where the constraints do not bind, we allow for sectoral total factor productivity (TFP) shocks. That is, in each period and sector we have one of the sectoral productivity or sectoral labor constraint in the set of exactly identified shocks.

We show a visual example of this approach in Figure 5. Each panel shows a hypothetical situation in the output market where the black dotted lines show the steady state supply and demand curves with the intersection denoting steady state price (vertical) and quantity (horizontal). In both examples we observe the output price and quantity in this market.[12] In the first case (left panel), we observe data (a combination of price and quantity) to the left of the initial supply curve. To explain this observation demand needs to shift (in this case up) but also supply needs to decrease.[13] Supply could decrease for 2 reasons being a supply constraint or a productivity decreased. The first is shown by the blue line with an estimated "shadow value" of the constraint given by the green line and the second case is shown in orange. With the data available it is not possible to separately identify a labor wedge increase from a productivity decrease. The identification assumption that negative supply shocks are due to the labor constraint allows us to identify the shock. Conversely, for case 2 in the right panel the observation lies to the right of the supply curve and is explained a positive productivity shock that shifts out the supply curve.

The quasi-nonlinear shock extraction methodology is implemented via the linear Kalman filter using a linearized version of the model, while ensuring shocks are consistent with assumptions above. For the 48 data observables, discussed above, we allow the data to be explained by 48 shocks in each period, as listed in Table 5.[14] Our identifying assumption requires that in each sector period that either the shadow price shock is zero or labor productivity is at steady state while the correspond shock is estimated.[15] We iterate the shock

[12] One simplification in this diagram is that we work with data on value added rather than gross output. For the purposes of exposition, we label the horizontal axis "quantity" and ignore these distinctions.

[13] Demand increasing is coincidental to this example. We could construct a similar case to the left of the steady state supply curve where demand falls.

[14] In additional to the labor shadow price or productivity shock we include aggregate demand shocks, sectoral demand shifters, monetary policy shocks, and a inflation measurement shock.

[15] In practice we use the calib_smooth function in Dynare DynareManual2024. Given this implementation of the Kalman filter, where we cant change what shocks explain the data in particular periods, we use 70 observables and 70 shocks with 22 (one of labor productivity or the shadow price) observed at steady state.

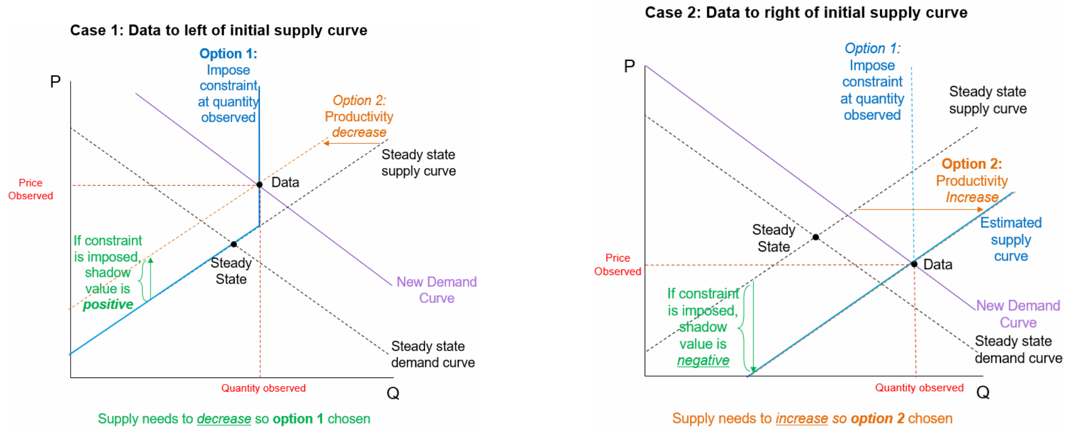


Figure 5: Stylized Example of Constraint and Productivity Estimation

extraction to ensure that the identified shocks are consistent with the identification assumptions.[16] The estimated shadow prices identify where labor constraints bind, and the level of the constraint is taken form the model estimated labor level. The shock extraction is nonlinear in that it embeds the nonlinear occasionally binding constraint. A positive deviation from trend in observed data would result in one set shocks, but a symmetrically negative deviation from trend would not lead to the sign of the shocks changing, instead the shocks identified that explain the data would change.

The strict assumption on the labor productivity and supply shocks, is motivated both by the challenges of alternate techniques and that this approach is broadly consistent with the recent literature, see for example Baqaee and Farhi (2021). An alternate approach would be to allow positive and negative productivity shocks and estimate an under identified model harnessing the statical distributions of the shocks and observables, following Comin et al. (2024). We do not follow this approach given its complexity as we have 22 occasionally binding constraints. We note the limitation of our approach is that as the identification does not allow productivity to decrease, the procedure assumes that all decreases in supply are driven by the imposition of labor supply bottlenecks, with productivity unchanged in these sector periods. Further, while this approach allows us to extract shocks, the binding or non-binding of the labor constraint is implemented in a manner that is not expectations-

In Dynare, NAs in the matrix of observables provide a convenient way to switch which shocks are observed or not. As such the observables matrix has 92 elements with 70 values in each period. The Kalman filter is conditioned so impacts of initial conditions is effectively zero.

[16]We start the iterative estimation by assuming there are no labor constraints, and estimate the shocks, this provides a first iteration. We identify sector periods where shocks inconsistent with the identifying assumptions and updated which shock as assume to explain the data for the sector and period before repeat the shock estimate. We continue the iterative process until we have shocks consistent with identifying assumptions.

consistent – agents in the model view the fundamental shock as a labor wedge shock and not an occasionally binding constraint. In the quasi-nonlinear simulations agents never expect constraints to bind in future periods.

4.3 Quasi-nonlinear counterfactual simulation

Computing counterfactuals is more complex than in typical linear DSGE environment due to the occasionally binding labor constraints.

The quasi nonlinear counterfactual simulation again harnesses the Kalman filter but selectively treat sectoral labor as an observable consistent with it being constrained.[17] To simulate the model most shocks estimated in the data-matching exercise are treated as observables. We then adjust one or more shocks to match the counterfactual exercise under consideration. For example, in scenarios that consider alternate monetary policy, the observable interest rate values are adjusted to match the alternate monetary policy path. To implement the occasionally binding constraints estimated for the shock extraction we start by assuming that all labor constraints bind in the counterfactual exercise. This means we set the quantity of labor as an observable for the Kalman filter at the constraint level estimated using the original observed data. The labor shadow price then becomes an unobservable for the Kalman filter to estimate. Where these re-estimated shadow prices are estimated to be negative, the constraint should be treated as non-binding, and we iterate to ensure this holds.[18] In effect the Kalman filter produces counterfactuals, consistent with the estimated labor supply constraints, preserving the non-linear dynamics of the constraints potentially not binding.

An exception arises in one set of counterfactuals intended to showcase the interaction of monetary policy and the labor constraints. This counterfactual is intended to show an alternative world where there were no labor constraints and labor is responsive. To implement this scenario we keep the value of the shadow constant constant and treat labor as unobserved in the sector where the constraints binds. [19]

[17] The Kalman filter is conditioned so that initial conditions play no role.

[18] We find all such cases with negative shadow prices and in those sectors and time periods, we treat that shadow price as observable and set it to zero re-estimating the quantity of labor in that sector and time period consistent with this. This process is iterated until there are no more negative shadow prices. We ensure labor does not rise above estimated constraints through the iteration.

[19] We assume the wedges are constant and not zero so that if we ran a scenario with this methodology without any shock changes, we would recover the original data.

5 Model Properties

In this section, we turn to the properties of the model with the 2 region calibration to the US and ROW. We begin by examining the model's key impulse-responses to stylized shocks under the Covid episode – a relative demand shift toward service sectors and US monetary stimulus – and focus on the response of US economy. This exercise helps us understand how the model behaves under different assumptions about supply constraints across sectors. We reveal how these frictions interact with the underlying shock to drive aggregate outcomes.

Next we explore the role of input-output linkages in our model. A benchmark theorem in the production networks literature – Hulten's theorem – shows that shock propagation a frictionless environment does not depend on the shape of the network *other than* each sectors' sales-to-GDP ratio (Domar weight). We verify that this is not the case in our model due to important features such as complementarities in demand and sticky prices – meaning that input-output linkages are an important feature moderating the propagation of shocks in our framework.

