Supply Chain Constraints and Inflation*

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Abstract

We develop a multisector, open economy, New Keynesian framework to evaluate how potentially binding capacity constraints, and shocks to them, shape inflation. We show that binding constraints for domestic and foreign producers shift domestic and import price Phillips Curves up, similar to reduced-form markup shocks. Further, data on prices and quantities together identify whether constraints bind due to increased demand or reductions in capacity. Applying the model to interpret recent US data, we find that binding constraints explain half of the increase in inflation during 2021-2022. In particular, tight capacity served to amplify the impact of loose monetary policy in 2021, fueling the inflation takeoff.

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In the later half of 2021 and into 2022, the United States experienced a burst of inflation as it emerged from the COVID-19 pandemic, led by a large increase in goods price inflation. Popular narratives suggest that strong consumer demand bumped up against constraints on the supply of goods, fueling inflation [The Economist (2021)]. Further, in their public statements, policymakers frequently blamed disruptions in both domestic and foreign segments of supply chains for restraining the supply of goods.[1] Despite the plausibility of this narrative, it has been difficult to evaluate the quantitative importance of supply chain constraints for inflation, not least because we lack models that capture their impact.

In this paper, we investigate how potentially binding capacity constraints for domestic and foreign producers shape inflation in a multisector, open economy, New Keynesian (NK) model with imported inputs and input-output linkages across sectors. Solving for the model's non-linear equilibrium dynamics via piecewise linear approximations, we develop a Bayesian maximum likelihood procedure to estimate key parameters and infer when constraints bind. We then apply the model to quantify how constraints in the supply chain, and potential shocks to them, have influenced recent data outcomes. We find that binding constraints account for about half (two percentage points) of the increase in inflation during 2021-2022. Interestingly, no single set of shocks can explain the inflation takeoff. Rather, shocks that tightened capacity set the stage for demand shocks – most importantly, monetary policy shocks – to trigger binding constraints and accelerate inflation in 2021. Relaxation of the constraints, in part due to monetary tightening, then also explains the rapid decline in goods price inflation in the latter half of 2022.

The framework we develop features occasionally binding constraints in two different places. The first is a constraint that applies at the level of individual foreign firms, whereby foreign producers are able to supply output at constant marginal costs up to a predetermined level, at which point production is quantity-constrained. Motivated by evidence on disruptions in markets for imported inputs, we devote particular attention to binding constraints on foreign input supply. The second constraint is a similar limit on production capacity for domestic firms, which impacts both downstream firms and consumers. These dual constraints allow us to separately capture the role of domestic versus foreign supply

[1] In International Monetary Fund (2021), Gita Gopinath writes: "Pandemic outbreaks in critical links of global supply chains have resulted in longer-than-expected supply disruptions, further feeding inflation in many countries." Smialek and Nelson (2021) characterize the views of the US Federal Reserve chair as follows: "[Jerome Powell] noted that while demand was strong in the United States, factory shutdowns and shipping problems were holding back supply, weighing on the economy and pushing inflation above the Fed's goal." See Lane (2022) for a discussion of views at the European Central Bank, and Goodman (2021) for a narrative of supply chain breakdowns.

chain disruptions on inflation.

Further, this framework features a distinction between supply-side versus demand-side explanations for binding constraints, with potentially important implications for policy. On the supply side, we assume the levels of the capacity constraints are exogenous and subject to stochastic shocks. This formulation captures the type of time-varying input shortages that occurred during the COVID period, both in the United States and abroad.[2] On the demand side, an increase in demand may also exhaust excess capacity and induce capacity constraints to bind in the model. This alternative mechanism is salient, because the abrupt recovery of demand in 2021 seemed to stress existing supply chain capacity.

Separating these two mechanisms – that binding constraints may be the result of strong demand, or disruptions to capacity – represents a key quantitative challenge. Breaking the challenge into two pieces, we must ascertain whether constraints bind, while also identifying why they bind.

To shed light on how binding constraints may be detected, we note that binding constraints impact pricing decisions. In the model, constraints are internalized by each firm as it sets its price, such that the firm's optimal markup differs depending on whether the constraint is binding. Assuming that both exports and imports are invoiced in US Dollars, and prices are subject to adjustment frictions, then domestic and import price inflation satisfy Phillips Curve type relationships. When the domestic constraint binds, we show that there is an additional term in sector-level, domestic price Phillips Curves that resembles a markup (equivalently, cost-push) shock. Similarly, there is a quasi-markup shock in the import price Phillips Curve when the import constraint binds. Thus, our framework provides a structural interpretation for reduced-form markup/cost-push shocks, based on binding constraints.

This "markup shock" interpretation of the role of binding constrains dovetails well with related work by Bernanke and Blanchard (2023), which uses an empirical model to argue that product market shocks (which raise prices given wages) explain a large share of recent US inflation. Importantly, our work investigates the structural origins of these empirically plausible shocks.[3] The markup shock interpretation also highlights the contrast

[2] One source of these shocks would be pandemic-related factory shutdowns, as occurred in the US, China, Vietnam and elsewhere. They also capture shortages of inputs due other disruptions to global supply relationships (e.g., cancellation of supply contracts early in the pandemic led to shortages of foreign-supplied semiconductors that curtailed US auto production). Other historical shocks, such as the 2011 Tōhoku earthquake/tsunami, are also plausibly thought of as capacity shocks.

[3] In a blog post, Del Negro et al. (2022) also argue that markup shocks are important, based on analyzing US data through the lens of a closed economy model without capacity constraints (the NYFed model).

between binding constraints and other competing mechanisms that work through marginal costs, such as factor reallocation frictions or labor shortages. Finally, the markup shock interpretation is also prima facie consistent with the fact that US profit margins increased as inflation took off in 2021, so binding constraints can also help rationalize concerns about "greedflation" in the U.S.

Turning to the second challenge, data on quantities and prices together serve to identify the reasons why constraints bind – i.e., to disentangle whether demand shocks or supply-side constraint shocks lead constraints to bind. While either a positive demand shock or negative constraint shock may trigger binding constraints and thus lead inflation to rise, these shocks have distinct implications for quantities. A demand shock pushes both inflation and output quantity up, while a negative constraint shock raises inflation whilst lowering output. Put differently, adverse constraint shocks lead to negative comovement between inflation and quantities (of output or imports). In contrast, there is positive comovement in these variables following a goods-biased demand shock. Implicitly, we use these quantitative patterns to identify shocks when applying the model to filter data.

To lay out the structure of the paper, we start by collecting stylized facts in Section 1, which both motivate elements of the framework and serve as inputs into quantification. Some are well known: headline consumer price inflation rose a lot, more for goods than services. And consumer expenditure shifted from services to goods, driving real goods expenditures above trend. On the import side, prices for imported industrial materials (inputs) rose rapidly in 2021, while prices for imported consumer goods were essentially flat. As for quantities, production of goods has recovered from its temporary pandemic downturn, but it has not increased in response to the surge in consumer demand for goods. Stagnant domestic production in the face of surging demand (and the corresponding lack of imported inputs) hints at potentially binding constraints, whether domestic or foreign in nature.

In Section 2, we develop a model to organize our interpretation of these facts, in which we study the impact of constraints for domestic goods producers and foreign goods input suppliers. In Section 3, we then apply the model to filter shocks from US national accounts data. To capture the rich data dynamics, we allow for a number of different shocks, including shocks to aggregate demand (time preference), demand for goods (preferences for goods versus services), monetary policy, capacity levels at home and abroad, sector-specific productivity, and foreign production costs. In an extended version of the model, we also allow for labor supply shocks (disutility of labor) and stochastic constraints on labor supply.

As a key intermediate step, we develop a Bayesian Maximum Likelihood estimation procedure to infer when constraints are binding and estimate structural parameters.[4] Our model presents several challenges for estimation. One challenge is that it features capacity shocks, and capacity is a latent variable that has no first order impact on other potentially observable equilibrium variables when constraints are slack. As a result, prior estimation routines (e.g., Guerrieri and Iacoviello (2017)) that use inversion filters to construct the likelihood function are not applicable in our context. Instead, our estimation procedure builds on prior work by Kulish, Morley and Robinson (2017), Kulish and Pagan (2017), and Jones, Kulish and Rees (2022), which treats the duration of binding constraints as a parameter to be estimated. In this, a second challenge is that the duration of binding constraints is an equilibrium outcome in our model, unlike prior applications of the duration-based estimation approach. Therefore, we adapt the maximum likelihood procedure to impose constraints on admissible duration parameter draws.[5]

Overall, our estimated model fits the data well; most importantly, it captures the evolution of inflation for goods, services, and imports during the post-2020 period, making it a useful laboratory for analysis. Further, smoothed values for multipliers on the constraints imply that constraints bind during most of 2021-2022, and how tight they are fluctuates over time.

With the model and estimates in hand, we evaluate the role of binding constraints in explaining the evolution of inflation through a sequence of counterfactual exercises. The first counterfactual allows all shocks to be active, but exogenously relaxes the capacity constraints in all periods. Comparing this counterfactual to the data, we find that binding constraints explain about half of the increase in inflation in 2021-2022, about two percentage points of the four percentage point increase in overall inflation. Further, easing of constraints in the latter half of 2022 helps explain recent declines in goods and import price inflation.

To evaluate the role of individual shocks, we run a series of counterfactuals in which

[4]The structural parameters we estimate are substitution elasticities between home and foreign inputs, coefficients in the monetary policy rule, the mean level of capacity, and the stochastic processes for shocks.

[5]In Kulish, Morley and Robinson (2017) and Jones, Kulish and Rees (2022), the binding constraint is the zero lower bound on interest rates, so the duration to be estimated reflects beliefs about how long the central bank will hold the interest rate at zero. Because this is a free policy variable, these papers treat durations as unconstrained in the estimation. In our application, the anticipated duration of binding capacity constraints is determined by the realized shock today and the state of the economy. Thus, we adapt the estimation procedure to this new environment.

we introduce shocks one at a time and in combination. We find that tight capacity, in part due to negative capacity shocks, set the stage for monetary policy shocks – looser policy than suggested by an extended Taylor rule – to ignite inflation in 2021. By implication, neither aggregate nor goods-biased consumer demand shocks play an important role in 2021, though they do account for inflation dynamics in 2020.[6] As monetary policy was tightened in 2022, demand shocks then play a larger role in accounting for sustained inflation.

Probing the robustness of these results, we show that these results are not spuriously driven by fluctuations in energy prices, by re-estimating and simulating the model using inflation data that excludes energy. We also investigate how our mechanism compares to a leading alternative – labor market shocks – in accounting for inflation. Specifically, we enrich the labor market to allow for wage rigidity, labor supply shocks, and (novel) potentially binding constraints on labor supply. While these additional features help us account for labor market dynamics (labor quantities and real wages) and the absence of disinflation in 2020, binding capacity constraints continue to play an important role in explaining inflation dynamics in 2021-2022.

In addition to work cited above, our paper is related to two distinct strands of work. First, our approach to modeling capacity constraints is related to models developed in Álvarez-Lois (2006) and Boehm and Pandalai-Nayar (2022), which feature heterogeneous firms that differ in terms of their exogenous capacity constraints on output.[7] As Boehm and Pandalai-Nayar emphasize, aggregating across heterogeneous firms yields smooth, convex industry supply curves. We instead employ a homogeneous firms framework, which allows for binding aggregate constraints that yield kinked, convex supply curves. One pedagogical advantage to our approach is that our model is easily comparable to standard log-linear New Keynesian models. A second is that we can use piecewise linear solution techniques to capture non-linearities, which in turn enables us to employ "fast" filtering and estimation routines, which exploit the Kalman Filter.[8]

Second, our paper is related to recent work on how global value chains transmitted shocks during the pandemic crisis.[9] Several contributions specifically study the role of

[6] Fiscal policy (changes in taxes and transfers) supported consumption during the pandemic. Thus, the consumption demand shocks that we recover from data partly capture the impact of these fiscal policies.

[7] Fagnart, Licandro and Portier (1999) studies the endogenous determination of capacity constraints on output, in a putty-clay model where firms pre-commit to "blueprint" technologies that constraint their ability to expand output.

[8] While one could use (exact or approximate higher order) non-linear solution techniques in our model, or alternative models with smooth convex supply curves, doing so would significantly raise the computational burden in taking the model to data.

[9] See Bonadio et al. (2021), Lafrogne-Joussier, Martin and Mejean (2023), Gourinchas et al. (2021), Cela-

supply chain disruptions in explaining price changes during the pandemic period. For the United States, Amiti, Heise and Wang (2021) and Santacreu and LaBelle (2022) find that output price changes across industries are related to their exposure to input price shocks and/or supply chain disruptions. Relatedly, Benigno et al. (2022) develop an index of global supply chain pressures, and they find it has predictive power for inflation in a local projections empirical framework. Focusing disruptions in the shipping sector (e.g., port blockages), Bai et al. (2023) and Finck and Tillmann (2023) also find that disruptions raise inflation in vector auto-regressive models. di Giovanni et al. (2022) examine the role of disruptions to input markets and trade linkages on inflation during the pandemic, using a sufficient statistics approach in a two period, multi-country, multi-sector input-output framework. Amiti et al. (2023) study how the combination of domestic labor market shocks and import supply chain disruptions contribute to inflation across sectors.

Relative to this literature, our paper is the first (to our knowledge) to analyze occasionally binding capacity constraints in the supply chain, within a complete DSGE model. In this, our paper extends the new literature on monetary policy in economies with production networks [e.g., La'o and Tahbaz-Salehi (2022)] to accommodate supply chain constraints. Thus, we believe it opens the door to further study of the implications of supply chain bottlenecks for the conduct of policy.

1 Collecting Facts

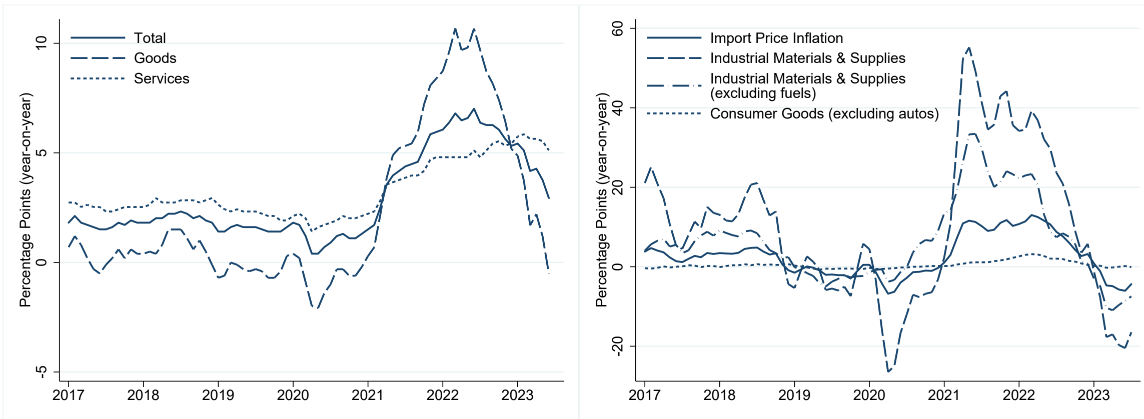
We begin by collecting several key facts about recent inflation, consumer expenditure, production, and imports that motivate various elements of the framework we construct. The first facts about consumer price inflation are well known: consumer price inflation rose substantially in 2021, led by inflation for goods. In Figure 1, we plot year-on-year growth in the price deflator for US personal consumption expenditure (PCE), as well as separate series for goods and services. The rise in headline inflation – from roughly 2 percent in 2021 to 6 percent as of early 2022 – is obviously startling. Importantly, this rise in inflation was led by goods price inflation, which rose from near zero to 10 percent in 2021 and then plummeted in the second half of 2022.