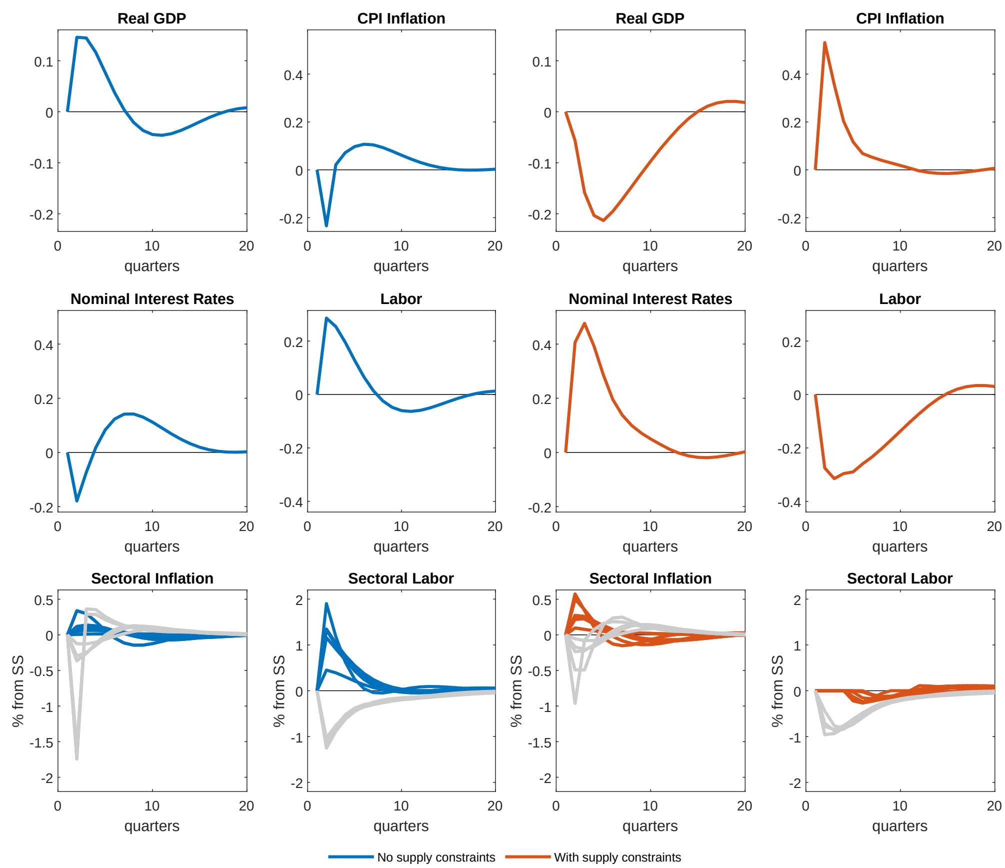
Lastly, we illustrate how supply constraints and demand shifts – both sectoral and aggregate – influence the aggregate Phillips curve. Our modeling framework implies that the Phillips curve is not stable but varies with the composition of shocks. By imposing sectoral supply constraints and interacting with demand shocks, we show that the slope and intercept of Phillips curve, as well as the shape can change substantially, depending on how these sectoral shocks occur.

5.1 Impulse-Response Functions

Figure 6 compares the effects of a 1 percentage point shift in global consumption toward service sectors relative to goods. The blue lines shows the response of US economy with no supply constraints, while red lines show alternative responses where we introduce supply constraints that prevent labor rising above steady state levels for the first 10 quarters after the shock. In the unconstrained case (blue), US real GDP rises and CPI inflation falls which suggests this relative demand shift manifests as something that appears to be an aggregate supply shock. The key driver is the composition of demand: since services make up a larger share of US consumption, the reallocation shock boosts overall demand in the US.[20] Moreover, as service prices are stickier than goods prices, the fall in demand for goods lowers

[20]For example, if US consumption comprises of 40% goods and 60% services, and there is a 10% demand shift toward services from goods, US consumption increases by 2% as $0.6 \times 1.1 + 0.4 \times 0.9 = 1.02$

Figure 6: Tilt in global demand toward services

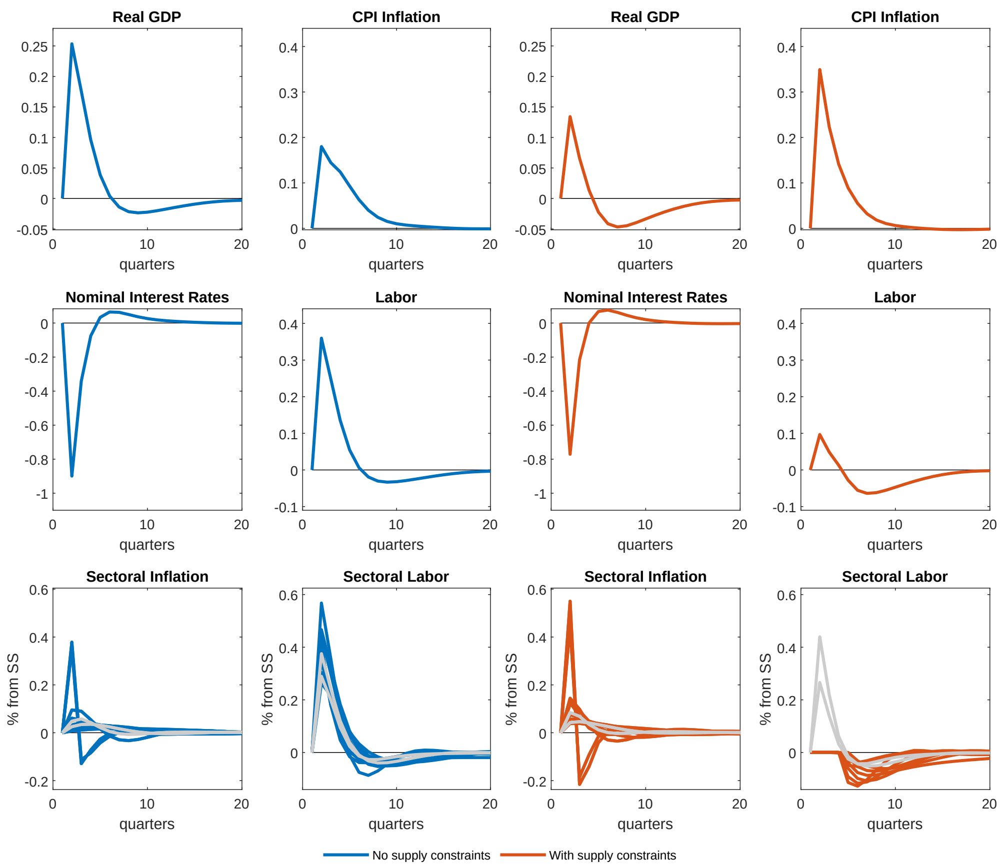


goods prices by more than the rise in demand raises services prices, pushing the overall inflation going down. These channels are clearly visible in the sectoral inflation plot (bottom left), meaning that goods inflation (grey) is driving the overall decline in inflation.

When services-sector labor is constrained (red), the overall response flips. With labor unable to expand (bottom right), production in service sectors cannot rise to meet the increased demand. As a result, inflation rises instead of falling, prompting a tighter monetary policy. Therefore, supply constraints makes this demand reallocation shock from something that appears as a positive aggregate supply shock into a negative one. This highlights the role of supply-side frictions, which can alter the macroeconomic implications of changing demand patterns.

Figure 7 compares the effect of a 25 basis point expansionary monetary policy shock in the US. Again, the blue line is the impact on the US economy with no supply constraints,

Figure 7: USA stimulatory monetary policy shock



while the red line is the impact of the same shock under labor constraints in service sectors. In the unconstrained case, the shock leads to a rise in real GDP, coming from both a rise in consumption as well as net exports from a depreciation fo the US real exchange rate. These effects are amplified by the assumption that both US exports and imports are denominated in the USD: exports become cheaper in foreign currency, boosting demand abroad, while import prices remain stable in USD, encouraging US consumers to buy more.

When labor is constrained in service sectors (red), the GDP response is significantly dampened, while inflation is modestly higher. The labor response is notably smaller due to labor in service sectors unable to expand (bottom right, red). This creates higher inflation and lower production in service sectors, leading to lower GDP and a higher inflation response. This suggests a different Philips curve relationship between GDP and inflation when supply constrained. We investigate further how the presence of supply bottleneck changes the inflation-output relationship in Section 5.3.

5.2 Aggregate Response

Next we analyze the GDP response to a temporary supply shock by varying model environments. Starting from a simple benchmark: a closed economy with flexible prices and Cobb-Douglas production functions, the model reproduces Hulten (1978)'s Theorem, where the GDP impact aligns closely with the Domar-weighted average of sectoral productivity changes under efficient economy. This serves as a reference point to assess the effect of more complex model features.

We then introduce model elements such as price rigidities, open economy considerations, and non-Cobb-Douglas elasticities to assess how each component contributes to deviations from the benchmark results. Complementing this, we run alternative exercise from a richer baseline model and modify assumptions like input-output linkages and shock persistence. These exercises allow us to benchmark the model's predictions against those implied by the sufficient statistics approach and highlight mechanisms behind the breakdown of Hulten's Theorem.

Table 3: From Simple model to Baseline model

Model	Elasticity	Price/Wage	Sector 1	Sector 2	Sector 3	…	Sector 9	Sector 10	Sector 11
Closed	Cobb-Douglas	Flexible	0.998	0.997	1.001	…	0.997	1.000	0.999
Open	Cobb-Douglas	Flexible	1.006	1.009	1.009	…	1.009	1.014	1.014
Open	Calibrated	Flexible	1.137	1.126	1.057	…	0.947	0.983	0.996
Open	Calibrated	Sticky	1.392	1.265	0.607	…	0.100	0.187	0.215
	Frequency of Price Adjustment		0.970	0.970	0.368	…	0.071	0.135	0.159

Notes: Each column represents a different sector in our model as detailed in Table 1. Each value is the response of aggregate GDP to a 1% productivity shock in the respective column's sector divided by the response we would expect if Hulten's theorem held exactly in an efficient economy with no flexible factors. Specifically, Hulten's theorem predicts that the elasticity of aggregate GDP to a sector i productivity shock is given by the ratio of that sectors' sales to aggregate GDP: the sectors "Domar weight".

Table 3 reports the impact response of real GDP to a 1% sector-specific TFP shock, normalized by the prediction from Hulten's Theorem. Each row corresponds to a different model specification, where one model feature is changed at a time to isolate the effect. Each column is the selected sectors, listed in Table 1, with a 1% TFP shock. A value close to 1 indicates that the model's GDP response closely matches the Hulten prediction. Values greater (or lower) than 1 suggest that the model amplifies (or mitigates) the aggregate impact of the sectoral shock beyond what Hulten's Theorem would imply.

The first and second row confirm that the simple models with Cobb-Douglas elasticities and flexible prices replicate Hulten's Theorem almost exactly. The introduction of an open economy consideration marginally amplifies the GDP response through exchange rate adjustment, though the results remain largely consistent with Hulten prediction.

The third row incorporates calibrated elasticities–production elasticities below one (complementarity) and trade elasticities above one (substitutability)–based on the benchmark calibration in Section 3.7. The model now shows heterogeneous deviations from Hulten's Theorem, with some sectors displaying amplification and others showing attenuation. This patterns arises from the dual roles of input complementarity and trade substitutability. As discussed in Baqaee and Farhi (2019), trade channels amplify the propagation of shocks, while production mitigates it. The net effect depends on a sector's position in the value chain and its reliance on domestic versus imported inputs.

The fourth row presents the full baseline model incorporating sticky prices and wages. In this environment, deviations from Hulten's prediction are strongly shaped by nominal rigidities, particularly the sector-specific frequency of price adjustment reported in the final row. In sectors with relatively flexible prices such as Sector 1 and 2, a positive productivity shock lowers input costs and raises markups in other sectors. This induces a reallocation of resources toward more distorted sectors and improves allocative efficiency, as discussed in Baqaee and Farhi (2020b). Conversely, when the shock occurs in a sector with sticky prices, resources reallocate away from distorted sector, dampening the aggregate impact.

Table 4: Role of IO linkages and Shock Persistence

Environment	Persistence	Sector 1	Sector 2	Sector 3	...	Sector 9	Sector 10	Sector 11
Full IO	Temporary	1.392	1.265	0.607	...	0.100	0.187	0.215
Full IO	Permanent	1.343	1.300	0.814	...	0.208	0.398	0.457
no IO	Temporary	1.180	1.069	0.451	...	-0.048	0.004	0.053

Table 4 explores how different model environments and shock persistence influence the aggregate GDP response to sector-specific shocks. Again, each value is the impact response of real GDP normalized by the benchmark predicted by Hulten's Theorem. We consider two main dimensions of variation: the persistence of shock, and whether the economy features full IO linkages or not.

The first row repeats the baseline model results from the fourth row in Table 3. In the second row of Table 4, the 1% TFP shock becomes persistent as AR(1) process with 0.8 persistence, which further amplifies the responses the responses in sticky price sectors. This is because agents anticipate higher future productivity, which encourages forward-looking behavior in consumption, even in the presence of nominal rigidities.

The third row shuts down IO linkages by removing intermediate consumptions across countries and sectors and shifting final consumption across sectors to match the gross output accounting. The absence of intersectoral spillovers generally dampens amplification effects, especially in downstream sectors such as Sector 10 and Sector 11 , or even generates negative responses such as Sector 9. This highlights the role of complementarities and propagation through the production network.

5.3 Supply Constraints and the Phillips Curve

Supply constraints in the model moderate the inflation output relationship at the sectoral level which in turn can modify the inflation-output relationship in reduced-form aggregate Phillips curve. Our model incorporates mechanism that can account for both a leftward shift and steepening of the aggregate Phillips curve– patterns observed in the post-pandemic period.

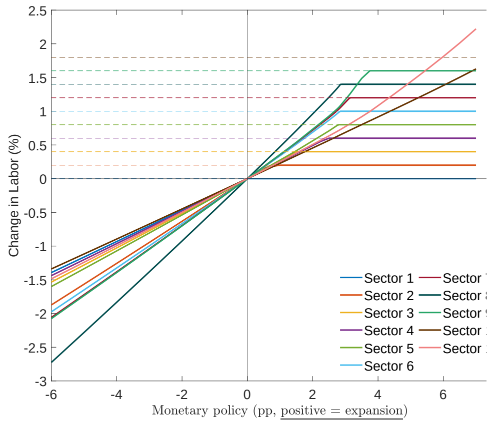
To illustrate the mechanism, we impose hypothetical sector-specific labor constraints and vary demand using monetary policy shocks. The dotted horizontal lines in panels (a) and (c) of Figure 8 represent the maximum employment of each sector, with the vertical axis showing labor relative to steady state. For clarity, we assume an ascending set of constraints where sector 1's employment cannot exceed steady state levels and sector 10's employment cannot exceed 1.75 percent above steady state.[21] The solid lines in panel (a) show equilibrium employment (on impact) as monetary policy stance changes, with 0 represents no monetary policy shocks and -6 indicates a 600 basis point *contraction*.

When monetary policy is tight, sectoral labor remains low and responds linearly to policy changes. As policy becomes expansionary, sectors begin hitting their constraints – starting with sector 1 – causing higher prices rather than higher output due to binding labor constraints. As policy becomes more expansionary and more sectors hit their constraints, inflation response is amplified and output response is dampened.

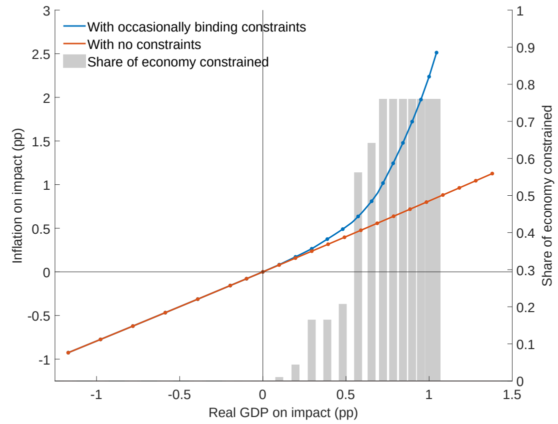
Panel (b) illustrates this mechanism: the blue line shows that as the policy becomes more expansionary and more sectors become supply constrained, inflation rises more sharply relative to output; a steepening of the Phillips Curve. In contrast, the red line – representing the Phillips Curve with no constraints – remains linear, highlighting how sector-level constraints

[21] Sector 11 is unconstrained.

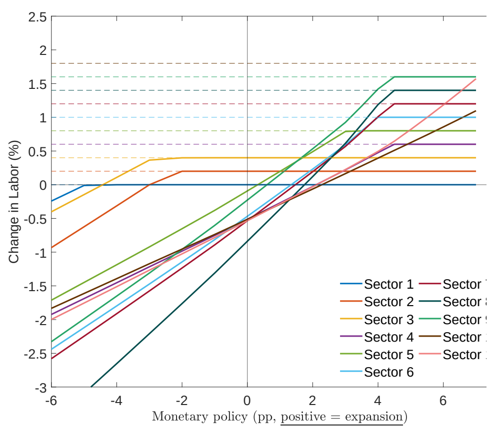
Figure 8: Constraints and the Aggregate Phillips Curve



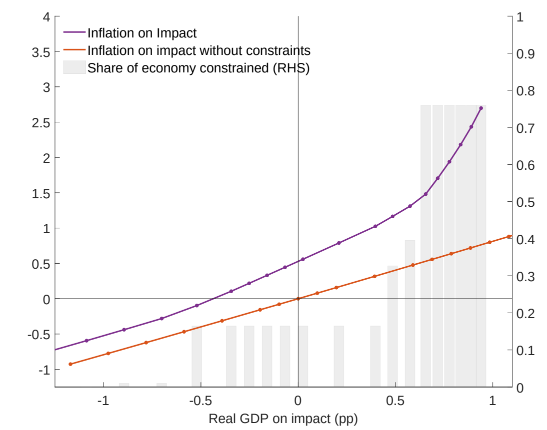
(a) Labor and constraints



(b) Phillips Curve with constraints



(c) Labor with demand shifts



(d) Phillips Curve with demand shifts

alter the slope of the aggregate Phillips Curve.

Panels (c) and (d) repeats the earlier exercise but add a tilt in demand toward sectors 1 to 3. While aggregate demand remains unchanged in partial equilibrium, the composition of demand changes causes these sectors hit the constraints even when aggregate demand is moderately low. This results in a steeper Phillips Curve as discussed earlier that shifts to the left. This shift comes from the fact that sectors 1 to 3 have more flexible prices. If CPI has a higher weight on more flexible-price sectors, inflation becomes more responsive to demand, even absent supply bottlenecks.