A second set of facts concerns import price inflation: prices for imported inputs rose

sun et al. (2022), and Alessandria et al. (2023). Additional contributions focus on the impacts of fiscal policy on inflation, including di Giovanni et al. (2023), de Soyres, Santacreu and Young (2023), and Bianchi, Faccini and Melosi (forthcoming).

Figure 1: Consumer and Import Price Inflation

(a) Consumer Price Inflation (b) Import Price Inflation by End Use



Note: Consumer price indexes are from the US Bureau of Economic Analysis, corresponding to the Personal Consumption Expenditure (PCE) price index and components (series identifiers: DPCERGM, DGDSRGM, and DSERRGM). Import price indexes are obtained from the US Bureau of Labor Statistics (series identifiers: IR for total imports, EIUIR1 for industrial materials, EUIIR1EXFUEL for industrial materials excluding fuels, and EIUIR4 for consumer goods).

dramatically in 2021, while price changes for imported consumer goods were modest. Plotting import price inflation by end use in Figure 1b, we see that inflation for imported industrial materials rose substantially in 2021, peaking at 50% year on year.[10] While the price of oil and derivative fuels doubled during this period, the price of industrial materials excluding fuels also rose over 30% in 2021. In contrast, inflation for imported consumer goods was subdued. This large difference between import price inflation for inputs versus consumer goods motivates our ensuing focus on disruptions impacting markets for imported inputs, rather than consumer goods.[11] In 2022, imported input price inflation dissipates rapidly, even excluding volatile fuels prices.

Tying the first and second set of facts together, goods production relies heavily on imported materials, relative production of services. Thus, the large increase in imported

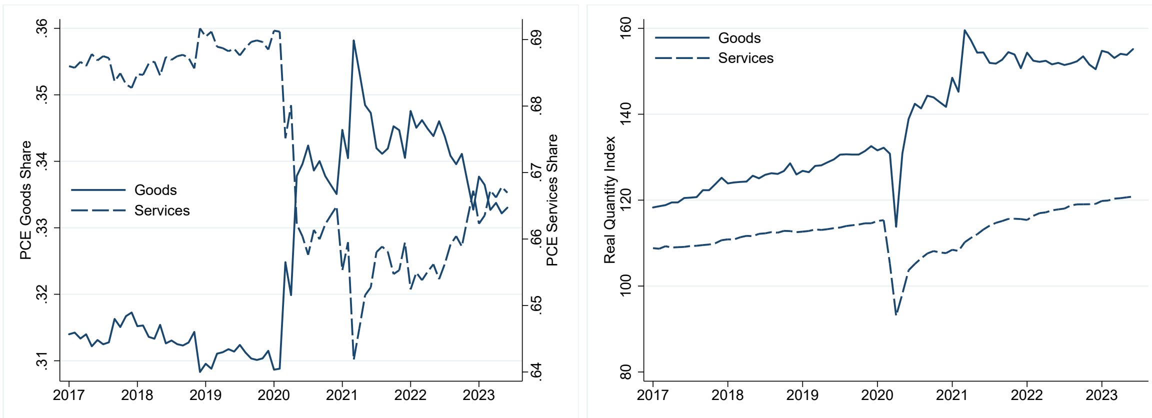
[10]This data is from the International Price Program of the Bureau of Labor Statistics. The source data consist primarily of free on board (FOB) prices (i.e., prices received by foreign producers at foreign dock). During 2021-2022, transport costs also increased dramatically, which then would be added to these FOB prices to arrive at CIF prices (inclusive of cost, insurance, and freight) paid by the importer. We abstract from these additional transport margins, in order to focus on changes in supply prices.

[11]We have omitted several categories of imports from the figure for clarity, including capital goods imports (IR2), imports of automotive vehicles, parts, and engines (IR3), and foods, feeds, and beverages (IR0). To verbally summarize, inflation for capital goods imports was generally low, similar to imported consumer goods. Inflation for the automotive sector was also very low, and inflation for foods tracked total import price inflation closely. Thus, the behavior of imported materials prices stands out.

Figure 2: Consumption by Sector

(a) Sector Shares in Expenditure

(b) Real Quantities Consumed by Sector



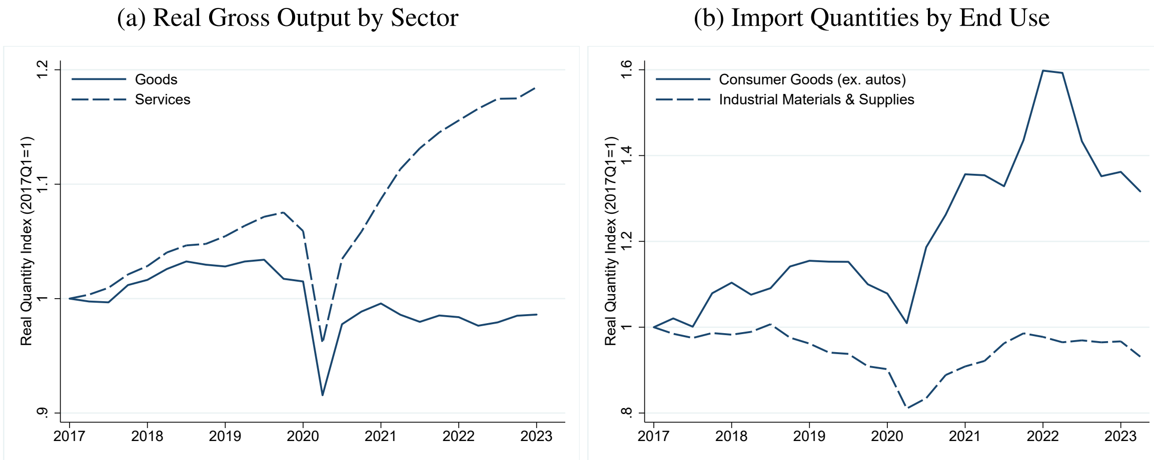
Note: Personal Consumption Expenditure shares and real quantity indexes by sector are obtained from the US Bureau of Economic Analysis (series identifiers: DPCERC, PCES, DGDSRA3, and DSERRA3).

materials prices may play a role in explaining the surge of inflation in the goods sector discussed above. Our model framework will include this potential mechanism, alongside other competing drivers of inflation.

The third set of facts relate to consumer expenditures. While consumer expenditure collapsed during the lockdown phase of the pandemic, it returned to trend by the end of 2021. At the same time, the sector composition of consumer expenditures changed dramatically, as consumers reallocated away from services toward goods. This is illustrated in terms of nominal expenditure shares in Figure 2a, and in terms of real quantities consumed for goods and services in Figure 2b. Further, note that the change in composition has proven remarkably persistent: real consumption of goods (correspondingly, the goods share in expenditure) remains high relative to pre-pandemic levels through 2023.

The final set of facts point to potential supply-side constraints. In Figure 3a, we plot real US gross output by broad sector. The key fact is that real production of goods (already stagnant before the pandemic) only just recovered and then trended slightly down in 2021-2022, which contrasts sharply with services output. Stagnant goods production in the face of high domestic demand for goods immediately suggests that US producers may have faced binding constraints. Correspondingly, consumer demand for goods was filled by imports: in Figure 3b, imported quantities for consumer goods (excluding autos) surge. In contrast, imports of industrial materials are flat, recovering only to its 2017 levels by the end of 2021 and plateauing there.

Figure 3: Production and Import Quantities



Note: Real gross output is constructed using data from the US Bureau of Economic Analysis (GDP by Industry, Table 17). Real quantity indexes for imports are obtained from the US Bureau of Economic Analysis (series identifiers: IB0000043 and B652RA3).

Deficient US goods production and stagnant imports of industrial materials are naturally connected, though the direction of causality is not immediately clear. Limited supplies of imported materials may have constrained domestic production, or distinct binding constraints of domestic origin may have curtailed production and indirectly depressed demand for imported inputs. Quantity and price data together will distinguish between binding domestic versus foreign supply constraints in our model. With this background in mind, we turn to details of the model.

2 Model

This section presents a small open economy model with many sectors, $s \in \{1, \ldots, S\}$, which are are connected through input-output linkages. Within each sector, there is a continuum of monopolistically competitive firms, who set prices subject to Rotemberg-type adjustment costs. As in Gopinath et al. (2020), we assume that both exports and imports for the Home country are denominated in Home currency (i.e., US Dollars). Motivated by the data, we also allow import prices to differ for final goods and inputs.

The principal new features of the model are the output capacity constraints, for foreign and domestic firms. In writing down the model here, we allow these constraints to be potentially binding in any domestic sector, and we distinguish constraints that apply to foreign final versus input producing firms. Looking forward, we then restrict attention to particular constraints in quantitative analysis of the model for reasons of both tractability and empirical relevance. We also assume that the constraints are exogenously determined and (potentially) time varying, subject to stochastic shocks. This sets up a framework in which constraints may bind either due to negative shocks to capacity, or because other shocks lead firms to exhaust their excess capacity.

2.1 Consumers

There is a representative Home consumer, with preferences over labor supply L_t and consumption of sector composite goods $\{C_t(s)\}_{s\in S}$ represented by:

$$U\left(\{C_t, L_t\}_{t=0}^{\infty}\right) = \mathbf{E}_0 \sum_{t=0}^{\infty} \beta^t \Theta_t \left[\frac{C_t^{1-\rho}}{1-\rho} - \frac{L_t^{1+\psi}}{1+\psi}\right] \tag{1}$$
$$\text{with} \quad C_t = \left(\sum_s \zeta_t(s)^{1/\vartheta} C_t(s)^{(\vartheta-1)/\vartheta}\right)^{\vartheta/(\vartheta-1)},$$

where $C_t(s) = \left(\sum_s \gamma(s)^{1/\varepsilon(s)} C_{Ht}(s)^{(\varepsilon(s)-1)/\varepsilon(s)} + (1-\gamma(s))^{1/\varepsilon(s)} C_{Ft}(s)^{(\varepsilon(s)-1)/\varepsilon(s)}\right)^{\varepsilon(s)/(\varepsilon(s)-1)}$ is consumption of a sector-composite good, which is comprised of domestic ($C_{Ht}(s)$) and foreign ($C_{Ft}(s)$) sub-composite goods. The parameter $\beta < 1$ is the usual time discount rate, $\rho \geq 0$ controls intertemporal substitution, $\psi > 0$ governs the elasticity of labor supply, $\vartheta \geq 0$ is the elasticity of substitution across sectors, and $\varepsilon(s) \geq 0$ is the elasticity of substitution between home and foreign consumption composites.

The parameter $\zeta_t(s)$ is a time-varying parameter that controls tastes for goods from sector s, and we require that $\sum_s \zeta_t(s) = 1$ throughout, so $\zeta_t(s)$ should be interpreted as a relative sectoral demand shock. The parameter Θ_t is an aggregate preference (discount rate) shock at date t. Though our setting does not directly consider fiscal policy shocks, fiscal shocks would be subsumed in these discount rate shocks when Ricardian equivalence fails, as in recent models by Gabaix (2020) and Angeletos, Lian and Wolf (2023). Therefore, our framework parsimoniously captures the combined effect of fiscal policy and other drivers of discount rates in this single exogenous variable.

Financial markets are complete, and the agent's budget constraint is given by:

$$P_t C_t + \mathbf{E}_t \left[S_{t,t+1} B_{t+1}\right] \leq B_t + W_t L_t, \tag{2}$$

where $P_t C_t = \sum_s P_t(s) C_t(s)$, with P_t being the price for one unit of the composite consumption good and and $P_t(s)$ being the price of the sector composite good. B_t denotes the portfolio of Arrow-Debreu securities that pay off in domestic currency, and $S_{t,t+1}$ is the Home consumer's stochastic discount factor (defined below). Further, sectoral consumption expenditure is $P_t(s)C_t(s) = P_{Ht}(s)C_{Ht}(s) + P_{Ft}(s)C_{Ft}(s)$, where $P_{Ht}(s)$ and $P_{Ft}(s)$ are the prices of the home and foreign consumption composites.

Given prices $\{P_t, P_t(s), P_{Ht}(s), P_{Ft}(s), S_{t,t+1}, W_t\}$ and initial asset holdings B_0, the consumer chooses consumption, labor supply, and asset holdings to maximize Equation 1 subject to Equation 2 and the standard transversality condition. Optimal consumption and labor choices satisfy:

$$C_t^{-\rho}\left(\frac{W_t}{P_t}\right) = L_t^{\psi} \tag{3}$$

$$C_t(s) = \zeta_t(s)\left(\frac{P_t(s)}{P_t}\right)^{-\vartheta} C_t \tag{4}$$

$$C_{Ht}(s) = \gamma(s)\left(\frac{P_{Ht}(s)}{P_t(s)}\right)^{-\varepsilon(s)} C_t(s) \tag{5}$$

$$C_{Ft}(s) = (1-\gamma(s))\left(\frac{P_{Ft}(s)}{P_t(s)}\right)^{-\varepsilon(s)} C_t(s) \tag{6}$$

$$1 = \mathbf{E}_t\left[S_{t,t+1}\frac{P_t}{P_{t+1}}(1+i_t)\right] \tag{7}$$

where $S_{t,t+1} = \beta\frac{\Theta_{t+1}}{\Theta_t}\left(\frac{C_{t+1}}{C_t}\right)^{-\rho}$ is the stochastic discount factor, and i_t is a one period, risk free nominal interest rate. The price indexes are given by $P_t = \left(\sum_s \zeta_t(s) P_t(s)^{1-\vartheta}\right)^{1/(1-\vartheta)}$ and $P_t(s) = \left(\gamma(s)\left(P_{Ht}(s)\right)^{1-\varepsilon(s)} + (1-\gamma(s))\left(P_{Ft}(s)\right)^{1-\varepsilon(s)}\right)^{1/(1-\varepsilon(s))}$.

2.2 Domestic Producers

There is a continuum of firms within each sector in Home, each of which produces a differentiated good (indexed by ω). In addition, there exist competitive intermediary firms that aggregate these varieties into composite goods, which are then consumed, used as inputs, and exported. We start by describing these intermediaries, and then turn to individual firms.

2.2.1 Composite Domestic Good

Each competitive intermediary firm purchases output from domestic producers to form a domestic composite, using the production function $Y_t(s) = \left(\int_0^1 Y_t(s,\omega)^{(\varepsilon-1)/\varepsilon} d\omega\right)^{\varepsilon/(\varepsilon-1)}$, where $Y_t(s,\omega)$ is the amount of output purchased from firm ω in sector s, and $\varepsilon > 1$ is the elasticity of substitution. Given prices $P_t(s,\omega)$ for individual domestic varieties, cost minimization yields demands $Y_t(s,\omega) = \left(\frac{P_t(s,\omega)}{P_{Ht}(s)}\right)^{-\varepsilon} Y_t(s)$, where the price of the sector composite good is $P_{Ht}(s) = \left[\int_0^1 P_t(s,\omega)^{1-\varepsilon} d\omega\right]^{1/(1-\varepsilon)}$.

2.2.2 Domestic Firms

Each domestic producer in sector s is able to supply output up to a pre-determined capacity of $\bar{Y}_t(s)$, which we refer to as a firm-level capacity constraint. We assume this capacity level is exogenously determined and equal across firms within each sector.