6 Policy implications

Next we utilize this model to understand the interaction between temporary sectoral supply constraints, inflation and monetary policy both through useful hypothetical scenarios and by taking the model to the data. First we use the model as a laboratory and show how the combination of supply constraints and sectoral demand shocks introduce new trade-offs for monetary policy. Monetary policy focuses on a weighted average of sectoral inflation – typically some measure of "core" inflation. We focus on a situation where one important sector is supply constrained to zoom in on how temporary supply constraints may complicate the appropriate "core" inflation to target.

Secondly we take the model to the data to understand the role of supply constraints in the COVID period. In addition, we simulate counterfactual scenarios with monetary policies set differently from those central banks actually adopted. In particular, we investigate whether binding supply constraints may alter the impact of these alternative monetary policies.

6.1 How to weight sectoral inflation when there are temporary supply constraints

In this section we investigate the question of which way to weight inflation in a world with multiple sectors and complex input-output linkages. Conventional practice is to target a "core" measure of inflation where inflation in sectors with flexible prices are removed.[22] Recent work by Rubbo (2023) produced a useful formula for constructing an appropriate measure of core inflation in an environment where there are heterogeneous Phillips curve slopes and rich input-output linkages – her "divine coincidence" index (DC index). We will

[22] Aoki (2001) argued that optimal policy should ignore inflation in flexible price sectors.

treat the stabilization of this index as a benchmark policy rule to understand the role of supply bottlenecks on monetary policy.

Each sector's inflation weight in the DC index are comprised of two components: a measure of a sector's "influence" in the input-output network (it's Domar weight) divided by the slope of the Phillips curve in that sector. As such, high influence sectors with sticky prices will receive high weight in the DC index and sectors with flexible prices (infinite Phillips curve slopes) receive weights of zero regardless of their influence.

We start by focusing on an environment similar to Rubbo (2023) where stabilizing the DC index would deliver a zero aggregate output gap in all periods.[23] The requirements for this are that the economy be closed, that wages be flexible with frictionless labor mobility between sectors and an undistorted steady state. We will relax these assumptions in our data matching results 6.2.[24]

As shown in Figure 8, supply constraints alter the slope of the Phillips curve and introduce a situation where the weights in the DC index might need to be adjusted. Furthermore, if the supply constraints are temporary, then the correct weights in the DC index become time-varying. In practice central banks may not immediately be aware of the existence of supply constraints in various sectors, nor may they be able to predict and adjust when the constraints are eased. We focus on the consequences of following rules that fail to adjust to the existence of a temporary supply constraint – either by failing to notice that a sector has become supply constrained or by failing to notice that the sector is no-longer constrained.

We focus on the most extreme situation where a supply constraint may influence the implementation of a DC index based rule: where the sector with the highest weight in the DC index ends up with a supply constraint. In our calibration, this sector is professional, scientific and technical services (PST) and comprises a weight of 35% in the DC index absent any supply constraints.

We impose an output-based supply constraint in this sector at this sector's steady state level of output.[25] Results are qualitatively similar if we utilized labor constraints. The spe-

[23]We define the output gap as the (percent) deviation of output from what would occur in a world where prices were flexible.

[24]While we can apply the formulation of the DC index from Rubbo (2023) outside this restricted model, that rule no-longer delivers a zero output gap (nor does any rule targeting a constant-weight inflation index. As is well known, divine coincidence can fail in open economy setups or in setups with sticky wages and other labor frictions.

[25]The primary purpose of a different form of supply constraint is for intuition as it makes the sectoral Phillips curve vertical (see Comin et al., 2023, Comin et al., 2024 and Gudmundsson et al., 2024).

cific form of each output constraint is:

$$Z_{c,i,t} \leq \hat{\zeta}_{c,i,t} \bar{Z}_{c,i}, \quad MC_{c,i,t} = \tilde{MC}_{c,i,t} + \lambda^{Z}_{c,i,t}$$

with $\hat{\zeta}_{c,i,t} \in [0, \infty]$ representing a exogenous movement in the output constraint, $\bar{Z}_{c,i}$ is the steady state level of output, $MC_{c,i,t}$ is shadow marginal cost in country c, sector i which includes the cost of the constraint, $\tilde{MC}_{c,i,t}$ is marginal cost if unconstrained and $\lambda^{Z}_{c,i,t}$ is the shadow value of the constraint. Then we implement a 10% sectoral demand shock for 4 quarters that raises final demand for output from this sector by 10% and lowers demand in other sectors proportionately. After the 4 quarters, we assume demand returns to steady state gradually with AR(1) persistence of 0.8.

Figure 9 show impulse response functions in response to the PST sector receiving a rises in relative demand along with a one-year supply constraint. Set A shows the responses of aggregate variables to a variety of different policy rules.

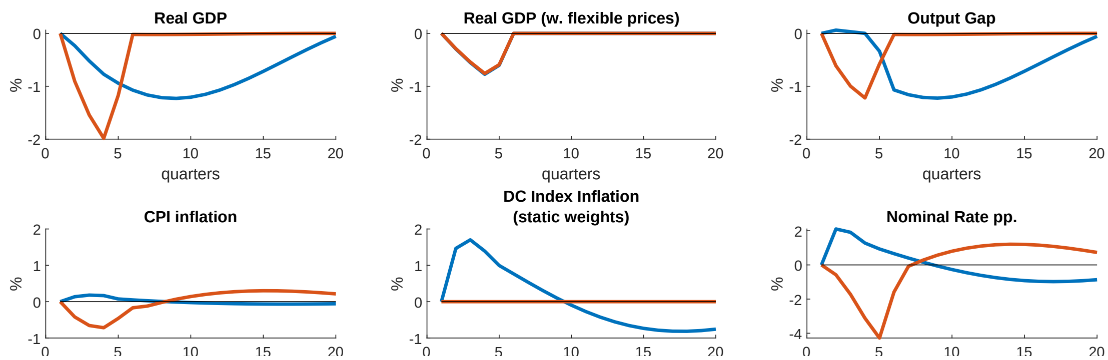
Because of supply bottlenecks, flex-price output (top middle chart) falls when demand is tilted towards the constrained sector. The reason for this is that the supply constraint creates shortages that require price rises to satiate demand. Because each type of good are complements, price rises for professional, scientific and technical services raises the expenditure share endogenously for this sectors' production. This further leads to less spending on other sectors' output which leads these sectors' to reduce output. If aggregate labor were in fixed supply, this lower demand would lower the real wage as well as costs in all non-constrained sectors which could allow them to maintain production at previous levels. However, because the labor supply curve is upward sloping, if households cannot work more in the sector with the most coveted production, they instead prefer to take leisure rather than consume more production from other sectors.

When prices are sticky, one option for the central bank is to ignore the supply constraint and target the DC index with weights as determined by each sectors' Phillips curve (red line). Following this rule no-longer stabilizes the output gap (top right chart) when supply constraints bind and instead deliver a negative output gap (output below the flex-price level). However, once the constraint disappears, all sectors return to their original Phillips curves and stabilizing the DC index with the original weights now also achieves divine coincidence once the constraint vanishes.

An alternative approach could be to instead adjust the DC index weights to account for the existence of supply constraints. When binding, supply constraints effectively make the

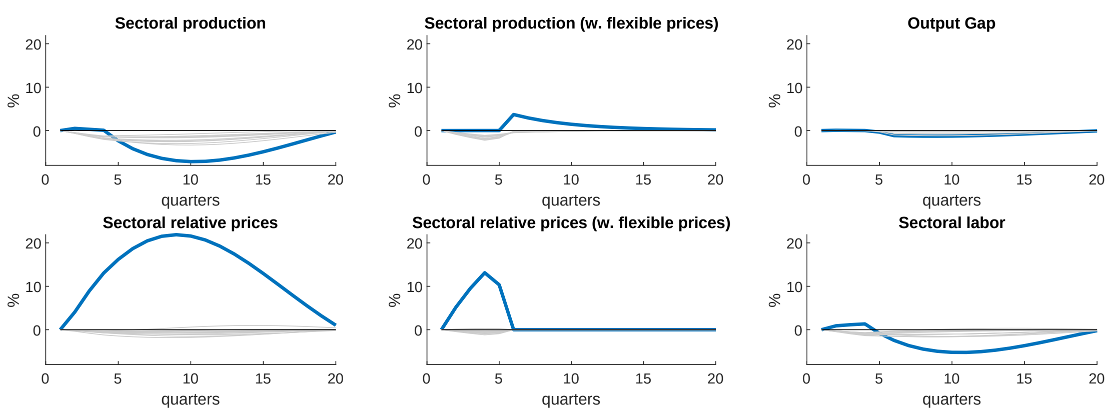
Figure 9: 10% sectoral demand shock with an output constraint in professional, scientific and professional services

Set A: Aggregate impacts with different policy rules



DC Index assuming a permanent supply constraint DC Index ignoring constraint

Set B: Sectoral Responses for DC index targeting assuming a permanent supply constraint



Professional, scientific & technical sector (sector with highest DC index weight) Other sectors

Notes:

Calvo Phillips curve irrelevant and the sector acts as if it has flexible prices. This would suggest a weight in the DC index of 0 for any supply constrained sector. The blue line implements the DC index with these updated weights both when the supply constraint binds *and afterwards*. While clearly not optimal, this rule serves to show the costs of adapting to a regime where supply constraints bind but failing to adjust when that regime ends.

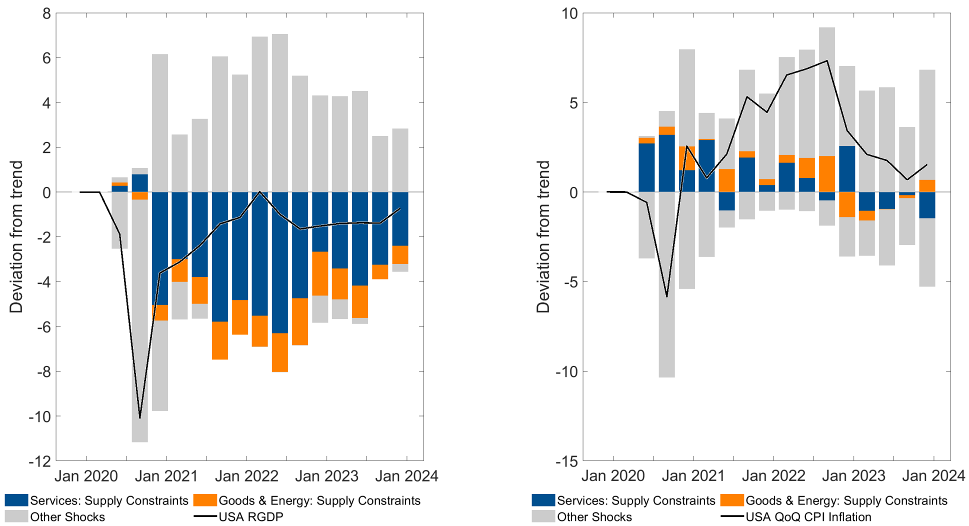
This rule does achieve a 0 output gap while the constraint binds, however once the constraint disappears, continuing to implement monetary policy as if supply constraints existed leads to a large negative output gap. The reason for this is that, once the supply constraint stops binding, costs fall to pre-constraint levels and there is pressure for prices to fall. This can be seen in Set B where flex-price output in the PST sector jumps up once the constraint disappears and its price relative to other sectors falls back to 0 (center top and bottom panels). By contrast, when prices are sticky production *falls* once the constraint disappears (left panel) because prices cannot fall sufficiently quickly. When prices are sticky, allowing price rises when supply constraints bind is very costly because those prices could take a long time to return to previous levels after the constraints end. Furthermore, policy keeps the prices in other sectors roughly stable which means that it is left to prices in the previously constrained sector to adjust. In the example here, this happens to be the sector with the highest DC index weight which means that it is both one of the most influential sectors and one of the stickiest. Rather than letting the flexible price sector restore relative price imbalances this monetary policy requires one of the stickiest sectors to do so.

This has important implications for thinking though appropriate policy in a pandemic situation like 2020-2024 and beyond if supply constraints return. Appropriate policy for normal times can lead to inefficiently low output while supply constrained. However, stimulating the economy during the period when supply constraints bind lead to higher prices in supply constrained sectors. While this does not matter when constrained, these relative price gaps can lead to a highly inefficient recovery once the constraints ease. In practice, central banks are unlikely to know the exact points in time when constraints ease which means that the temptation to stimulate the economy to close negative output gaps while constrained comes with considerable medium term risks.

In the next subsection we investigate this further by fitting our model to the 2020-2024 experience and showing the trade offs in terms of inflation stabilization of running expansionary policy while supply constrained.

6.2 Lessons from the 2020-2024 experience

When we fit the model to 2020-2024 data, we find that supply constraints were important in explaining COVID and post COVID period. Our procedure estimates that supply constraints were an important persistent drag on real GDP during this period, as shown in Figure 10. In addition, they led to significant upward price pressures early in the pandemic, contributing 2–3 percentage points to US inflation during 2020–22 and playing a role in the subsequent disinflation, with a negative net contribution after 2023. The inflation impacts appear to be less significant than GDP effects, largely because the supply bottlenecks—even if they may last for an extended period—raise prices persistently, leading to one-off rather than persistent increases in inflation. Figure 14 in the appendix shows in which sectors and which periods



(a) US GDP

(b) US inflation

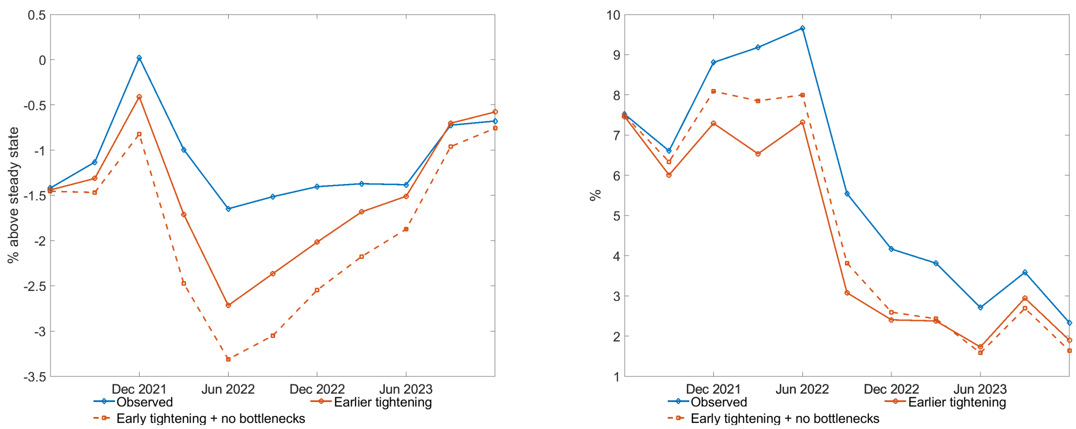
Figure 10: Contributions of labor constraints to US GDP and inflation

the data matching identified constraints, with the value of the constraint shown as an index relative to the steady state labor value. A strength of the labor constraint identification is that it identifies constraints both above and below steady state. However, the assumption that essentially all negative supply shock are due labor constraints leads to labor constraints being identified in many periods and in many sectors. In some way this is to be expected, the COVID period was a significant economics downturn and output remain below trend through the post COVID period.

6.2.1 Counterfactual scenarios

The counterfactual scenarios ask, firstly, if different policy choices by central banks would have made a difference during the inflation surge? Secondly, how these policy choices would have interacted with bottlenecks? To answer these questions, Figure 11 presents cases in which policy tightens three quarters earlier than observed, combined with different assumptions about the presence of bottlenecks. Tightening earlier, shown by the solid red lines, lowers peak inflation by about 2 percentage points relative to the data (Figure Figure 11, panel

1) but results in a 0.8 percentage point reduction in real GDP (Figure Figure 11, panel 2) for 2022. Comparing two versions of the "earlier tightening" counterfactual further reveals the role of supply bottlenecks. When capacity constraints are imposed at levels estimated from fitting the model to the data (solid red lines), tighter policy has greater potency in lowering inflation, with low output cost relative to the case in which the constraints are assumed away (dashed red lines). This is because the constraints steepen the Phillips curve, as shown earlier, making expansionary policies more inflationary but also making it less costly to bring down inflation through monetary tightening. This comparison highlights how supply bottlenecks can steepen the Phillips curve and affect the cost of disinflation.

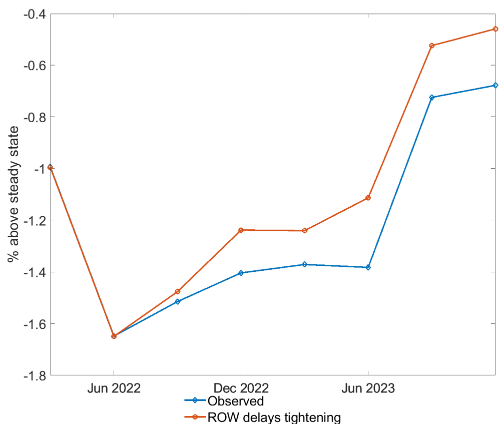


(a) US GDP

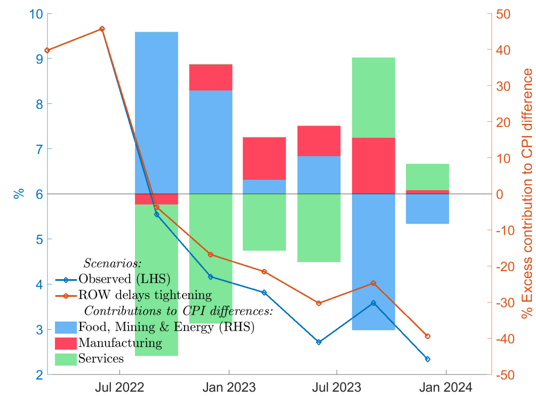
(b) US inflation

Figure 11: Counterfactual Monetary Policy (Percent)
Sources: Federal Reserve Economic Data; Organisation for Economic Co-operation and Development, and authors calculations.
Note: "Earlier tightening" scenario assumes rates rise three quarters earlier. Standard monetary policy counterfactuals assume identified labor constraints remain. "No bottlenecks" assumes the wedge between the marginal product of labor and wages (shadow price of constraint) is kept consistent with the data, but the constraint does not bind.