The production function for domestic variety ω in sector s is:

$$Y_t(s,\omega) = Z_t(s,\omega)A(s)\left(L_t(s,\omega)\right)^{1-\alpha(s)}\left(M_t(s,\omega)\right)^{\alpha(s)} \tag{8}$$

$$\text{with} \quad M_t(s,\omega) = \left(\sum_{s'}\left(\alpha(s',s)/\alpha(s)\right)^{1/\kappa} M_t(s',s,\omega)^{(\kappa-1)/\kappa}\right)^{\kappa/(\kappa-1)},$$

$$M_t(s',s,\omega) = \left[\xi(s',s)^{\frac{1}{\eta(s')}} M_{Ht}(s',s,\omega)^{\frac{\eta(s')-1}{\eta(s')}} + (1-\xi(s',s))^{\frac{1}{\eta(s')}} M_{Ft}(s',s,\omega)^{\frac{\eta(s')-1}{\eta(s')}}\right]^{\frac{\eta(s')}{\eta(s')-1}},$$

where $L_t(s,\omega)$ is the quantity of labor used by the firm, $M_t(s,\omega)$ is the firm's use of a composite input, $Z_t(\omega)$ is productivity, and $A(s) = \alpha(s)^{-\alpha(s)}(1-\alpha(s))^{-(1-\alpha(s))}$ is a normalization constant. The composite input combines inputs purchased from upstream sectors $M_t(s',s,\omega)$, with elasticity of substitution $\kappa \geq 0$. And those upstream inputs are themselves a CES composite of Home ($M_{Ht}(s',s,\omega)$) and Foreign ($M_{Ft}(s',s,\omega)$) composite inputs. The parameters $\eta(s) \geq 0$ are elasticities of substitution across country sources for inputs (conventionally termed the Armington elasticity), while $\xi(s',s) \in (0,1)$ controls relative demand for home inputs conditional on prices.

Producers set prices in domestic currency under monopolistic competition, and they select the input mix to satisfy the implied demand. These two problems can be analyzed separately. The firm chooses $\left\{L_t(s,\omega), M_t(s,\omega), M_t(s',s,\omega), M_{Ht}(s,\omega), M_{Ft}(s',s,\omega)\right\}$ to minimize the cost of producing $Y_t(s,\omega)$, which is $W_t L_t(s,\omega) + P_{Mt}(s)M_t(s,\omega)$, with $P_{Mt}(s)M_t(s,\omega) =$

$\sum_{s'} P_t(s',s)M_t(s',s,\omega)$ and $P_t(s',s)M_t(s',s,\omega) = P_t(s')M_{Ht}(s',s,\omega) + P_{Ft}(s')M_{Ft}(s',s,\omega)$, where $P_{Ft}(s')$ is the (domestic currency) price of the foreign composite input from sector s' . The first order conditions to this problem can be written as follows:

$$W_t L_t(s,\omega) = \alpha(s) MC_t(s,\omega) Y_t(\omega) \tag{9}$$

$$P_{Mt}(s) M_t(s,\omega) = (1-\alpha(s)) MC_t(s,\omega) Y_t(s,\omega) \tag{10}$$

$$M_t(s',s,\omega) = \frac{\alpha(s',s)}{\alpha(s)} \left(\frac{P_t(s',s)/P_t}{P_{Mt}(s)/P_t} \right)^{-\kappa} M_t(s,\omega) \tag{11}$$

$$M_{Ht}(s',s,\omega) = \xi(s',s) \left(\frac{P_{Ht}(s')/P_t}{P_t(s',s)/P_t} \right)^{-\eta(s')} M_t(s',s,\omega) \tag{12}$$

$$M_{Ft}(s',s,\omega) = (1-\xi(s',s)) \left(\frac{P_{Ft}(s')/P_t}{P_t(s',s)/P_t} \right)^{-\eta(s')} M_t(s',s,\omega), \tag{13}$$

where $P_{Mt}(s) = \left(\sum_{s'} \left(\frac{\alpha(s',s)}{\alpha(s)} \right) P_t(s',s)^{1-\kappa} \right)^{1/(1-\kappa)}$ is the price of the composite input, and the firm's marginal cost is $MC_t(s,\omega) = (Z_t(s,\omega))^{-1} W_t^{1-\alpha(s)} (P_{Mt}(s))^{\alpha(s)}$.

Given this solution for marginal costs, the domestic firm chooses a sequence of prices to maximize profits, with knowledge of the demand curve for its output, and subject to quadratic adjustment cost for prices [Rotemberg (1982)]. The pricing problem is:

$$\max_{\{P_t(s,\omega)\}} \mathbf{E}_0 \sum_{t=0}^{\infty} \frac{S_{0,t}}{P_t} \left[P_t(s,\omega) Y_t(s,\omega) - MC_t(s,\omega) Y_t(s,\omega) - \frac{\phi(s)}{2} \left(\frac{P_t(s,\omega)}{P_{t-1}(s,\omega)} - 1 \right)^2 P_{Ht}(s) Y_t(s) \right]$$
$$\text{s.t.} \quad Y_t(s,\omega) \leq \bar{Y}_t(s),$$

where the discount rate for profits reflects the domestic agent's stochastic discounting.[12] The final term in the first line captures the adjustment costs, where $\phi(s)$ governs the degree of price rigidity. Note also that the firm accounts for the potentially binding constraint in its pricing decisions. Denoting the Lagrange multiplier attached to the capacity constraint $\mu_t(s,\omega)$, optimal prices satisfy:

$$\begin{aligned} 0 = 1 - \varepsilon \left(1 - \frac{MC_t(s,\omega) + \mu_t(s,\omega)}{P_t(s,\omega)} \right) - \phi(s) \left(\frac{P_t(s,\omega)}{P_{t-1}(s,\omega)} - 1 \right) \frac{P_{Ht}(s) Y_t(s)}{P_{t-1}(s,\omega) Y_t(s,\omega)} \\ + E_t \left[S_{t,t+1} \frac{P_t}{P_{t+1}} \phi(s) \left(\frac{P_{t+1}(s,\omega)}{P_t(s,\omega)} - 1 \right) \frac{P_{Ht+1}(s) Y_{t+1}(s)}{P_t(s,\omega) Y_t(s,\omega)} \frac{P_{t+1}(s,\omega)}{P_t(s,\omega)} \right]. \end{aligned} \tag{14}$$

[12] Of course, with complete markets, it is immaterial whether domestic or foreign agents own the firm.

The corresponding complementary slackness condition is:

$$\mu_t(s,\omega)\left[Y_t(s,\omega) - \bar{Y}_t(s)\right] = 0. \tag{15}$$

And we require $\mu_t(s,\omega) \geq 0$ and the constraint to hold in equilibrium ($Y_t(s,\omega) \leq \bar{Y}_t(s)$) as usual. When the constraint binds, then $\mu_t(s,\omega) > 0$. In Equation 14, we see this is equivalent to an increase in the marginal cost of the firm, which drives up the optimal price. When the capacity constraint is slack, such that $\mu_t(s,\omega) = 0$, then Equation 14 collapses to a standard intertemporal pricing equation.

2.3 Foreign Producers

Turning to foreign producers, we again start with aggregation of varieties by competitive intermediaries, and then we present the pricing problem for foreign firms. Here we distinguish between producers of foreign consumption goods versus inputs, which allows us to to analyze data on import prices by end use.

2.3.1 Composite Foreign Goods

For each end use $u \in \{C, M\}$, where C and M denote consumption and intermediate use respectively, there is a unit continuum of foreign firms that produce foreign inputs, indexed by ϖ. A competitive intermediary firm aggregates output produced by each foreign firm, and bundles it into the foreign composite according to the production function: $Y^*_{ut}(s) = \left(\int_0^1 Y^*_{ut}(s,\varpi)^{(\varepsilon-1)/\varepsilon} d\varpi\right)^{\varepsilon/(\varepsilon-1)}$. Demand for each variety then takes takes the standard CES form: $Y^*_{ut}(s,\varpi) = \left(\frac{P_{uFt}(s,\varpi)}{P_{uFt}(s)}\right)^{-\varepsilon} Y^*_{ut}(s)$, where $P_{uFt}(s,\varpi)$ is the price of variety ϖ and $P_{uFt}(s) = \left(\int_0^1 P_{uFt}(s,\varpi)^{1-\varepsilon} d\varpi\right)^{1/(1-\varepsilon)}$ is the price of the foreign composite, both denominated in Home currency.

2.3.2 Foreign Firms

Each foreign firm (in sector s, producing for end use u) is able to supply output up to a pre-determined capacity of $\bar{Y}^*_{ut}(s)$, and this capacity is exogenous and equal across firms. Foreign marginal costs are given by $MC^*(s,\varpi)$, and we assume this cost is exogenous (as in a small open economy), denominated in foreign currency, and equal across end uses.

Each firm chooses a sequence for the price of its variety in Home currency $\{P_{uFt}(s,\varpi)\}$, subject to price adjustment frictions, to solve:

$$\max_{\{P_{Ft}(s,\varpi)\}} \mathbf{E}_0 \sum_{t=0}^{\infty} \frac{S^*_{0,t}}{P^*_t E_t} \left[P_{uFt}(s,\varpi) Y^*_{ut}(s,\varpi) - E_t MC^*_t(s) Y^*_{ut}(s,\varpi) - \frac{\phi(s)}{2} \left(\frac{P_{uFt}(s,\varpi)}{P_{uFt-1}(s,\varpi)} - 1 \right)^2 P_{uFt}(s) Y^*_{ut}(s) \right]$$

$$\text{s.t.} \quad Y^*_{ut}(s,\varpi) \le \bar{Y}^*_{ut}(s),$$

with knowledge of the demand curve for its output specified above. Here $S^*_{0,t} = \beta^t \left(\frac{C^*_t}{C^*_0} \right)^{-\rho}$ is the foreign stochastic discount factor (with C^*_tdenoting foreign consumption), P^*_t is the foreign price level (in foreign currency), and E_t is a the nominal exchange rate (units of home currency to buy one unit of foreign currency).

Denoting the Lagrange multiplier attached to the capacity constraint $\mu^*_{ut}(s,\varpi)$, then the first order condition is:

$$\begin{aligned} &1 - \varepsilon \left(1 - \frac{E_t \left(MC^*_t(s,\varpi) + \mu^*_{ut}(s,\varpi) \right)}{P_{uFt}(s,\varpi)} \right) - \phi(s) \left(\frac{P_{uFt}(s,\varpi)}{P_{uFt-1}(s,\varpi)} - 1 \right) \frac{P_{uFt}(s) Y^*_{ut}(s)}{P_{uFt-1}(s,\varpi) Y^*_{ut}(s,\varpi)} \\ &+ \mathbf{E}_t \left[S^*_{t,t+1} \left(\frac{E_t P^*_t}{E_{t+1} P^*_{t+1}} \right) \phi(s) \left(\frac{P_{uFt+1}(s,\varpi)}{P_{uFt}(s,\varpi)} - 1 \right) \frac{P_{uFt+1}(s) Y^*_{ut+1}(s)}{P_{uFt}(s,\varpi) Y^*_{ut}(s,\varpi)} \frac{P_{uFt+1}(s,\varpi)}{P_{uFt}(s,\varpi)} \right] = 0. \quad (16) \end{aligned}$$

The complementary slackness condition is:

$$\mu^*_{ut}(s,\varpi) \left[Y^*_{ut}(\varpi) - \bar{Y}^*_{ut} \right] = 0. \quad (17)$$

In equilibrium, $\mu^*_{ut}(\varpi) \ge 0$ and $Y^*_{ut}(\varpi) \le \bar{Y}^*_{ut}$.

2.4 Closing the Model

We assume that demand for exports of the home composite good takes the CES form:

$$X_t(s) = \left(\frac{P_{Ht}(s)}{P_t Q_t} \right)^{-\sigma(s)} X^*_t(s), \quad (18)$$

where $Q_t \equiv \frac{E_t P^*_t}{P_t}$ is the real exchange rate and $X^*_t(s)$ is an exogenous export demand factor.

The market clearing condition for the home composite good is:

$$Y_t(s) = C_{Ht}(s) + \sum_{s'=1}^{S} \int_0^1 M_{Ht}(s,s',\omega) d\omega + X_t(s) + \int_0^1 \left[\frac{\phi(s)}{2} \left(\frac{P_t(s,\omega)}{P_{t-1}(s,\omega)} - 1 \right)^2 Y_t(s) \right] d\omega, \quad (19)$$

where the composite good is sold to consumers and domestic producers, exported, and used to cover price adjustment costs. For the foreign composite goods, we impose similar market clearing conditions:

$$Y^*_{Ct}(s) = C_{Ft}(s) + \int_0^1 \left[\frac{\phi(s)}{2} \left(\frac{P_{CFt}(s,\varpi)}{P_{CFt-1}(s,\varpi)} - 1 \right)^2 Y^*_{Ct}(s) \right] d\varpi \tag{20}$$

$$Y^*_{Mt}(s) = \sum_{s'} M_{Ft}(s,s') + \int_0^1 \left[\frac{\phi(s)}{2} \left(\frac{P_{MFt}(s,\varpi)}{P_{MFt-1}(s,\varpi)} - 1 \right)^2 Y^*_{Mt}(s) \right] d\varpi. \tag{21}$$

Labor market clearing is given by:

$$L_t = \sum_{s=1}^{S} L_t(s) \quad \text{with} \quad L_t(s) = \int_0^1 L_t(s,\omega) d\omega. \tag{22}$$

Trade in Arrow-Debreu securities implies that Home and Foreign consumers share risk, such that:

$$\Theta_t \left(\frac{C_t}{C_t^*} \right)^{-\rho} Q_t = \Xi, \tag{23}$$

where Ξ is a constant.

Turning to monetary policy, we specify an extended inflation-targeting rule for interest rates. Since we allow for sector-specific preference shocks, we now distinguish measured price inflation from changes in the welfare-theoretic price index. We define an auxiliary price index under the assumption that preferences are constant over time: $\bar{P}_t = \left(\sum_s \zeta_0(s) \left(P_t(s)\right)^{1-\vartheta} \right)^{1/(1-\vartheta)}$, where $\zeta_0(s)$ are steady-state CES weights. Then $\bar{\Pi}_t = \bar{P}_t / \bar{P}_{t-1}$ is the ratio of measured prices across periods, and the approximate inflation rate is given by $\bar{\pi}_t = \sum_s \left(\frac{P_0(s)C_0(s)}{P_0 C_0} \right) [\ln P_t(s) - \ln P_{t-1}(s)]$.[13] We write the monetary policy rule in terms of measured inflation:

$$1 + i_t = (1 + i_{t-1})^{\rho_i} \bar{\Pi}_t^{\omega(1-\rho_i)} \left(Y_t / Y_0 \right)^{(1-\rho_i)\rho_y} \Psi_t \tag{24}$$

where $Y_t = \sum_s P_0(s) Y_t(s)$ is aggregate real gross output and Ψ_t is a monetary policy shock. The parameters ω and ρ_y determine how aggressively the central bank responds to infla-

[13] The following relationship holds between the ratios of measured and welfare-based price indexes across periods: $\bar{\Pi}_t = \frac{\bar{P}_t/P_t}{\bar{P}_{t-1}/P_{t-1}} \Pi_t$, where $\frac{\bar{P}_t}{P_t} = \left(\sum_s \zeta_0(s) \left(\frac{P_t(s)}{P_t} \right)^{1-\vartheta} \right)^{1/(1-\vartheta)}$ and the ratio of aggregate prices across periods is $\Pi_t \equiv \frac{P_t}{P_{t-1}}$. We include these among auxiliary price definitions in the model equilibrium.

tion and the output gap (defined as the deviation of output from steady state), while the parameter ρ_i controls the degree of interest rate inertia.

2.5 Equilibrium with Symmetric Firms

We focus on an equilibrium with symmetric producers within each sector and country. Further, we write all prices relative to the domestic price level, and we define $\Pi_t \equiv \frac{P_t}{P_{t-1}}$. Given parameters and exogenous variables, an equilibrium is a sequence of aggregate quantities $\{C_t, L_t\}$, sector-level quantities $\left\{C_t(s), C_{Ht}(s), C_{Ft}(s), L_t(s), Y_t(s), M_t(s), X_t(s), Y^*_{Ct}(s), Y^*_{Mt}(s)\right\}_s$, input use $\{\{M_t(s',s), M_{Ht}(s',s), M_{Ft}(s',s)\}_{s'}\}_s$, aggregate prices $\left\{W_t/P_t, i_t, Q_t, \Pi_t, \bar{\Pi}_t, \bar{P}_t/P_t\right\}$, sector-level relative prices $\{P_t(s)/P_t, MC_t(s)/P_t, P_{Mt}(s)/P_t, P_{Ht}(s)/P_t, P_{CFt}(s)/P_t, P_{MFt}(s)/P_t\}_s$, sector-level inflation $\{\Pi_t(s), \Pi_{CFt}(s), \Pi_{MFt}(s)\}_s$, input prices $\{\{P_t(s',s)/P_t\}_{s'}\}_s$, and (normalized) multipliers $\left\{\mu_t(s)/P_t, \mu^*_{Ct}(s)/P^*_t, \mu^*_{Mt}(s)/P^*_t\right\}_s$ that satisfy the equilibrium conditions in Table 1. This system is $8+21S+4S^2$ equations in the same number of unknowns.

Table 1: Equilibrium Conditions

Labor Supply	$C_t^{-\rho}\frac{W_t}{P_t} = \chi L_t^{\psi}$
Consumption Allocation	$C_t(s) = \zeta_t(s)\left(\frac{P_t(s)}{P_t}\right)^{-\vartheta} C_t$
	$C_{Ht}(s) = \gamma(s)\left(\frac{P_{Ht}(s)/P_t}{P_t(s)/P_t}\right)^{-\varepsilon(s)} C_t(s)$
	$C_{Ft}(s) = (1-\gamma(s))\left(\frac{P_{CFt}(s)/P_t}{P_t(s)/P_t}\right)^{-\varepsilon(s)} C_t(s)$
Euler Equation	$1 = E_t\left[\beta\frac{\Theta_{t+1}}{\Theta_t}\left(\frac{C_{t+1}}{C_t}\right)^{-\rho}\left(\frac{1+i_t}{\Pi_{t+1}}\right)\right]$
Consumer Prices	$1 = \left(\sum_s \zeta_t(s)\left(\frac{P_t(s)}{P_t}\right)^{1-\vartheta}\right)^{1/(1-\vartheta)}$
	$\frac{P_t(s)}{P_t} = \left(\gamma(s)\left(\frac{P_{Ht}(s)}{P_t}\right)^{1-\varepsilon(s)} + (1-\gamma(s))\left(\frac{P_{CFt}(s)}{P_t}\right)^{1-\varepsilon(s)}\right)^{1/(1-\varepsilon(s))}$
Labor Demand	$\frac{W_t}{P_t}L_t(s) = (1-\alpha(s))\frac{MC_t(s)}{P_t}Y_t(s)$
Input Demand	$\frac{P_{Mt}(s)}{P_t}M_t(s) = \alpha(s)\frac{MC_t(s)}{P_t}Y_t(s)$
	$M_t(s',s) = \frac{\alpha(s',s)}{\alpha(s)}\left(\frac{P_t(s',s)/P_t}{P_{Mt}(s)/P_t}\right)^{-\kappa} M_t(s)$
	$M_{Ht}(s',s) = \xi(s',s)\left(\frac{P_{Ht}(s')/P_t}{P_t(s',s)/P_t}\right)^{-\eta(s')} M_t(s',s)$
	$M_{Ft}(s',s) = (1-\xi(s',s))\left(\frac{P_{MFt}(s')/P_t}{P_t(s',s)/P_t}\right)^{-\eta(s')} M_t(s',s)$
Marginal Cost	$\frac{MC_t(s)}{P_t} = \frac{1}{Z_t(s)}\left(\frac{W_t}{P_t}\right)^{1-\alpha(s)}\left(\frac{P_{Mt}(s)}{P_t}\right)^{\alpha(s)}$

Table 1: Equilibrium Conditions

Input Prices	$\frac{P_{Mt}(s)}{P_t} = \left(\sum_{s'} \left(\frac{\alpha(s',s)}{\alpha(s)}\right)\left(\frac{P_t(s',s)}{P_t}\right)^{1-\kappa}\right)^{1/(1-\kappa)}$
	$\frac{P_t(s',s)}{P_t} = \left[\xi(s',s)\left(\frac{P_{Ht}(s')}{P_t}\right)^{1-\eta(s')} + (1-\xi(s',s))\left(\frac{P_{MFt}(s')}{P_t}\right)^{1-\eta(s')}\right]^{1/(1-\eta(s'))}$
Domestic Pricing	$0 = 1-\varepsilon\left(1-\frac{MC_t(s)/P_t+\mu_t(s)/P_t}{P_{Ht}(s)/P_t}\right) - \phi(s)(\Pi_{Ht}(s)-1)\Pi_{Ht}(s)$
	$+E_t\left[\beta\frac{\Theta_{t+1}}{\Theta_t}\left(\frac{C_{t+1}}{C_t}\right)^{-\rho}\frac{\phi(s)}{\Pi_{t+1}}(\Pi_{Ht+1}(s)-1)\Pi_{Ht+1}(s)^2\frac{Y_{t+1}(s)}{Y_t(s)}\right]$
Consumption Import Pricing	$0 = 1-\varepsilon\left(1-\frac{Q_t}{P_{CFt}(s)/P_t}\frac{MC^*_t(s)+\mu^*_{Ct}(s)}{P^*_t}\right) - \phi(s)(\Pi_{CFt}(s)-1)\Pi_{CFt}(s)$
	$+E_t\left[\beta\left(\frac{C^*_{t+1}}{C^*_t}\right)^{-\rho}\frac{Q_t}{Q_{t+1}}\frac{\phi(s)}{\Pi_{t+1}}(\Pi_{CFt+1}(s)-1)\Pi_{CFt+1}(s)^2\frac{Y^*_{Ct+1}(s)}{Y^*_{Ct}(s)}\right]$
Input Import Pricing	$0 = 1-\varepsilon\left(1-\frac{Q_t}{P_{MFt}(s)/P_t}\frac{MC^*_t(s)+\mu^*_{Mt}(s)}{P^*_t}\right) - \phi(s)(\Pi_{MFt}(s)-1)\Pi_{MFt}(s)$
	$+E_t\left[\beta\left(\frac{C^*_{t+1}}{C^*_t}\right)^{-\rho}\frac{Q_t}{Q_{t+1}}\frac{\phi(s)}{\Pi_{t+1}}(\Pi_{MFt+1}(s)-1)\Pi_{MFt+1}(s)^2\frac{Y^*_{Mt+1}(s)}{Y^*_{Mt}(s)}\right]$
Comp. Slackness and Firm Constraints	$\min\{\mu_t(s), \bar{Y}_t(s)-Y_t(s)\}=0$
	$\min\{\mu^*_{Ct}(s), \bar{Y}^*_{Ct}(s)-Y^*_{Ct}(s)\}=0$
	$\min\{\mu^*_{Mt}(s), \bar{Y}^*_{Mt}(s)-Y^*_{Mt}(s)\}=0$
Market Clearing	$Y_t(s) = C_{Ht}(s)+\sum_{s'} M_{Ht}(s,s')+X_t(s)+\frac{\phi(s)}{2}\left(\frac{P_t(s)}{P_{t-1}(s)}-1\right)^2 Y_t(s)$
	$X_t(s) = \left(\frac{P_{Ht}(s)}{P_t Q_t}\right)^{-\sigma(s)} X^*_t(s)$
	$Y^*_{Ct}(s) = C_{Ft}(s)+\frac{\phi(s)}{2}(\Pi_{CFt}(s)-1)^2 Y^*_{Ct}(s)$
	$Y^*_{Mt}(s) = \sum_{s'} M_{Ft}(s,s')+\frac{\phi(s)}{2}(\Pi_{MFt}(s)-1)^2 Y^*_{Mt}(s)$
	$\Theta_t\left(\frac{C_t}{C^*_t}\right)^{-\rho} Q_t = \Xi$
	$\sum_s L_t(s) = L_t$
Monetary Policy Rule	$1+i_t = (1+i_{t-1})^{\rho_i}\bar{\Pi}_t^{\omega(1-\rho_i)}(Y_t/Y_0)^{(1-\rho_i)\rho_y}\Psi_t$ with $Y_t=\sum_s P_0(s)Y_t(s)$
Auxiliary Inflation and Price Definitions	$\Pi_{Ht}(s) = \left(\frac{P_{Ht}(s)/P_t}{P_{Ht-1}(s)/P_{t-1}}\right)\Pi_t$
	$\Pi_{CFt}(s) = \left(\frac{P_{CFt}(s)/P_t}{P_{CFt-1}(s)/P_{t-1}}\right)\Pi_t$
	$\Pi_{MFt}(s) = \left(\frac{P_{MFt}(s)/P_t}{P_{MFt-1}(s)/P_{t-1}}\right)\Pi_t$
	$\bar{\Pi}_t = \frac{\bar{P}_t/P_t}{\bar{P}_{t-1}/P_{t-1}}\Pi_t$
	$\frac{\bar{P}_t}{P_t} = \left(\sum_s \zeta_0(s)\left(\frac{P_t(s)}{P_t}\right)^{1-\vartheta}\right)^{1/(1-\vartheta)}$

2.6 Discussion

We briefly discuss some technicalities associated with solving the model. We then describe Phillips Curves, which contain important insights for interpreting simulation results.

2.6.1 Solving the Model

Because the model features occasionally binding constraints, we need to adopt an appropriate solution technique that captures the non-linearities induced by them. Among alternatives, we adopt the piecewise linear solution technique developed by Guerrieri and Iacoviello (2015). The perturbation-based solution algorithm combines first order approximations to the model equilibrium for both the unconstrained and constrained equilibria, where the point of approximation is the unconstrained equilibrium in all cases.[14] The log-linear approximation for the model used in our quantitative analysis, and details regarding the solution procedure, are presented in the Online Appendix.

Collecting log deviations from steady state for endogenous (both control and state) variables in the vector X_t, the general solution for the model can be written as:

$$X_t = \mathbf{J}(X_{t-1}, \varepsilon_t; \theta) + \mathbf{Q}(X_{t-1}, \varepsilon_t; \theta) X_{t-1} + \mathbf{G}(X_{t-1}, \varepsilon_t; \theta) \varepsilon_t, \tag{25}$$

where ε_t is the vector of exogenous shocks in period t, θ is a collection of structural parameters, and $\mathbf{J}(\cdot)$, $\mathbf{Q}(\cdot)$, and $\mathbf{G}(\cdot)$ are time-varying matrices (dependent on the state and current shocks) that describe the optimal policy function. Given parameters and the initial steady-state shares needed to parameterize the approximate model, as well as lagged values X_{t-1} and a realization for ε_t, we solve for the policy functions using the OccBin toolbox in Dynare.

2.6.2 Domestic and Import Price Phillips Curves

It is instructive to examine log-linear approximations for the dynamic pricing equations for domestic and imported goods. Noting that $\mu_t(s)/P_t$ and $\mu^*_{ut}(s)/P^*_t$ for $u \in \{C, M\}$ take on zero values in the unconstrained equilibrium, we define auxiliary variables $\tilde{\mu}_t(s) \equiv \mu_t(s)/P_t + 1$ and $\tilde{\mu}^*_{ut}(s) \equiv \mu^*_{ut}(s)/P^*_t + 1$, and then we log-linearize the equilibrium with

[14] The solution procedures requires that the model satisfies two important conditions. First, it is assumed that the model returns to the unconstrained equilibrium in finite time after a once-off shock, if agents expect future shocks to be zero. Second, the unconstrained equilibrium must be stable, in the usual Blanchard-Kahn sense. Both requirements are satisfied for our baseline model and parameter values.

respect to these auxiliary variables. The resulting approximate pricing equations are:

$$\pi_{Ht}(s) = \left(\frac{\varepsilon - 1}{\phi(s)}\right)\left(\widehat{rmc}_t(s) - \widehat{rp}_{Ht}(s)\right) + \left(\frac{\varepsilon}{\phi(s)}\frac{P_0}{P_{H0}(s)}\right)\hat{\hat{\mu}}_t(s) + \beta E_t\left[\pi_{Ht+1}(s)\right] \tag{26}$$

$$\pi_{uFt}(s) = \left(\frac{\varepsilon - 1}{\phi(s)}\right)\left(\widehat{rmc}^*_t(s) + \hat{q}_t - \widehat{rp}_{uFt}(s)\right) + \left(\frac{\varepsilon}{\phi(s)}\frac{P_0}{P_{uF0}(s)}\right)\hat{\hat{\mu}}^*_{ut}(s) + \beta E_t\left[\pi_{uFt+1}(s)\right], \tag{27}$$

where hat-notation denotes deviations from steady state, $\pi_t(s) \equiv \ln P_t(s) - \ln P_{t-1}(s)$, $\pi_{Ft}(s) \equiv \ln P_{Ft}(s) - \ln P_{Ft-1}(s)$, $rmc_t(s) = \ln(MC_t(s)/P_t)$, $rmc^*_t(s) = \ln(MC^*_t(s)/P^*_t)$, $rp_{Ht}(s) = \ln(P_{Ht}(s)/P_t)$, $rp_{uFt}(s) = \ln(P_{uFt}(s)/P_t)$, and $q_t = \ln Q_t$. Equations 26-27 are sector-level domestic and import price Phillips curves.

Binding Constraints as Markup Shocks An important conceptual point is that binding constraints – when $\mu_t(s)$ or $\mu^*_{ut}(s)$ are strictly positive – appear as "markup shocks" in reduced form. That is, binding constraints lead inflation to be higher than can be accounted for given parameters, real marginal costs, and expected inflation. Thus, one can identify whether constraints bind in our model using the same approaches that would typically be used to identify exogenous, reduced-form markup shocks in standard New Keynesian models.

Whereas exogenous markups shocks in New Keynesian models typically are micro-founded by assuming that there are shocks to the elasticity of demand, the endogenous "markups shocks" in our model have a different structural interpretation. Markup shocks arise in our model not because the competitive environment per se has changed – i.e., market structure and demand elasticities are time invariant – rather firm conduct changes when constraints bind. Firms cease to make price changes to target their ideal (flexible price, CES) markups; they instead "price to demand," based on willingness to pay for their constrained output.[15] Further, markups may rise and fall sharply (reflecting non-linearities) as constraints are triggered and relaxed, such that the evolution of markups in times of binding constraints will be different than in normal times when constraints are always slack.

[15]The conclusion that capacity constraints influence firm conduct, holding market structure fixed, is not unique to our set up. For example, in oligopoly models with symmetric firms, Bertrand competition leads to competitive (marginal cost) pricing when firms are unconstrained. However, the Bertrand equilibrium features prices set above marginal cost when firms are capacity constrained, such that they cannot collectively meet total market demand when prices equal marginal cost.

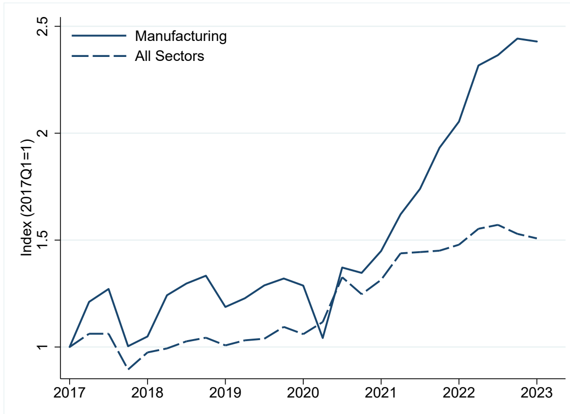
This "markup shock" interpretation of binding constraints also serves to highlight how the mechanism we emphasize is distinct from alternative explanations for the inflation surge. First, much attention has focused on the role of labor shortages. At the aggregate level, these may reflect changes in worker preferences for supplying labor, or other constraints on labor supply. At the sector level, worker shortages may be explained by impediments to reallocating workers in response to differential changes in demand across sectors.[16] In either case, demand for workers outstripping supply ought to manifest as higher wages, which would then drive marginal costs higher. Thus, one would expect to see that changes in real marginal costs explain inflation outcomes, not markups (one might even expect markups to be compressed where labor shortages are tightest). To the extent that constraints masquerading as markup shocks explain inflation, this then limits the scope for these alternative labor market mechanisms. All that said, we will discuss exactly how incorporating labor market shocks and constraints affects inflation in Section 4.2.