Secondly, we ask whether different policy choices by other central banks have made a difference? We simulate a counterfactual scenario where the rest of the world tightens monetary policy later than the United States, as shown in Figure 12. This delayed synchronization in tightening slows the domestic disinflation process. The difference between observed inflation and the counterfactual scenario is displayed by the bars in left hand panel of Figure 12 for each sector. Agriculture, mining, and energy—sectors with highly flexible prices—experience stronger inflation than the other sectors, and although inflation diminishes in these sectors over time, they generate further price increases in manufacturing and services through input-output linkages.



(a) US GDP



(b) US inflation

Figure 12: Uncoordinated Global Monetary Policy (Percent)
Sources: Federal Reserve Economic Data; Organisation for Economic Co-operation and Development, and authors calculations.

7 Conclusion

This paper studied monetary policy in the pandemic and post-pandemic period through the lens of a rich production network model with heterogeneous price stickiness. We found that supply bottlenecks imposed a sharp temporal trade-off onto monetary policymakers: when there are both demand constrained and supply constrained sectors, addressing demand shortfalls has low economic costs while constraints bind but imposes high costs on the economy when the constraints unwind. These trade-offs are new relative to typical shocks and more challenging to address.

When fitting our model to data on the 2020-2024 period, we find that supply constraints contributed significantly to U.S. inflation during 2020–2024 by as much as 2–3 percentage points—and imposed a persistent drag on output from 2021 onward. Our counterfactual simulations show that earlier monetary tightening could have reduced peak inflation by about 2 percentage points, with a relatively modest output cost of 0.8 percentage points. These findings underscore that when supply constraints bind, the Phillips curve steepens, making inflation more responsive to demand and output less so—a dynamic that improves the short-run trade-off facing monetary policy.

In sum, the pandemic-era inflation episode reveals that supply constraints are not merely transitory disturbances to be ignored. Instead, they are central to understanding inflation dynamics and must be explicitly incorporated into the design and conduct of monetary policy. As supply-side shocks become more frequent—whether due to geopolitical tensions, climate events, or structural shifts—central banks will need to adapt their frameworks to remain effective stewards of price and output stability.

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Appendix A: Additional model details

7.1 Households – Overlapping Generation Structure

We denote Ricardian households as OLG households, and hand-to-mouth household as HtM households.

We first define the demographics of OLG households. Let $N_{c,t}$ be the total population of region c at time t. In each time period, young households are born at a fraction ι_c (birth rate) of $N_{c,t-1}$. In addition, each household stays alive with a fraction θ_c (survival rate) of $N_{c,t-1}$. In this case, population grow with a rate of $n_c = \iota_c + \theta_c$.

$$N_{c,t} = n_c N_{c,t-1}$$

Then, the share of cohort of age a at time t $sp_{c,a,t}$ follows the law of motion:

$$sp_{c,a=0,t} = \frac{i_c}{n_c}, \quad sp_{c,a,t} = \frac{\theta_c}{n_c} sp_{c,a-1,t-1}$$

The representative OLG households of age a at time t in region c maximizes their lifetime utility $\mathcal{W}_{c,a,t}$

$$\mathcal{W}_{c,a,t} = \mathbb{E}_t \left[\sum_{s=0}^{\infty} (\beta_c \theta_c)^s \, u(c_{c,a,t}, h_{c,a,t}) \right]$$

where one-period ahead discount factor is β_c and $u(c_{c,a,t}, h_{c,a,t})$ is per-period utility function with constant relative risk aversion

$$u(c_{c,a,t}, h_{c,a,t}) = \frac{\kappa_t^{\sigma_c}}{1-\sigma_c} \left[\left(c_{c,a,t}\right)^{\eta_c} \left(\bar{h}_{c,a,t} - h_{c,a,t}\right)^{1-\eta_c} \right]^{1-\sigma_c}$$

where κ_t is a non-decision variable governing consumption habits, η_c is the share of consumption in utility, and $\bar{h}_{c,a,t}$ is endowment of work hours decreasing with a rate of $0 < \chi_c \leq 1$.

OLG households are subject to budget constraint at time t:

$$P^C_{c,t} c_{c,a,t} + \mathcal{E}_{c,t} b^{\$}_{c,a+1,t+1} + \mathbb{E}_t \left[\mathcal{H}_{c,t+1} b_{c,a+1,t+1} \right] = \frac{b_{c,a,t}}{\theta_c} + \mathcal{E}_{c,t}(1+i_{US,t-1}) b^{\$}_{c,a,t} + W_{c,t} \Phi_{c,a,t} h_{c,a,t} + \Pi_{c,a,t}$$

where $P^C_{c,t}$ is aggregate consumer price level in domestic currency, $c_{c,a,t}$ is aggregate consumption of OLG households, $\mathcal{E}_{c,t}$ is the dollar exchange rate of region c[26], $b^{\$}_{c,a,t}$ is the non-contingent dollar bond holding, $\mathcal{H}_{c,t}$ is the price of Arrow–Debreu security normalized by the price of event, $b_{c,a,t}$ is the security holding of OLG households, $i_{US,t}$ is the US nominal interest rate, $W_{c,t}$ is nominal wage level in domestic currency, $\Phi_{c,a,t}$ is the labor productivity decreasing with a rate of $0 < \gamma \leq 1$, $h_{c,a,t}$ is actual work hours of OLG households, and

[26] $\mathcal{E}_{US,t} = 1$ for every t

$\Pi_{c,a,t}$ is per-period dividend accrued to OLG households. Total holding of the security is subject to net zero supply condition: $b_{c,a=0.t} = 0$ and $\sum_{a\geq 1} sp_{c,a,t} b_{c,a,t} = 0$.

Under flexible wage, the first-order conditions for the consumption and leisure imply the upward-sloping labor supply curve in cohort-level.

$$h_{c,a,t} = \bar{h}_{c,a,t} - \frac{1-\eta_c}{\eta_c} \frac{P^C_{c,t}}{\Phi_{c,a,t} W_{c,t}} c_{c,a,t}$$

The first-order conditions of domestic and dollar bonds imply the uncovered interest rate parity (UIP) condition.

$$\ln(i_{c,t}) = \ln(i_{US,t}) + \ln\left(\frac{\mathcal{E}_{c,t+1}}{\mathcal{E}_{c,t}}\right) + \ln\left(\frac{\pi^C_{c,t}}{\pi^C_{US,t}}\right)$$

The trasversality condition is

$$\lim_{T\to\infty} \mathbb{E}_t[\mathcal{F}_t^{t+T} b_{c,a+T+1,t+T+1}] = 0$$

where $\mathcal{F}_t^{t+T} = \prod_{s=1}^{T} \mathcal{F}_{c,t+s}$ is the nominal stochastic discount factor (SDF) between period t and $t+T$, $\mathcal{F}_{c,t+1} = \mathcal{H}_{c,t+1}\theta_c$ and $\mathcal{J}_{c,t+1} = \mathcal{F}_{c,t+1}\pi^C_{c,t+1}$ is the nominal and real SDF between period t and $t+1$, and $\pi^C_{c,t+1}$ is the CPI inflation rate.

To simplify the budget constraint, firstly $h_{c,a,t}$ is substituted with labor supply relation. Second, the linear combination of expected future budget constraints eliminates future bond holdings. Third, expected future consumptions are rewritten as consumption now with same growth rate for all cohorts. Lastly, aggregate variables are defined as weight average across cohorts.

$$C^{OLG}_{c,t} = N_t c_{c,t}, \quad c_{c,t} = \sum_{a\geq 0} sp_{c,a,t} c_{c,a,t}$$

$$L_{c,t} = N_{c,t} l_{c,t}, \quad l_{c,t} = \sum_{a\geq 0} sp_{c,a,t} l_{c,a,t} = \sum_{a\geq 0} sp_{c,a,t} \Phi_{c,a,t} h_{c,a,t}$$

$$\bar{L}_{c,t} = N_{c,t} \bar{l}_{c,t}, \quad \bar{l}_{c,t} = \sum_{a\geq 0} sp_{c,a,t} \bar{l}_{c,a,t} = \sum_{a\geq 0} sp_{c,a,t} \Phi_{c,a,t} \bar{h}_{c,a,t}$$

Therefore, aggregate household budget constraint of OLG households is

$$\Omega_{c,t} P^C_{c,t} C^{OLG}_{c,t} = \eta_c \left(\mu_c \bar{L}_{c,t} \mathcal{LW}_{c,t} + \mathcal{DW}_{c,t} + \frac{i_{c,t-1}}{\pi^C_{c,t}} NFA_{c,t-1}\right)$$

where $\Omega_{c,t}$ is the inverse of marginal propensity of consumption from wealth, μ_c is the share of OLG households, $\bar{L}_{c,t}$ is the total labor endowment, $i_{c,t}$ is the nominal interest rate, $NFA_{c,t}$ is the net foreign asset position. The law of motions of dividends wealth $\mathcal{DW}_{c,t}$ and labor wealth per unit of endowment $\mathcal{LW}_{c,t}$ are

$$\mathcal{DW}_{c,t} - \mathcal{J}_{US,t}\mathcal{DW}_{c,t+1} = P^C_{c,t}C_{c,t} + TB_{c,t} - W_{c,t}L_{c,t} - (1-\mu_c)G_{c,t}$$
$$\mathcal{LW}_{c,t} - \mathcal{J}_{c,t}\chi_c\mathcal{LW}_{c,t+1} = W_{c,t}$$

where $TB_{c,t}$ is the trade balance and $G_{c,t}$ is the fiscal transfer from OLG households to HtM households.