In a related vein, the approach we adopt for modeling capacity differs from prior literature, which has emphasized variable capital utilization rather than output-based capacity constraints [Greenwood, Hercowitz and Huffman (1988); Gilchrist and Williams (2000)]. In this literature, it is typically assumed that higher rates of capital utilization lead capital to depreciate faster. As a result, higher utilization raises the effective marginal cost for the firm (including wages, user costs of capital, and increased capital depreciation), so utilization affects inflation through marginal costs. Further, with the functional form assumptions in Greenwood, Hercowitz and Huffman, the standard log-linear Phillips Curve relationship between marginal costs and inflation (equivalently, utilization and inflation) holds. Thus, this alternative approach to capacity utilization will struggle to explain the highly non-linear response of inflation observed in recent data, as well as the role of reduced-form markup shocks in explaining it.

Profits Our model implies that price-cost margins (realized markups) are high when firms face binding constraints. To examine the plausibility of this channel, we turn to data on profits per unit of output, which serves as an observable proxy for price-cost margins. To formalize this link, note that the absolute markup is equal to profits per unit of output in the steady state: $P_t(s) - MC_t(s) = \frac{\Xi_t(s)}{Y_t(s)}$, where $\Xi_t(s) \equiv P_t(s)Y_t(s) - MC_t(s)Y_t(s)$ is the profit of the representative producer in sector s. Thus, tracking profits per unit over time sheds light

[16]We have assumed that factors are perfectly mobile across sectors in our model, with a common economy-wide wage. This contrasts with Ferrante, Graves and Iacoviello (forthcoming), who analyze how asymmetric demand shocks lead to inflation when there are worker reallocation frictions.

Figure 4: Corporate Profits per Unit of Gross Output



Note: Corporate profits (with inventory valuation adjustments) and gross output are from the US Bureau of Economic Analysis (series identifiers: N400RC and A390RC). The corporate profits per unit of gross output are are reported as an index, measured relative to their value in 2017Q1.

on how markups are changing.

In Figure 4, we plot indexes of US corporate profits per unit of gross output for both the manufacturing sector and the aggregate private sector.[17] The takeaway is that profits per unit escalated sharply for manufacturing firms during the pandemic recovery, coinciding with the takeoff in goods price inflation and widespread complaints about binding (supply chain) constraints that limited production. Further, total profits (profits per unit times quantity sold) were at historically high levels in 2021. This pattern of high profitability alongside high inflation is a natural outcome of binding (domestic) constraints in our model. It is also remarkably consistent with concerns about "greedflation" in the U.S., wherein corporations have been criticized for fueling inflation by gouging consumers [DePillis (2022)].[18] More recently, profit margins appear to be falling as inflation has declined in 2023 [Kerr (2023)].

3 Accounting for Recent Inflation Experience

We now apply the model to parse recent data. We describe the procedure we use to estimate the model in Section 3.1, with additional details in the Online Appendix. Then, we discuss

[17]This corporate profit measure omits profits attributable to non-corporate entities; We focus on corporate profits because data is available for manufacturing on a quarterly frequency in the national accounts.

[18]Greedflation is often attributed to the secular rise of market power, which has potentially increased the ability of corporations to pass cost shocks through to consumers. Our mechanism is not about pass-through of cost shocks; it is about how firms set prices conditional on costs when constraints bind.

data, calibration, and estimated parameters in Section 3.2. In Section 3.3, we review model fit. We then discuss what the model tells us about recent inflation in Section 3.4.

3.1 Estimation Framework

Referring back to Section 2.6.1, the impact of a given structural shock in the model depends on whether constraints bind today following the shock, as well as the expected duration that constraints are expected to continue to bind into the future following that shock. To make this dependence explicit, let us define a set of regimes ($\mathbb{R}_t$), which record which constraints are binding at a given point in time: $\mathbb{R}_t = \{\mathbf{1}(Y_t(1) = \bar{Y}_t(1)), \mathbf{1}(Y^*_{Mt}(1) = \bar{Y}^*_{Mt}(1))\}$, where the indicator functions switch on when individual constraints bind. Given a sequence $\left\{\mathbb{R}_{t+j}\right\}$ for $0 \leq j \leq J$, together with the assumption that $\left\{\mathbb{R}_{t+j}\right\} = \{0,0\}$ for $j > J$, we can solve for an equilibrium path for $\{X_t\}$, using the method described in Cagliarini and Kulish (2013) and Kulish and Pagan (2017).

Building on this idea, we re-parameterize the model solution in a convenient way. Specifically, let us define the duration that constraints are expected to bind from date t forward as $\mathbf{d}_t = [d_t, d^*_t]$, where each entry is a non-negative integer that records the number of periods that the domestic (d_t) or foreign constraint (d^*_t) binds. By convention, d_t and d^*_t take on zero values when constraints are slack today and expected to remain so in the absence of future shocks, and they are positive when they are binding today. As in Guerrieri and Iacoviello (2015), we construct policy matrices under the assumptions that agents know the state (X_{t-1}) and the current realization of the shocks (ε_t), but that they do not anticipate that future shocks will occur. Under these assumptions, $\mathbf{d}_t$ summarizes all the information about the anticipated sequence of regimes that is needed to solve for equilibrium responses to a one-time shock in our model. Specifically, constraints may switch on immediately in response to shock at date t, then bind for some (non-negative) number of consecutive periods, and switch off thereafter. In the absence of future shocks, constraints do not then switch on again in periods after they switch off (e.g., following a shock ε_t, constraints cannot be slack at date t and then binding at date $t+1$).[19] With these observations,

[19]To be careful, this is not a general property of models with potentially binding constraints, but rather one that holds given the structural assumptions in our model about behavior and shock processes. While we lack a general proof of this property, we verify it holds numerically in the model in practice, and we can demonstrate that imposing this criterion in the estimation procedure is reasonable via simulation analysis. One could capture a more complex structure of potential regime changes via introduction of additional parameters (e.g., durations for binding constraints that start one period forward), at the cost of added computational complexity.

we re-write the model solution directly in terms of durations:

$$X_t = \mathbf{J}(\mathbf{d}_t, \theta) + \mathbf{Q}(\mathbf{d}_t, \theta) X_{t-1} + \mathbf{G}(\mathbf{d}_t, \theta) \varepsilon_t, \tag{28}$$

where duration $\mathbf{d}_t$ implies a specific anticipated sequence of regimes over time.

Following Kulish, Morley and Robinson (2017), Kulish and Pagan (2017), and Jones, Kulish and Rees (2022), our estimation framework exploits the fact that durations enter the policy function like parameters. As is standard, let us assume that observables (S_t) are linearly related to the unobserved state, as in $S_t = H_t X_t + \nu_t$, where ν_t is an i.i.d. vector of normally distributed measurement errors. Given $\mathbf{d} \equiv \{\mathbf{d}_t\}_{t=1}^{T}$ and θ, we can construct the piecewise linear solution with time-varying coefficients, and then apply the Kalman filter to construct the Likelihood function $\mathscr{L}(\theta, \mathbf{d} | \{S_t\}_{t=1}^{T})$. We put priors over structural parameters and independent priors over durations to construct the posterior, and then estimate the model via Bayesian Maximum Likelihood.

In implementing this approach to estimation, we are careful to account for the fact that the duration of binding constraints is an equilibrium object in the model – i.e., d_t depends on both the state X_{t-1} and current shock ε_t in our model. Thus, we impose a rational expectations equilibrium restriction on admissible durations, which requires that agents' forecasts about how long constraints bind following a given shock are consistent with equilibrium model responses. To impose this restriction, we proceed as follows. For each proposed duration and parameter draw, we filter the data for smoothed shocks. We then evaluate whether the equilibrium model response to those smoothed shocks is consistent with the proposed duration draw. We retain the proposed draw if this requirement is satisfied; otherwise, we reject it and draw again.

In the Online Appendix, we study the performance of this procedure using simulated data, for which we know the true data generating process and the exact incidence of endogenously binding constraints. First, we confirm that our estimation procedure is able to recover unobserved durations from the observables that we use, by directly examining likelihood functions. Then, we also show that the reduced-form multipliers implied by the duration and parameter estimates align with true latent multipliers, which summarize the impacts of binding constraint on inflation, our key outcome.

Lastly, as a practical matter to restrict the size of the parameter space, we impose priors that allow capacity constraints to bind only periods from 2020:Q2 forward. Put differently, we impose dogmatic priors that assign zero probably to binding constraints prior to

2020:Q2, thus focusing on the role of capacity in explaining the unusual post-pandemic inflation dynamics.[20]

3.2 Data and Parameters

To populate Y_t, we collect standard macro variables together with particular series that serve to identify whether constraints are binding and shocks to them. Among standard macro variables, we include consumption price inflation and the growth rates of consumption expenditure for goods and services. We also use data on aggregate nominal GDP growth, the growth rate of (real) industrial production (which we treat as a proxy for output of the goods sector), and labor productivity growth by sector (measured as real value added per worker).[21] On the international side, we use data on import price inflation for consumption goods, and we proxy input price inflation in the model using data on inflation for imported industrial materials (excluding fuels). We then also use data on the growth of total expenditure on imported consumption goods and imported materials inputs (again excluding fuels), which we associate with imported inputs of goods.[22]

These data are all obtained from quarterly US national accounts produced by the Bureau of Economic Analysis, with the exception of labor productivity data from the Bureau of Labor Statistics and industrial production from the Federal Reserve Board (G.17 program). Having constructed growth rates for individual variables from the first quarter of 1990 through the fourth quarter of 2022, we detrend the data by removing the mean growth rate from each series. Finally, because our estimation sample includes a significant period during which interest rates are at the zero lower bound, we use data on the "shadow Fed Funds rate" to estimate parameters in the monetary policy rule.[23]

[20]As a robustness check, we have estimated the model allowing constraints to potentially bind starting in 2018:Q1, prior to the pandemic. We find that the mode of estimated durations before 2020:Q2 is zero, and that the mode of estimated durations after 2020:Q2 is not affected by the initial date when capacity constraints are allowed to bind.

[21]We use data on labor productivity growth in manufacturing and total (private sector) labor productivity growth from the Bureau of Labor Statistics. We assume that labor productivity growth in manufacturing coincides with goods labor productivity (growth in real value added per worker) in the model, while also matching aggregate (economy-wide) labor productivity growth in the model. While the definition of industrial production and goods output do not align exactly, the dynamics of gross output for the goods sector and industrial production are similar.

[22]We use data for consumer goods (except food and automotive) to proxy for consumption imports, and we construct proxies for imported inputs (excluding fuels) by removing the subcategory of petroleum and products from industrial materials and supplies using standard chain index formulas and auxiliary NIPA data on the sub-categories of imports.

[23]During periods where the nominal Fed Funds rate is at zero, we replace it with the shadow rate from

We present the full set of parameters for the model in the Online Appendix, which we obtain through a mix of estimation and calibration. We calibrate key value shares in the model – e.g., consumer expenditure, input use, export and import shares, etc. – to match US national accounts and input-output data. We set a subset of the structural parameters to standard values from the literature, including preference parameters and some elasticities of substitution.

We also calibrate the level of excess capacity for domestic and foreign firms, setting $\bar{Y}_0(1) = 1.05Y_0(1)$ and $\bar{Y}^*_{M0}(1) = 1.10Y^*_{M0}(1)$. These levels are chosen to be sufficiently high that constraints are slack prior to 2020:Q2.[24] Further, note that the model and data allows us to estimate the level of capacity that actually prevailed during the pandemic. Alternative values for steady state capacity then re-scale the size of the capacity shocks needed to achieve this realized capacity level.[25]

Turning to the final set of parameters, we estimate (a) the elasticities of substitution between home and foreign goods, in consumption and production separately; (b) the parameters in the extended Taylor rule governing the response of interest rates to inflation and output, as well as interest rate inertia, (c) parameters governing the stochastic processes for exogenous variables, and (d) the variance of measurement errors. Regarding (c), we assume that exogenous variables evolve according to AR1 stochastic processes.

We obtain an estimated mean value for the elasticity of substitution between home and foreign goods of about 1.5 in consumption and 0.5 for inputs, so consumer goods are substitutes while inputs are complements. These values are not far from standard values estimated using aggregate time series variation in the macroeconomic literature, though there is limited prior work that distinguishes consumption and input elasticities. We find

Wu and Xia (2016): https://www.atlantafed.org/cqer/research/wu-xia-shadow-federal-funds-rate. Changes in the shadow rate capture the consequences of unconventional policy actions taken by the Federal Reserve, such as forward guidance or quantitative easing policies. We have checked the results using an alternative shadow rate series from Jones, Kulish and Morley (2022) as well, which yields similar results.

[24] This amount of domestic excess capacity is consistent with historical fluctuations in capacity utilization for the US, as measured by the Federal Reserve's G.17 data series, for which the maximal value for capital utilization about five percent higher than the minimum. Further, cyclical fluctuations in this capacity utilization measure are almost entirely driven by changes in industrial production itself, rather than the Fed's estimate of capacity (based on firm survey data). Thus, our calibration accommodates historically normal fluctuations in industrial production, absent shocks to capacity.

[25] Consistent with this observation, the level of calibrated steady state capacity is not an important parameter in understanding the key quantitative results. To demonstrate this robustness, we estimate steady-state capacity levels directly in the Online Appendix, using data from the pandemic period, and show that our main counterfactual results go through with this alternative parameterization.

that the policy rule displays inertia, and it responds to both inflation and output gaps with reasonable magnitudes.[26] There is significant persistence in most exogenous variables, and measurement error variances are plausible. See the Online Appendix for the full set of estimated parameters.

3.3 Model Fit

Applying the quantitative model framework to the data, we construct Kalman-smoothed values for endogenous variables and observables. In Figure 5, we plot data and smoothed values for several key observables – goods, services, and aggregate price inflation for consumers, and imported input price inflation – over the 2017-2022 period, where each data point is the annualized value of quarterly inflation. To compute the smoothed inflation series, we take 1000 draws from the posterior distribution for model parameters, compute Kalman-smoothed inflation for each draw, and then plot statistics (the median, 5th, and 95% percentiles) for the distribution of smoothed values.

The model fits the dynamics of aggregate consumer price inflation well, accounting for essentially all of the four percentage point increase in headline inflation after 2020 (Figure 5a).[27] It also accounts well for the two percentage point rise in inflation for the services sector (Figure 5b). Because goods price inflation is substantially more volatile than that for services, the model attributes more of its variation to measurement error. Nonetheless, smoothed values for goods price inflation also track the data well (Figure 5c). The model replicates the initial (roughly six percentage point) surge in goods price inflation in 2021, and goods price inflation then remains elevated into 2022. While the model captures its transitory (up/down) dynamics, it moderately undershoots the level of goods price inflation in 2022, meaning that the model attributes the gap to measurement error. The model also matches inflation for imported goods inputs well (Figure 5d), matching both levels and dynamics closely.

For brevity here, we present similar figures illustrating model fit for the remaining ob-

[26] In unreported analysis, we have verified that our results are robust to alternative formulations and parameters for the monetary policy rule.

[27] Recall that aggregate consumer price inflation is treated as an unobserved variable. In the model, it is constructed by aggregating sector-level consumer price growth using fixed (steady-state) expenditure weights. In the data, however, the PCE deflator is a chain-weighted index, which features time-varying weights. Thus, part of the discrepancy between aggregate inflation in the model and data is likely due to differing index number concepts. Specifically, the dramatic increase in the goods expenditure share, combined with high goods price inflation, likely pushed measured inflation up relative to our fixed-weight index. Going forward, we focus entirely on decomposing model-based measures of inflation, so we do not belabor this point.

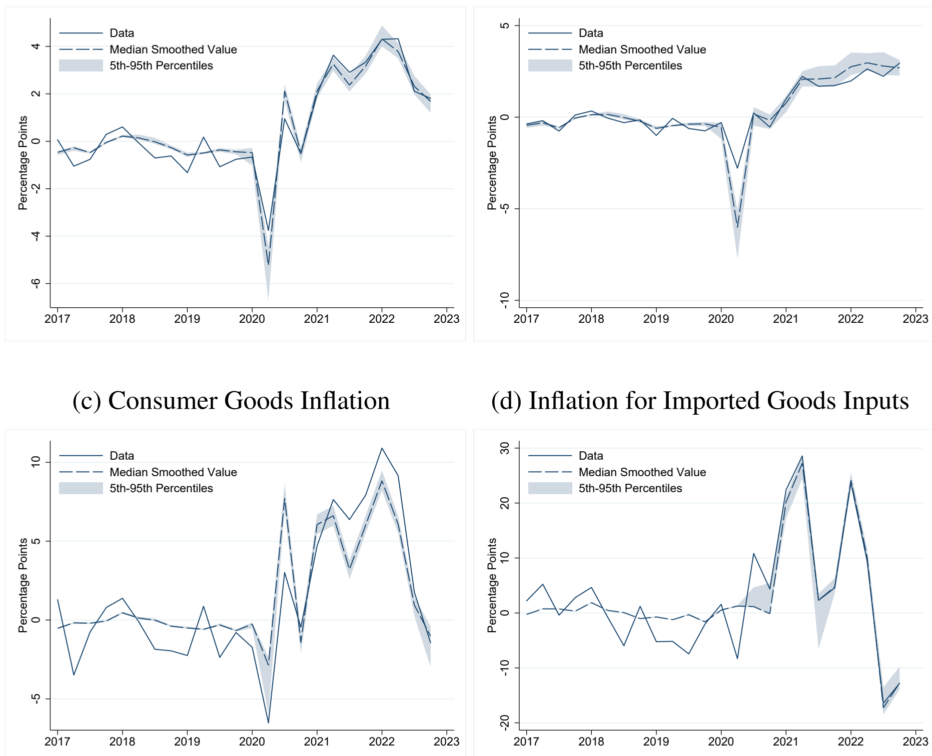
Figure 5: Consumer Price Inflation in Model and Data

(a) Aggregate Consumer Inflation

(b) Consumer Services Inflation

(c) Consumer Goods Inflation

(d) Inflation for Imported Goods Inputs



Note: Inflation at each date is the annualized value for demeaned quarterly inflation, in percentage points. If demeaned quarterly inflation is $\pi_t(s) = \ln P_t(s) - \ln P_{t-1}(s)$ where t indexes quarters, then the annualized inflation rate is $4\pi_t(s)$. Data is raw data. We take 1000 draws from the posterior distribution of model parameters, compute the Kalman-smoothed values for model variables for each draw, and then plot the median smoothed value as the dashed line. We shade the area covering the 5% to 95% percentile for smoothed values (the interval is imperceptibly small prior to 2020).

servables in the Online Appendix. Together with the inflation figures here, we assess that the model captures the behavior of economic variables well during the pandemic, so it is a useful laboratory for exploring the driving forces underlying the inflation surge.

3.4 Explaining the Inflation Surge

We provide three sets of results. The first two illustrate the role of constraints in explaining inflation. First, we examine the dynamics of the multipliers on the constraints. Second, we present counterfactuals in which we switch off the constraints, comparing model responses to the same set of shocks with and without constraints. The third set of results focuses on how individual shocks and constraints shape inflation outcomes, both individually and via interactions between them.

3.4.1 Multipliers on Constraints

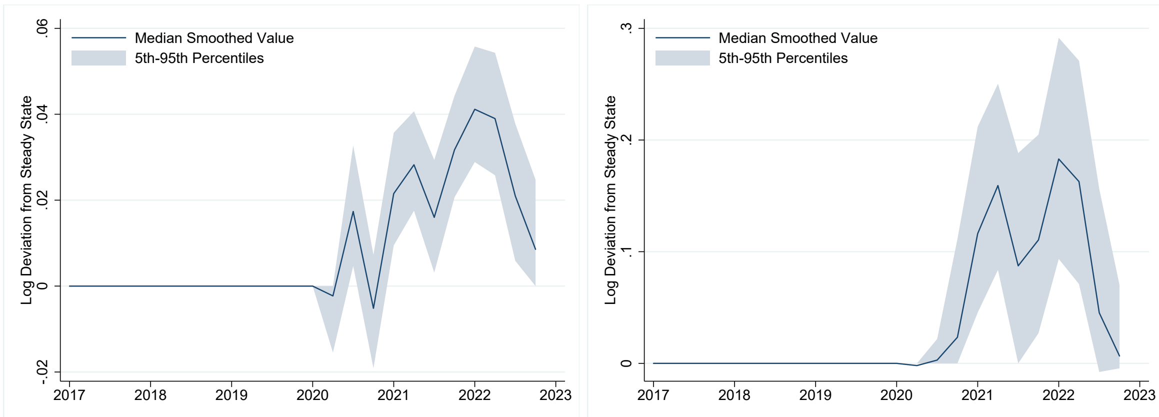
To start, we can directly illustrate the impact of constraints by examining the smoothed value of multipliers on the domestic and foreign constraints. Because the multipliers themselves do not have intuitive economic units, we plot the reduced-form markup shocks implied by the value of the multipliers – given by $\left(\frac{\varepsilon}{\phi(s)}\frac{P_0}{P_{H0}(s)}\right)\hat{\hat{\mu}}_t(s)$ in Equation 26 and $\left(\frac{\varepsilon}{\phi(s)}\frac{P_0}{P_{uF0}(s)}\right)\hat{\hat{\mu}}^*_{ut}(s)$ in Equation 27 – which summarize the impulse of binding constraints for domestic and import price inflation. As is evident, the values of the multipliers rise in 2021, coincident with the rise in headline inflation.[28] On the import side, constraints appear to be slack in 2020, then bind sharply at the start of 2021, relax somewhat, then bind sharply again into 2022, and ease in the latter half of 2022. Domestic multipliers fluctuate in 2020 with gyrations in the US economy, but are near zero heading into 2021. They rise steadily through 2021 into 2022, and then slacken (though still bind) through 2022:Q3.

While there is limited external data to which we can benchmark the estimated multipliers, we note that their joint dynamics align well with fluctuations in the New York Federal Reserve's Global Supply Chain Pressure Index over the post-2020 period, as we illustrate in the Online Appendix. For both multipliers, the high frequency dynamics also correspond to fluctuations in goods price inflation and imported input price inflation in Figure 5, which foreshadows the quantitative role of the constraints in explaining inflation. Further, the large absolute size of increases in multipliers, and their volatility translate into large, abrupt shifts in the Phillips Curves. In the Online Appendix, we show that these quasi-markup shocks are substantially larger than would be consistent with a stochastic process for (exogenous) markup shocks estimated from pre-pandemic data. Thus, our model appears to capture a source of markup variation that is distinct from run-of-the-mill markup (elasticity of demand) shocks. We turn to model counterfactuals to parse the role of constraints further.

[28] We place positive mass in our priors on positive values for d_t only starting in 2020:Q2, so multipliers are identically zero before that date. Further, while multipliers are typically positive, they sometimes take on negative values in the simulations. This is due to model approximation error, due to the piecewise linear solution technique that we employ. When constraints bind, the multipliers are computed as residuals in the log-linearized Phillips Curves. As such, the computed multipliers are approximations to the exact equilibrium multipliers; further, we do not impose a zero lower bound on them, as would be required in the full non-linear solution to the model. Despite this, the estimated multipliers are typically positive, consistent with the underlying theory.

Figure 6: Smoothed Values for the Reduced-Form Markup Shock Implied by the Multipliers on Constraints

(a) Domestic Constraint (b) Foreign Constraint



Note: Figure 6a plots composite variable $\left(\frac{\varepsilon}{\phi(s)}\frac{P_0}{P_{H0}(s)}\right)\hat{\hat{\mu}}_t(s)$ and Figure 6b plots composite variable $\left(\frac{\varepsilon}{\phi(s)}\frac{P_0}{P_{uF0}(s)}\right)\hat{\hat{\mu}}^*_{ut}(s)$, which are the reduced-form markup shocks in domestic and import price Phillips Curves induced by binding constraints. We take 1000 draws from the posterior distribution of model parameters, compute the Kalman-smoothed values for model variables for each draw, and then plot the median smoothed value as the solid line. We shade the area covering the 5% to 95% percentile for smoothed values.

3.4.2 Relaxing Constraints

We now provide counterfactual analysis as to how inflation would have evolved in the absence of capacity constraints, given the path of realized shocks that we infer hit the US economy after 2020.

To describe this exercise more precisely, the mechanics of each iteration are as follows. We first draw model parameters from the estimated posterior distributions, including the durations for binding constraints. Given these parameters, we apply the Kalman-filter to the data and construct smoothed model outcomes and shocks. Note that we construct smoothed shocks here assuming that constraints are potentially binding, in line with posterior duration estimates. Using these smoothed shocks, we then simulate the path of the economy under the counterfactual assumption that constraints are slack throughout, such that the solution conforms to the unconstrained equilibrium dynamics of the model. We repeat this procedure for one thousand posterior draws, and we plot statistics (means and percentiles) across these simulations in Figures 7 and 8.

Figure 7 presents results for consumer price inflation. The figures present raw data on annualized values of (de-meaned) quarterly inflation, along with data from counterfactual simulations in which we allow for measurement error in these observables.[29] In Figure 7a, we see that realized inflation for consumer goods is substantially higher than counterfactual inflation with slack capacity constraints during 2021 and into 2022, with the absolute gap peaking near six percentage points in early 2021. Put differently, given the shocks we infer from data, binding constraints account for about half of the acceleration in goods price inflation from 2020:Q2 through 2021:Q2. Likewise, they appear to explain about half of the decline in goods price inflation in the latter half of 2022.

Under the hood, these inflation outcomes are tied to the impact of binding constraints in holding back production of domestic goods and foreign goods inputs. In Figure 8a, we plot the path for smoothed domestic goods output along with counterfactual output. As is evident, in the absence of constraints, goods output would have risen significantly in 2021 relative to its pre-pandemic level, as a result of the other shocks (principally, demand shocks) that hit the economy. The fact that output did not rise in reality speaks directly to the role of constraints. Output of foreign goods inputs is similarly constrained in Figure 8b. Correspondingly, smoothed inflation for both domestically-produced goods and foreign-produced inputs is substantially higher than counterfactual inflation in Figures 8c and 8d.

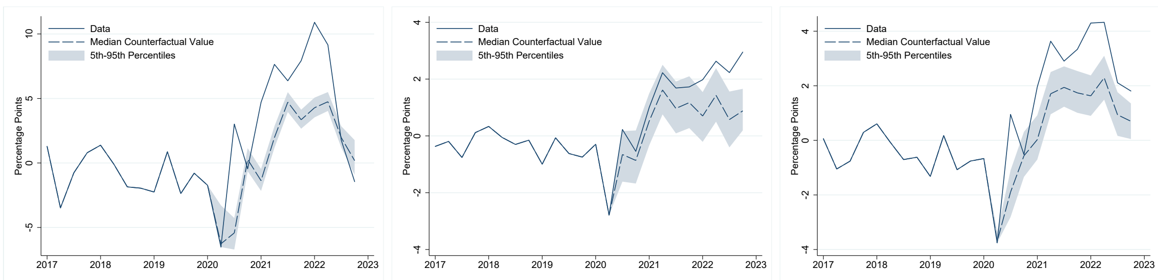
Interestingly, binding constraints also play an important role in driving price inflation for services in Figure 7b. While services price inflation initially accelerates due to the underlying shocks, it is between one and two percentage points higher in 2021 as a result of binding constraints. In the background, this reflects both the fact services use goods as inputs, so there is a direct inflation spillover from binding constraints in the goods sector via input-output linkages. Further, binding constraints serve to tighten the labor market as well, as the price increases they generate trigger substitution from goods inputs toward labor in production.

Adding up these results in Figure 7c, headline consumer price inflation is between one and two percentage points higher than counterfactual inflation during 2021-2022. And binding constraints account for about one third of the acceleration in headline goods price inflation from 2020:Q2 through 2021:Q2. Note further that the effect of constraints is substantially diminished late in 2022, as actual and counterfactual inflation converge again.

[29] For each iteration, we draw the variance of the measurement error from the posterior and filter the data for smoothed shocks. We then add a draw from the measurement error to the smoothed counterfactual endogenous variables to get counterfactual values for the observables that are comparable to data.

Figure 7: Counterfactual Consumer Price Inflation without Capacity Constraints

(a) Goods Inflation (b) Services Inflation (c) Aggregate Inflation



Note: We take 1000 draws from the posterior distribution of model parameters, compute the Kalman-smoothed values for model variables for each draw, add measurement error to the observables, and then plot the median smoothed value as the solid line. We shade the area covering the 5% to 95% percentile for smoothed values.

Finally, we revisit the discussion about profits per unit. In Figure 4, we presented an index of nominal profits per unit of gross output for manufacturing and the aggregate economy. In Figures 8e and 8f, we present analogous results from the model for goods and services.[30] Similar to the data, our model yields a sharp increase in profits for the goods sector during the 2021-2022 period, even though this is not a targeted data moment. In contrast, the counterfactual economy with slack constraints yields no such goods profit surge. Moreover, profits per unit are essentially flat through the pandemic period (outside the 2020 spike), for both the economies with and without capacity constraints. We conclude that the model provides a plausible explanation for the run-up in profits for goods producers that occurred alongside the inflation takeoff, where both are explained in large measure by binding capacity constraints.