7.1.1 Aggregate Variables

Relative Wage Evolution:

$$\frac{W_{c,t}}{W_{c,t-1}} = \frac{\pi^W_{c,t}}{\pi^C_{c,t}}\frac{\mathcal{E}_{c,t-1}}{\mathcal{E}_{c,t}}$$

Wage Phillips Curve:

$$\ln(\pi^W_{c,t}) = \ln(\mathbb{E}_t[\pi^W_{c,t+1}]) + \kappa_w \cdot \left(\ln\left(\frac{1-\eta_c}{\eta_c} \cdot \frac{C_{c,t}}{\bar{L}_c - L_{c,t}}\right) - \ln\left(\frac{W_{c,t}}{P^C_{c,t}}\right)\right)$$

Wage Inflation Expectations:

$$\mathbb{E}_t[\pi^W_{c,t+1}] = \rho_{1,\pi^W}\mathbb{E}_{t-1}[\pi^W_{c,t}] + \rho_{2,\pi^W}\pi^W_{c,t-1} + (1-\rho_{1,\pi^W}-\rho_{2,\pi^W})\pi^W_{c,t+1}$$

Law of Motion for Inverse of Marginal Propensity to Consume from Wealth:

$$\Omega_{c,t} = 1 + (\beta_c\theta_c)^{\frac{1}{\sigma_c}}\left(\frac{\mathcal{J}_{c,t}P^C_{c,t+1}}{P^C_{c,t}}\right)^{1-\frac{1}{\sigma_c}}\left(\frac{\chi^L_c W_{c,t+1}}{W_{c,t}}\frac{P^C_{c,t}}{P^C_{c,t+1}}\right)^{(1-\eta_c)\left(1-\frac{1}{\sigma_c}\right)} \cdot \frac{C^{habit}_{c,t+1}}{C^{habit}_{c,t}}\Omega_{c,t+1}$$

Consumption Habits in Utility:

$$C^{habit}_{c,t} = (C^{OLG}_{c,t-1})^{\gamma^b_c} \cdot (C^{OLG}_{c,t+1})^{\gamma^f_c}$$

Real Interest Rate:

$$\mathcal{J}_{c,t}\mathrm{r}_{c,t} = \theta_c$$

Law of Motion for Dividends Wealth:

$$\mathcal{DW}_{c,t} - \mathcal{J}_{US,t}\mathcal{DW}_{c,t+1} = P^C_{c,t}C_{c,t} + TB_{c,t} - W_{c,t}L_{c,t} - (1-\mu_c)G_{c,t}$$

Trade Balance:

$$TB_{c,t} = \left(\sum_{d\neq c}\sum_{i\in S}PC^d_{c,i,t}C^d_{c,i,t} + \sum_{d\neq c}\sum_{i\in S}\sum_{j\in S}PIC^{d,j}_{c,i,t}IC^{d,j}_{c,i,t}\right) - \left(\sum_{o\neq c}\sum_{i\in S}PC^c_{o,i,t}C^c_{o,i,t} + \sum_{o\neq c}\sum_{i\in S}\sum_{j\in S}PIC^{c,j}_{o,i,t}IC^{c,j}_{o,i,t}\right)$$

Law of Motion for Human Wealth Per Unit of Labor Endowment:

$$\mathcal{LW}_{c,t} - \mathcal{J}_{c,t}\chi_c\mathcal{LW}_{c,t+1} = W_{c,t}$$

Household Budget Constraint:

$$\Omega_{c,t}P^C_{c,t}C^{OLG}_{c,t} = \eta_c\left(\mu_c\bar{L}_{c,t}\mathcal{LW}_{c,t} + \mathcal{DW}_{c,t} + \frac{i_{c,t-1}}{\pi^C_{c,t}}NFA_{c,t-1}\right)$$

Hand-to-mouth Consumption:

$$P^C_{c,t}C^{HtM}_{c,t} = (1-\mu_c)(W_{c,t}L_{c,t} + G_{c,t})$$

Aggregate Consumption:

$$C_{c,t} = C^{OLG}_{c,t} + C^{HtM}_{c,t}$$

Net Foreign Asset:

$$NFA_{c,t} = \frac{i_{c,t-1}}{\pi^C_{c,t}}NFA_{c,t-1} + TB_{c,t}$$

UIP Condition:

$$\ln(i_{c,t}) = \ln(i_{US,t}) + \ln\left(\frac{\mathcal{E}_{c,t+1}}{\mathcal{E}_{c,t}}\right) + \ln\left(\frac{\pi^C_{c,t}}{\pi^C_{US,t}}\right)$$

7.1.2 Final Demand and Price

Household Demand Share:

$$b^d_{o,i,t} = \frac{b^d_{o,i}\xi^d_{o,i,t}}{\sum_{c\in C}\sum_{i\in S} b^d_{c,i}\xi^d_{c,i,t}}$$

Sectoral Demand Function:

$$C^d_{o,i,t} = b^d_{o,i,t}\left(\frac{PC^d_{o,i,t}}{PC^d_{i,t}}\right)^{-\gamma_i}\left(\frac{PC^d_{i,t}}{P^C_{d,t}}\right)^{-\gamma^c} C_{d,t}$$

Sectoral Price Function:

$$\left(PC^d_{i,t}\right)^{1-\gamma_i} = \sum_{o\in C}\frac{b^d_{o,i,t}}{\sum_{o'\in C} b^d_{o',i,t}}\left(PC^d_{o,i,t}\right)^{1-\gamma_i}$$

Aggregate Price Function:

$$\left(P^C_{d,t}\right)^{1-\gamma^c} = \sum_{i\in S}\left(\sum_{o\in C} b^d_{o,i,t}\right)\left(PC^d_{i,t}\right)^{1-\gamma^c}$$

7.2 Firms

7.2.1 Intermediate Demand and Price

Sectoral Demand Function:

$$IC_{o,i,t}^{d,j} = \omega_{o,i}^{d,j} \left(\frac{PIC_{o,i,t}^{d,j}}{PIC_{i,t}^{d,j}} \right)^{-\gamma_i} \left(\frac{PIC_{i,t}^{d,j}}{PIC_{d,j,t}} \right)^{-\gamma^x} IC_{d,j,t}$$

Sectoral Price Function:

$$\left(PIC_{i,t}^{d,j} \right)^{1-\gamma_i} = \sum_{o \in C} \frac{\omega_{o,i}^{d,j}}{\sum_{o' \in C} \omega_{o',i}^{d,j}} \left(PIC_{o,i,t}^{d,j} \right)^{1-\gamma_i}$$

Aggregate Price Function:

$$\left(PIC_{d,j,t} \right)^{1-\gamma^x} = \sum_{i \in S} \left(\sum_{o \in C} \omega_{o,i}^{d,j} \right) \left(PIC_{i,t}^{d,j} \right)^{1-\gamma^x}$$

7.2.2 Production

Labor Constraint:

$$\Lambda_{d,j,t}^{L} = \max \left(A_{d,j,t}^{L} PZ_{d,j,t} \left(\frac{\alpha_{d,j}^{L} Z_{d,j,t}}{A_{d,j,t}^{L} \bar{L}_{d,j,t}} \right)^{1/\gamma^Z} - W_{d,j,t}, 0 \right)$$

Demand for Labor:

$$L_{d,j,t} A_{d,j,t}^{L} = \alpha_{d,j}^{L} \left(\frac{W_{d,j,t} + \Lambda_{d,j,t}^{L}}{A_{d,j,t}^{L} PZ_{d,j,t}} \right)^{-\gamma^Z} Z_{d,j,t}$$

Demand for Capital:

$$\bar{K}_{d,j,t} = \alpha_{d,j}^{K} \left(\frac{PK_{d,j,t}}{PZ_{d,j,t}} \right)^{-\gamma^Z} Z_{d,j,t}$$

Demand for Intermediate Bundle:

$$IC_{d,j,t} = \alpha_{d,j}^{IC} \left(\frac{PIC_{d,j,t}}{PZ_{d,j,t}} \right)^{-\gamma^Z} Z_{d,j,t}$$

Marginal Cost:

$$\left(PZ_{d,j,t}\right)^{1-\gamma^z} = \alpha^L_{d,j}\left(\frac{W_{d,j,t}+\Lambda^L_{d,j,t}}{A^L_{d,j,t}}\right)^{1-\gamma^z} + \alpha^K_{d,j}\left(PK_{d,j,t}\right)^{1-\gamma^z} + \alpha^{IC}_{d,j}\left(PIC_{d,j,t}\right)^{1-\gamma^z}$$