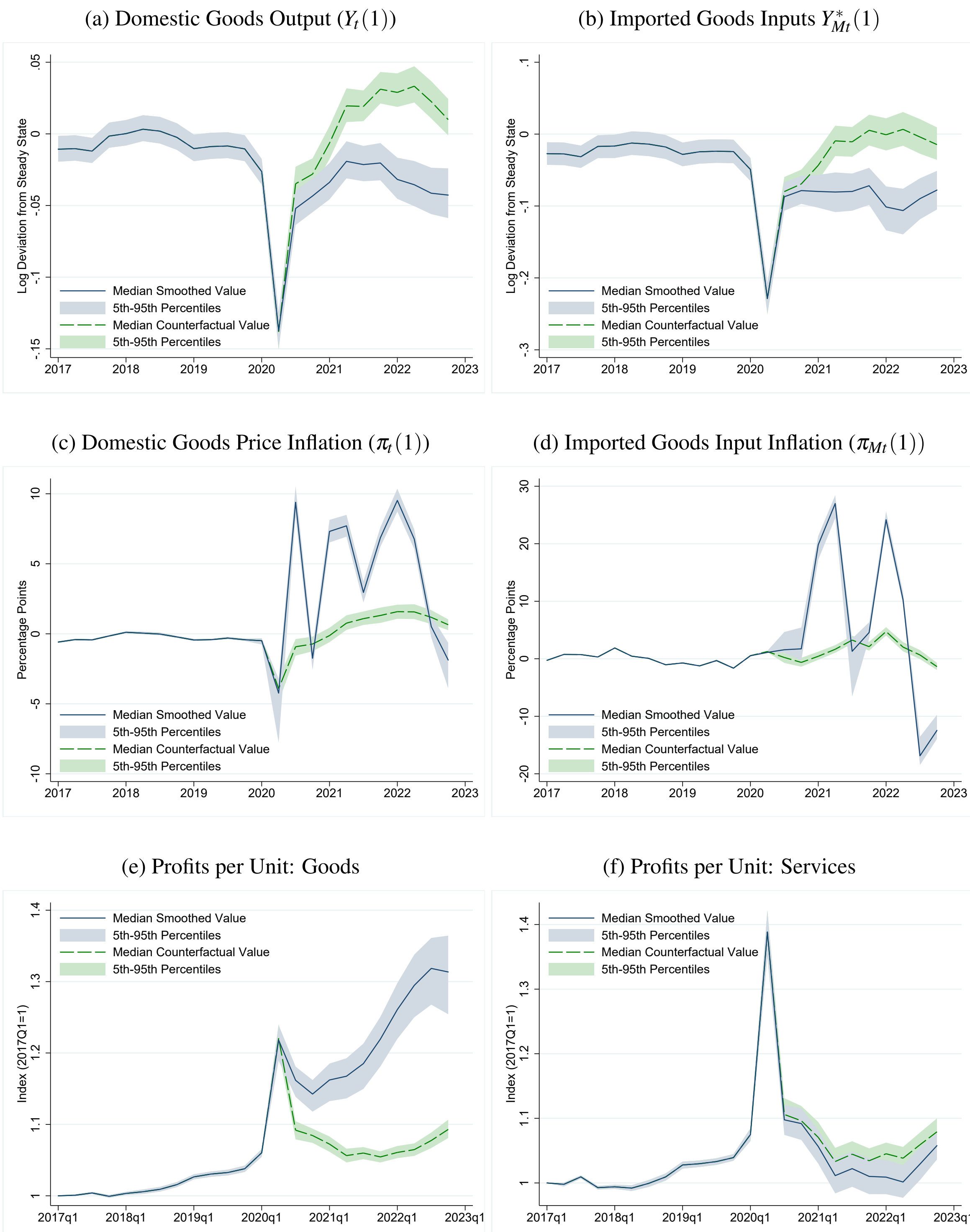
3.4.3 Decomposing the Role of Individual Shocks

We now examine the role of individual shocks in explaining inflation outcomes.[31] To construct the counterfactual series, we take a draw from the posterior distributions for structural parameters and durations. Using this draw to parameterize the state equation (Equation 28),

[30]In the model, the log change in nominal profits per unit of output from a given base period ($t = 0$) is given by: $\left[\hat{\Xi}_t(s) - \hat{y}_t(s)\right] - \left[\hat{\Xi}_0(s) - \hat{y}_0(s)\right] = \left[\hat{p}_{Ct} - \hat{p}_{C0}\right] + \varepsilon\left[\widehat{rp}_t(s) - \widehat{rp}_0(s)\right] - (\varepsilon - 1)\left[\widehat{rmc}_t(s) - \widehat{rmc}_0(s)\right]$, where $\hat{p}_{Ct} - \hat{p}_{C0} = \sum_{s=0}^{t} \pi_{Cs}$. We add trend inflation to these log changes to make it comparable to the data in Figure 4, and then we convert the log change to levels to plot the index.

[31]In the Online Appendix, we provide an additional set of counterfactuals, in which we parse the individual roles that the domestic and import constraints play in accounting for the overall impact of the constraints. Roughly speaking, the domestic constraint accounts for about three-quarters of the overall effect, with the remainder attributable to the import constraint.

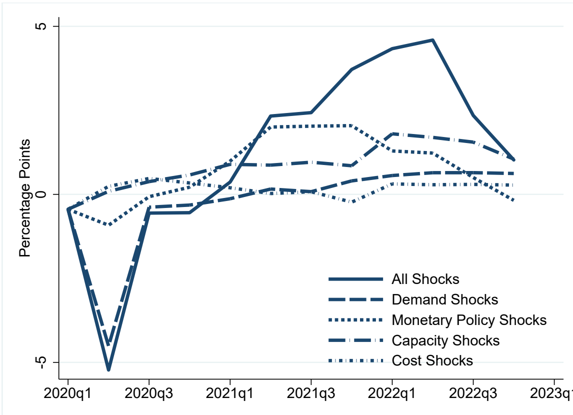
Figure 8: Counterfactual Quantities, Inflation, and Profits without Capacity Constraints



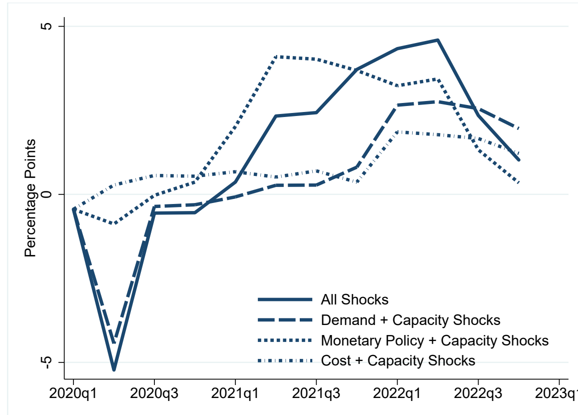
Note: We take 1000 draws from the posterior distribution of model parameters, compute the Kalman-smoothed values for model variables for each draw, and then plot the median smoothed value as the solid line. We shade the area covering the 5% to 95% percentile for smoothed values. Counterfactual assumes that constraints are slack in all periods.

Figure 9: Counterfactual Consumer Price Inflation for Individual Shocks

(a) Individual Shocks



(b) Capacity Shocks plus Individual Shocks



Note: Each series represents the simulated path of consumer price inflation (quarterly value, annualized) for the indicated subset of smoothed shocks during 2020-2022. See text for definition of the counterfactuals.

we Kalman filter the data to obtain smoothed shocks. We then feed a subset of these shocks into the structural model (summarized by Equation 25) to compute counterfactual model outcomes. In each case, we solve for the simulated equilibrium path using Dynare's OccBin procedure. By doing so, we ensure that whether constraints bind at particular points in time in response to shocks is endogenous. We repeat this procedure 1000 times and compute the median across the simulated counterfactual series, and these medians are plotted in Figure 9.

In Figure 9a, we plot the path of aggregate consumer price inflation following four types of shocks, each fed individually into the model: demand shocks (including both the discount rate and goods-biased preference shocks), monetary policy shocks, capacity shocks, and cost shocks (including domestic productivity and foreign cost shocks). The final line is the value for inflation when all shocks are fed simultaneously into the model. At the outset, temporary negative demand shocks yield a decline then rebound of inflation in 2020. Into 2021, however, no single shock appears to play a particularly important role in explaining the path of inflation on its own. The underlying reason is that no single shock is capable of causing capacity constraints to bind, so model outcomes conform closely to those observed in the prior counterfactuals in which we exogenously relaxed the constraints.

In Figure 9b, we plot a second set of counterfactuals, in which individual shocks are fed into the model in combination with shocks to capacity. In contrast to the prior figure, monetary policy stands out here. While monetary policy shocks play essentially no role in

2020, expansionary monetary policy shocks in 2021 – combined with prevailing negative capacity shocks – lead to a surge in inflation of about 4 percentage points in 2021. Put differently, while negative capacity shocks are insufficient on their own to trigger binding constraints, negative capacity shocks set the stage for demand-side shocks – especially expansionary monetary policy – to trigger the constraints. In turn, as monetary shocks dissipate in 2021 (i.e., as the Federal Reserve raises interest rates to bring them back in line with the extended Taylor rule), then inflation falls rapidly in 2022 as constraints are relaxed again. In contrast, the role of the demand shock is much more muted in 2021 possibly reflecting the smaller expansionary effects of fiscal vs. monetary policy in that year, but continued to stoke inflation in 2022.[32] Thus, we conclude that the dynamics of monetary policy during this period interacted with shocks to capacity, are the driving force behind the rapid rise and subsequent fall in inflation during the post-pandemic period.

4 Extensions

In this section, we present two sets of additional results, which probe the robustness of our findings. First, we examine whether our results change when we account more carefully for energy shocks. Second, we enrich the labor market structure of the model, to account for labor market stress during the pandemic.

4.1 Accounting for Energy Shocks

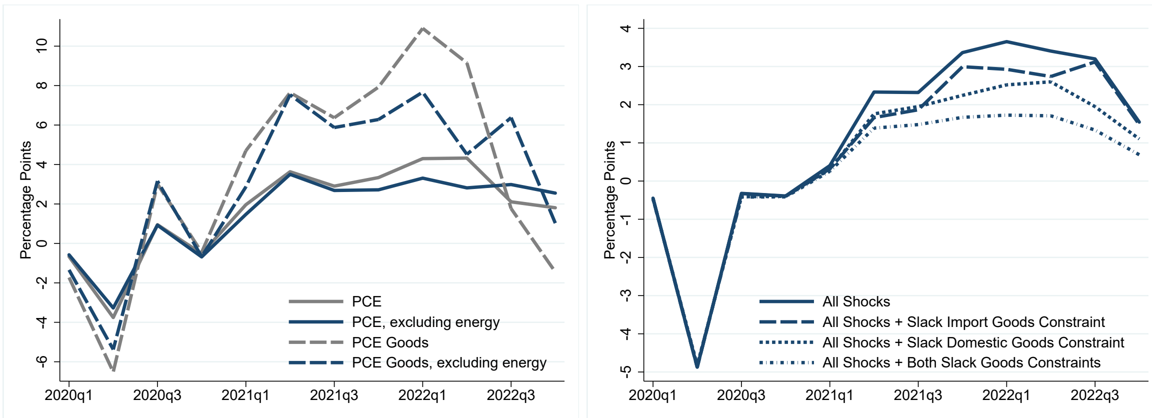
During 2021-2022, global energy prices escalated, as strong demand for energy combined with supply disruptions (e.g., following from the Ukraine war) to drive energy prices up. Further, since the middle of 2022, energy prices have receded rapidly as inflation has cooled. A natural question arises then about whether the dynamics of inflation that we attribute to occasionally binding constraints might instead be driven by these energy price fluctuations.

To frame this discussion, note that our model abstracts from the peculiar features of energy markets – i.e., we do not attempt to model energy prices, production, and demand explicitly. Therefore, we think it reasonable to estimate our model using data that also excludes energy prices. In part, we have already done this in prior sections, in that we have

[32]Both in variance and historical decompositions we observe a predominant role of shocks to the discount rate in driving output consistent with a realistic fiscal multiplier. However, in 2021 the historical decompositions for goods and overall output reveal a stronger role for monetary than discount rate shocks.

Figure 10: Accounting for Energy Shocks

(a) PCE Inflation with and without Energy (b) Capacity Shocks plus Individual Shocks



Note: In Figure 10b, each series represents the simulated path of consumer price inflation (quarterly value, annualized) for all shocks and the indicated set of constraints during 2020-2022. See text for definition of the counterfactuals.

stripped out petroleum and fuels when we constructed the price index for imported materials. Here we also remove energy prices from the domestic price indexes used in estimation – constructing PCE inflation for goods and services, excluding energy. Specifically, we remove prices for "gasoline and other energy goods" (which includes motor vehicle fuels and lubricants, fuel oil, and other fuels) from the goods PCE price index, and then we remove prices for electricity and gas utilities from the services PCE price index. We then re-estimate the model using the modified domestic price indexes.

In Figure 10a, we plot the adjusted PCE inflation series for goods prices and overall consumption.[33] Goods price inflation is virtually indistinguishable with/without energy through 2021:Q3, during the initial inflation takeoff. Thereafter, energy prices push inflation up during early 2022, and then rapidly bring goods price inflation down thereafter. Nonetheless, the basic inverted U-shape for goods price inflation appears in both series, with non-energy goods price inflation falling from 8 percent to near zero during the course of 2022. Overall PCE price inflation then reflects these deviations in goods price inflation.

In Figure 10b, we investigate the role of these differences for our conclusions about the role of constraints in explaining inflation dynamics. The simulations here follow the same scheme as in Section 3.4.3: we compare simulated inflation when all shocks are fed through the model to counterfactual inflation when one or both constraints are relaxed. As

[33] Services inflation looks very similar with and without energy prices, so we omit it for clarity in the figure.

in the prior counterfactuals, binding constraints continue to play a large quantitative role in driving inflation. Further, note that here we decompose the role of binding constraints for domestic goods production versus imports. Both constraints appear to be important, though the domestic constraint has a larger impact on inflation than the import constraint in most periods.

4.2 Enriching the Labor Market

Motivated by pervasive discussion of labor markets during the pandemic period and recovery, we enrich the labor market of the model in three ways. First, we allow for adjustment frictions for nominal wages, in addition to price adjustment frictions. Second, we introduce shocks to the disutility of labor supply, which stand in for various pandemic-related supply shocks (e.g., responses to disease risk, the great resignation, etc.). Third, we incorporate an occasionally-binding constraint on labor supply, in addition to the goods market capacity constraints considered previously. Unlike normal times, labor supply constraints plausibly loomed large during the COVID period, where stay-at-home orders, school closures, and other abnormal policies constrained households' ability to supply labor to the market.

For brevity, we consign the details about this extended model to the Online Appendix, and we instead focus on one key result here. The model yields a wage Phillips Curve:

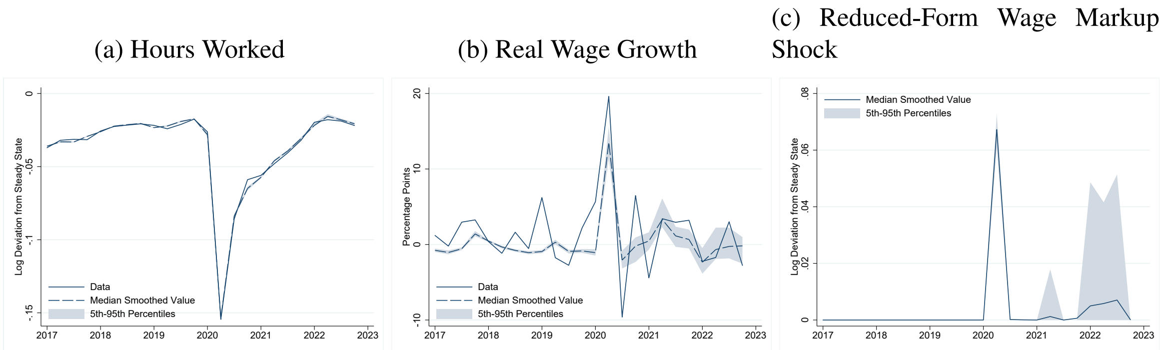
$$\pi_{Wt} = \left(\frac{\varepsilon_L - 1}{\phi_W}\right)\left[\widehat{mrs}_t - \widehat{rw}_t\right] + \left(\frac{\varepsilon_L}{\phi_W}\frac{P_0}{W_0}\right)\hat{\tilde{\mu}}_{Lt} + \beta E_t\left(\pi_{Wt+1}\right), \tag{29}$$

where π_{Wt} is nominal wage inflation, mrs_t is the log of the marginal rate of substitution between labor supply and consumption in preferences, rw_t is the log real wage, and $\tilde{\mu}_{Lt} \equiv 1 + (\mu_{Lt}/C_t{}^{-\rho})$ is a function of the multiplier on the labor constraint (μ_{Lt}).[34]

Two important results follow from inspection of Equation 29. The first (standard) result is that labor (disutility) supply shocks enter the wage Phillips curve via the marginal rate of substitution ($\widehat{mrs}_t$), where increased disutility of supplying labor raises $\widehat{mrs}_t$ and thus wage inflation. Elsewhere in the model, increases in the disutility of labor supply also naturally lower the equilibrium quantity of labor employed as well. The second (non-standard) result is that binding labor constraints appear as reduced-form "markup shocks" in the wage Phillips Curve. As a result, binding labor constraints drive up wage inflation,

[34] For completeness, the parameter ε_L controls steady-state wage markups (the degree of market power exercised by workers) and the parameter ϕ_W controls the flexibility of wages. See the Online Appendix for the details underlying derivation of Equation 29, and how it fits into the remainder of the model.

Figure 11: Model Fit with Labor Market Extensions



Note: We take 1000 draws from the posterior distribution of model parameters, compute the Kalman-smoothed values for model variables for each draw, and then plot the median smoothed value as the solid line. We shade the area covering the 5% to 95% percentile for smoothed values. In Figure 11c, we plot the reduced form labor markup shock term $\left(\frac{\varepsilon_L}{\phi_W}\frac{P_0}{W_0}\right)\hat{\tilde{\mu}}_{Lt}$.

conditional on the other labor market fundamentals.

With these results in hand, we turn to quantitative analysis. We calibrate several new parameters (e.g., ε_L and ϕ_W) based on external references. We then re-estimate the extended model along with stochastic processes for labor disutility and labor constraint shocks using two new observable data series: aggregate hours worked and real wage growth, which are constructed using data from the US Bureau of Labor Statistics. Details on these steps are provided in the Online Appendix.

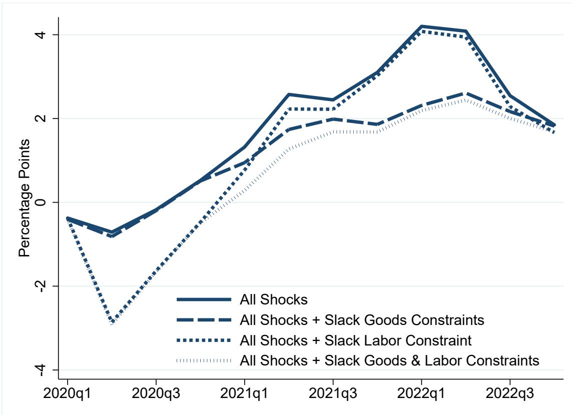
Turning to results, we illustrate model fit and smoothed multipliers on the labor constraint in Figure 11. In Figure 11a, there is an obvious dramatic collapse in hours in early 2020:Q2, a rapid partial rebound in Q3, and then a slow recovery thereafter through 2021. The model matches these dynamics well, in large part through shocks to labor supply. In addition, Figure 11b illustrates that there were sharp gyrations in real wage growth during the early pandemic. However, real wage growth from 2020:Q4 forward was similar to the pre-pandemic period. Turning to Figure 11c, the model clearly favors a binding labor constraint in 2020:Q2, in order to explain the spike and subsequent collapse in real wage growth. Labor constraints then play a less important role in 2021-2022. The median simulation has a slack or nearly slack labor constraint in most periods, though labor constraints do appear to bind in 2022 for a non-trivial share of the simulations.

To evaluate how incorporating labor supply shocks and constraints affect our prior results, we present two sets of counterfactuals.[35] First, in Figure 12a, we illustrate how

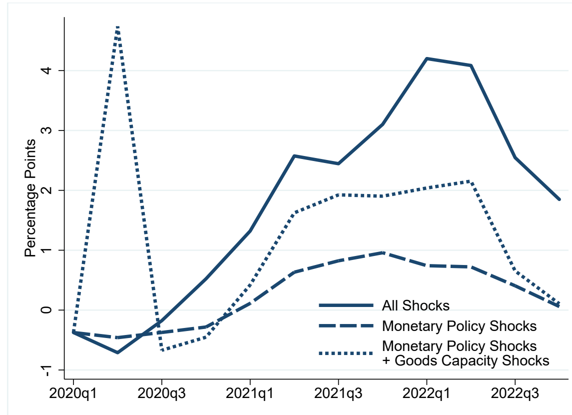
[35]Like prior counterfactuals, we draw form the posterior to parameterize the model and filter smoothed

Figure 12: Counterfactuals with Labor Market Extensions

(a) Relaxing Goods Capacity or Labor Constraints



(b) Monetary Policy Shocks and Capacity Shocks



Note: Each series represents the simulated path of consumer price inflation (quarterly value, annualized) for the indicated subset of smoothed shocks and constraints during 2020-2022. See text for definition of the counterfactuals.

relaxing the goods and labor constraints separately and in combination affects inflation. When the labor constraint is assumed to be slack, inflation falls substantially at the outset of the pandemic, which is counterfactual; thus, binding labor constraints help explain the absence of disinflation in 2020. However, their impact dissipates rapidly, such that inflation is essentially similar across versions of the model with and without labor constraints in 2021-2022. In contrast, assuming goods constraints are slack has little impact on inflation in 2020, but then inflation would have been significantly lower in 2021-2022 with slack goods constraints (this echoes Figure 7c). Further, we point out that the quantitative impact of removing the goods market constraints is essentially the same in this model with labor supply (disutility) shocks as in the baseline without them.

Second, in Figure 12b, we investigate again how monetary policy interacts with constraint shocks in this version of the model. In these simulations, the first simulation shuts off all shocks except for the monetary policy shocks, and the second considers the joint impact of monetary policy shocks and capacity shocks for both domestic and imported goods.

shocks from data, and we then simulate responses to subsets of the smoothed shocks under various assumptions about whether constraints bind. Repeating this procedure 1000 times, we report median outcomes in the figures. As a technical matter, we allow goods constraints to bind endogenously in all these simulations. The labor constraint is a third constraint, which complicates simulation, as the Dynare implementation of OccBin only admits two potentially binding constraints. Therefore, we impose the labor constraint by assuming that there are reduced-form wage markup shocks, which are tied to the smoothed values of the multiplier on the labor constraint. We then solve for whether the two goods constraints are binding endogenously.

As in the prior simulations, monetary policy alone has a moderate effect on inflation, while monetary policy combined with capacity shocks lead to a rapid increase in inflation in 2021, sustained high inflation through 2021 into 2022, and then a collapse in inflation from 2022:Q3 forward.

5 Concluding Remarks

We have developed a quantitative macro-framework that places potentially-binding capacity constraints at center stage. We show that binding constraints alter the Phillips Curve relationship between inflation and real marginal costs, introducing a term that looks like a markup shock in reduced form. Applying the quantitative framework to interpret recent US data, we show that binding constraints are quantitatively important drivers of inflation, explaining half of the rise in US inflation during 2021-2022. We also find that negative capacity shocks tightened constraints during the pandemic period, which set the stage for modestly-sized demand shocks to have outsized impacts on inflation. In particular, monetary policy shocks loom large in driving inflation in 2021.

Going forward, there are various extensions of this framework that would be useful to consider. While the demand-side (discount rate) shocks in our model capture important aspects of fiscal policy, it would be useful to extend the model to provide a more careful treatment of fiscal shocks. Further, we have included capacity as an exogenous, stochastic variable in our framework. We also see high returns to extending the model to include endogenous capacity investment. Lastly, while we have focused on applying the framework to analyze US data in this paper, we intend to apply the model to parse data for other countries (e.g., the UK and euro area) that experienced similar high inflation episodes.

More generally, the framework we have developed can be deployed to study optimal policy, and by extension potential policy mistakes during the pandemic recovery. In our framework, binding constraints imply that demand shocks work through both the IS and Phillips Curves, appearing like a markup shock. This would appear to complicate policy design, relative to canonical frameworks in which shocks to the IS and Phillips Curves are unrelated. Further, when reduced-form markups may reflect either the influence of exogenous markup shocks, or the impact of binding constraints, optimal policy will depend on the central bank's ability to discriminate between them. Given the importance of monetary policy shocks in our quantitative analysis, a critical analysis of policy is warranted.

References

Alessandria, George A., Shafaat Y. Khan, Armen Khederlarian, Carter B. Mix, and Kim J. Ruhl. 2023. "The Aggregate Effects of Global and Local Supply Chain Bottlenecks: 2020-2022." *Journal of International Economics*, 103788.

Álvarez-Lois, Pedro P. 2006. "Endogeneous Capacity Utilization and Macroeconomic Persistence." *Journal of Monetary Economics*, 53: 2213–2237.

Amiti, Mary, Sebastian Heise, and Aidan Wang. 2021. "High Import Prices along the Global Supply Chain Feed Through to U.S. Domestic Prices." Federal Reserve Bank of New York Liberty Street Economics 20211108.

Amiti, Mary, Sebastian Heise, Fatih Karahan, and Ayşegül Şahin. 2023. "Inflation Strikes Back: The Role of Import Competition and the Labor Market." NBER Working Paper No. 31211.

Angeletos, George-Marios, Chen Lian, and Christian K. Wolf. 2023. "Can Deficits Finance Themselves?" NBER Working Paper No. 31185.

Bai, Xiwen, Jesús Fernández-Villaverde, Yiliang Li, and Francesco Zanetti. 2023. "The Causal Effects of Global Supply Chain Disruptions on Macroeconomic Outcomes: Evidence and Theory." Unpublished Manuscript.

Benigno, Gianluca, Julian di Giovanni, Jan J.J. Groen, and Adam I. Noble. 2022. "The GSCPI: A New Barometer of Global Supply Chain Pressures." Federal Reserve Bank of New York Staff Reports, no. 1017.

Bernanke, Ben, and Olivier Blanchard. 2023. "What Caused the U.S. Pandemic-Era Inflation?" NBER Working Paper No. 31417.

Bianchi, Francesco, Renato Faccini, and Leonardo Melosi. forthcoming. "A Fiscal Theory of Persistent Inflation." *The Quarterly Journal of Economics*.

Boehm, Christoph E., and Nitya Pandalai-Nayar. 2022. "Convex Supply Curves." *The American Economic Review*, 112(12): 3941–3969.

Bonadio, Barthélémy, Zhen Huo, Andrei A. Levchenko, and Nitya Pandalai-Nayar. 2021. "Global Supply Chains in the Pandemic." *Journal of International Economics*, 133: 103534.

Cagliarini, Adam, and Mariano Kulish. 2013. "Solving Linear Rational Expectations Models with Predictable Structural Changes." *The Review of Economic Studies*, 95(1): 328–336.

Celasun, Oya, Niels-Jakob Hansen, Aiko Mineshima, MarianoSpector, and Jing Zhou. 2022. "Supply Bottlenecks: Where, Why, How Much,and What Next?" IMF Working Paper WP/22/31.

Del Negro, Marco, Aidan Gleich, Shlok Goyal, Alissa Johnson, and Andrea Tambalotti. 2022. "Drivers of Inflation: The New York Fed DSGE Model's Perspective." The Federal Reserve Bank of New York Liberty Street Economics 20220301.

DePillis, Lydia. 2022. "Is 'Greedflation' Rewriting Economics, or Do Old Rules Still Apply?" *The New York Times*, https://www.nytimes.com/2022/06/03/business/economy/price-gouging-inflation.html.

de Soyres, Francois, Ana Maria Santacreu, and Henry Young. 2023. "Demand-Supply Imbalance during the Covid-19 Pandemic: The Role of Fiscal Policy." *Federal Reserve Bank of St. Louis Review*, 105(1): 21–50.

di Giovanni, Julian, Şebnem Kalemi-Özcan, Alvaro Silva, and Muhammed A. Yildirim. 2023. "Quantifying the Inflationary Impact of Fiscal Stimulus Under Supply Constraints." *AEA Papers and Proceedings*, 113.

di Giovanni, Julian, Şebnem Kalemli-Özcan, Alvaro Silva, and Muhammed A. Yildirim. 2022. "Global Supply Chain Pressures, International Trade, and Inflation." NBER Workign Paper 30240.

Fagnart, Jean-François, Omar Licandro, and Franck Portier. 1999. "Firm Heterogeneity, Capacity Utilization, and the Business Cycle." *Review of Economic Dynamics*, 2: 433–455.

Ferrante, Francesco, Sebastian Graves, and Matteo Iacoviello. forthcoming. "The Inflationary Effects of Sectoral Reallocation." *Journal of Monetary Economics*.

Finck, David, and Peter Tillmann. 2023. "The Macroeconomic Effects of Global Supply Chain Disruptions." Unpublished Manuscript.

Gabaix, Xavier. 2020. “A Behavioral New Keynesian Model.” *American Economic Review*, 110(8): 2271–2327.

Gilchrist, Simon, and John C. Williams. 2000. “Putty-Clay and Investment: A Business Cycle Analysis.” *Journal of Political Economy*, 108(5): 928–960.

Goodman, Peter. 2021. “How the Supply Chain Broke, and Why It Won’t Be Fixed Anytime Soon.” *The New York Times*, https://www.nytimes.com/2021/10/22/business/shortages-supply-chain.html.

Gopinath, Gita, Emine Boz, Camila Casas, Federico Díez, Pierre-Olivier Gourinchas, and Mikkel Plaborg-Møller. 2020. “Dominant Currency Paradigm.” *American Economic Review*, 110(3): 677–719.

Gourinchas, Pierre-Olivier, Şebnem Kalemli-Özcan, Veronika Penciakova, and Nick Sander. 2021. “Fiscal Policy in the Age of COVID: Does it “Get in all of the Cracks”?” NBER Working Papers 29293.

Greenwood, Jeremy, Zvi Hercowitz, and Gregory Huffman. 1988. “Investment, Capacity Utilization, and the Real Business Cycle.” *American Economic Review*, 78(3): 402–17.

Guerrieri, Luca, and Matteo Iacoviello. 2015. “OccBin: A Toolkit for Solving Dynamic Models with Occasionally Binding Constraints Easily.” *Journal of Monetary Economics*, 70: 22–38.

Guerrieri, Luca, and Matteo Iacoviello. 2017. “Collateral Constraints and Macroeconomic Asymmetries.” *Journal of Monetary Economics*, 90: 28–49.

International Monetary Fund. 2021. “Recovery During a Pandemic: Health Concerns, Supply Disruptions, and Price Pressures.” *World Economic Outlook*.

Jones, Callum, Mariano Kulish, and Daniel M. Rees. 2022. “International Spillovers of Forward Guidance Shocks.” *Journal of Applied Econometrics*, 37(1): 131–160.

Jones, Callum, Mariano Kulish, and James Morley. 2022. “A Structural Measure of the Shadow Federal Funds Rate.” Finance and Economics Discussion Series 2021-064. Washington: Board of Governors of the Federal Reserve System.

Kerr, Jaren. 2023. "US Companies Face Biggest Decline in Profits since Covid Shutdowns." *The Financial Times*, https://on.ft.com/41dIw6n.

Kulish, Mariano, and Adrian Pagan. 2017. "Estimation and Solution of Models with Expectations and Structural Changes." *Journal of Applied Econometrics*, 32: 255–274.

Kulish, Mariano, James Morley, and Tim Robinson. 2017. "Estimating DSGE Models with Zero Interest Rate Policy." *Journal of Monetary Economics*, 88: 35–49.

Lafrogne-Joussier, Raphaël, Julien Martin, and Isabelle Mejean. 2023. "Supply Shocks in Supply Chains: Evidence from the Early Lockdown in China." *IMF Economic Review*, 71: 170–215.

Lane, Philip. 2022. "Bottlenecks and Monetary Policy." The European Central Bank The ECB Blog, 10 February.

La'o, Jennifer, and Alireza Alireza Tahbaz-Salehi. 2022. "Optimal Monetary Policy in Production Networks." *Econometrica*, 90(3): 1295–1336.

Rotemberg, Julio J. 1982. "Monopolistic Price Adjustment and Aggregate Output." *The Review of Economic Studies*, 49(4): 517–531.

Santacreu, Ana Maria, and Jesse LaBelle. 2022. "Global Supply Chain Disruptions and-Inflation During the COVID-19 Pandemic." *Federal Reserve Bank of St. Louis Review*, 104(2): 78–91.

Smialek, Jeanna, and Eshe Nelson. 2021. "The world's top central bankers see supply chain problems prolonging inflation." *The New York Times*, https://www.nytimes.com/2021/09/29/business/central-bankers-supply-chains-inflation.html.

The Economist. 2021. "The World Economy's Shortage Problem." *Print Edition*, https://www.economist.com/leaders/2021/10/09/the-world-economys-shortage-problem.

Wu, Jing Cynthia, and Fan Dora Xia. 2016. "Measuring the Macroeconomic Impact of Monetary Policy at the Zero Lower Bound." *Journal of Money, Credit and Banking*, 48(2-3): 253–291.