7.3 Price Setting

Domestic Price:

$$PY_{c,i,t} = PC^c_{c,i,t} = PIC^{c,j}_{c,i,t}$$

Export Price (DCP):

$$PX_{c,i,t} = PC^d_{c,i,t} = PIC^{d,j}_{c,i,t} \quad \text{where} \quad c \neq d$$

Relative Price Evolution:

$$\frac{PY_{c,i,t}}{PY_{c,i,t-1}} = \frac{\pi^Y_{c,i,t}}{\pi^C_{c,t}}\frac{\mathcal{E}_{c,t-1}}{\mathcal{E}_{c,t}}$$

$$\frac{PX_{c,i,t}}{PX_{c,i,t-1}} = \frac{\pi^X_{c,i,t}}{\pi^C_{US,t}}$$

Sectoral Phillips curve:

$$\ln(\pi^Y_{c,i,t}) = \ln(\mathbb{E}_t[\pi^Y_{c,i,t+1}]) + \kappa^Y_{c,i}\cdot\left(\ln\left(PZ_{c,i,t}\right) - \ln\left(A^Y_{c,i,t}PY_{c,i,t}\right)\right)$$

$$\ln(\pi^X_{c,i,t}) = \ln(\mathbb{E}_t[\pi^X_{c,i,t+1}]) + \kappa^X_{c,i}\cdot\left(\ln\left(PZ_{c,i,t}\right) - \ln\left(A^X_{c,i,t}PX_{c,i,t}\right)\right)$$

Sectoral Inflation Expectations:

$$\mathbb{E}_t[\pi^Y_{c,i,t+1}] = \rho_{1,\pi^Y}\mathbb{E}_{t-1}[\pi^Y_{c,i,t}] + \rho_{2,\pi^Y}\pi^Y_{c,i,t-1} + (1-\rho_{1,\pi^Y}-\rho_{2,\pi^Y})\pi^Y_{c,i,t+1}$$

$$\mathbb{E}_t[\pi^X_{c,i,t+1}] = \rho_{1,\pi^X}\mathbb{E}_{t-1}[\pi^X_{c,i,t}] + \rho_{2,\pi^X}\pi^X_{c,i,t-1} + (1-\rho_{1,\pi^X}-\rho_{2,\pi^X})\pi^X_{c,i,t+1}$$

7.4 Market Clearing

Domestic Output:

$$Y_{c,i,t} = C^c_{c,i,t} + \sum_{j\in S} IC^{c,j}_{c,i,t}$$

Export:

$$X_{c,i,t} = \sum_{d\neq c}\left(C^d_{c,i,t} + \sum_{j\in S} IC^{d,j}_{c,i,t}\right)$$

Total Output:

$$Z_{c,i,t} = \frac{Y_{c,i,t}}{A^Y_{c,i,t}\mu^Y_{c,i}} + \frac{X_{c,i,t}}{A^X_{c,i,t}\mu^X_{c,i}}$$

Assets:

$$\sum_{c\in C} NFA_{c,t} = 0$$

Walras law:

$$P^C_{c,t} = 1/\mathcal{E}_{c,t}$$
$$P^C_{US,t} = 1$$

7.5 Monetary Policy

Nominal Interest Rate:

$$i_{c,t} = r_{c,t}\mathbb{E}_t[\pi^C_{c,t+1}]$$

Taylor Rule:

$$\ln(i_{c,t}) = \rho^i_c \ln(i_{c,t-1}) + (1-\rho^i_c)\left(\ln\left(\bar{\pi}_{c,t}r^*_c\right) + \alpha^i_c \ln\left(\frac{\pi^C_{c,t}}{\bar{\pi}_{c,t}}\right)\right) + \varepsilon^i_{c,t}$$

7.6 Imperfect Labor Mobility

Sector-specific Labor Supply:

$$L_{c,i,t} = s_{c,i}\left(\frac{W_{c,i,t}}{W_{c,t}}\right)^{\zeta^c} L_{c,t}$$

Aggregate Wage:

$$W^{1+\zeta^c}_{c,t} = \sum_{i\in N} W^{1+\zeta^c}_{c,i,t}$$

7.7 Shock Processes

Labor-augmenting Productivity:

$$\ln(A^L_{c,i,t}) = \rho_L \ln(A^L_{c,i,t-1}) + \ln(\varepsilon^L_{c,i,t})$$

Domestic Total Factor Productivity:

$$\ln(A^Y_{c,i,t}) = \rho_Y \ln(A^Y_{c,i,t-1}) + \ln(\varepsilon^Y_{c,i,t})$$

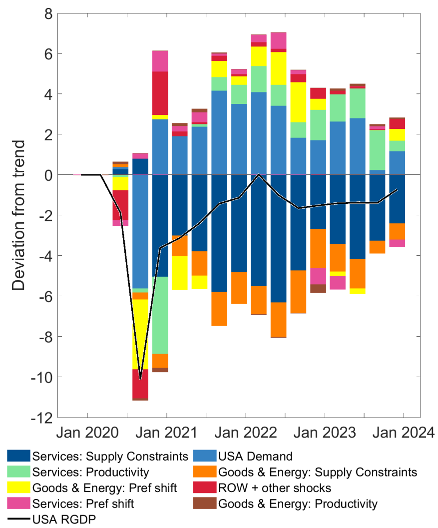
Export Total Factor Productivity:

$$\ln(A^X_{c,i,t}) = \rho_X \ln(A^X_{c,i,t-1}) + \ln(\varepsilon^X_{c,i,t})$$

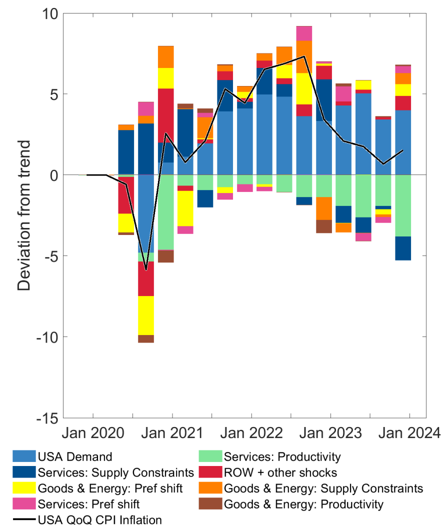
Household Demand Shifter:

$$\ln(\hat{\xi}^d_{o,i,t}) = \rho_\xi \ln(\hat{\xi}^d_{o,i,t-1}) + \ln(\varepsilon^\xi_{c,i,d,t})$$

Appendix B: Additional figures and tables



(a) US GDP



(b) US inflation

Figure 13: Contributions of shocks to US GDP and inflation

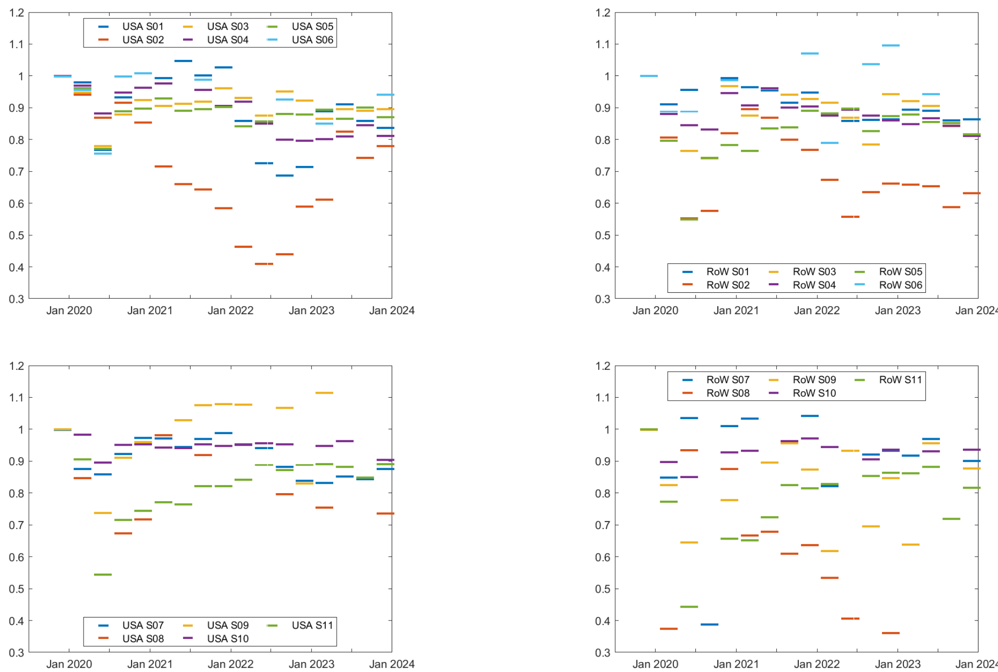


Figure 14: Estimated values of labor constraints in the data (1 = steady state labor)

Observations (48)	**Shocks (48)**
Value add by sector (22)	Sectoral demand shifter (20)
	Aggregate demand shock (2)
Value add deflator by sector, ex RoW Enrg (21)	Productivity or shadow price labor constraint (22)
USA energy import prices (1)	
Monetary policy rate (2)	Monetary policy shock (2)
Headline CPI (2)	Inflation measurement shock (2)

Table 5: Observation and shocks in data matching exercise (number of each)

Figure 15: Full production network for large closed economy calibration