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This paper studies the optimal conduct of monetary policy in a multisector economy in which firms buy and sell intermediate goods over a production network. We first provide a necessary and sufficient condition for the monetary policy's ability to implement flexible-price equilibria in the presence of nominal rigidities and show that, generically, no monetary policy can implement the first-best allocation. We then characterize the optimal policy in terms of the economy's production network and the extent and nature of nominal rigidities. Our characterization result yields general principles for the optimal conduct of monetary policy in the presence of input-output linkages: it establishes that optimal policy stabilizes a price index with greater weights assigned to larger, stickier, and more upstream industries, as well as industries with less sticky upstream suppliers but stickier downstream customers. In a calibrated version of the model, we find that implementing the optimal policy can result in quantitatively meaningful welfare gains.

KEYWORDS: Monetary policy, production networks, nominal rigidities, misallocation.

1. INTRODUCTION

OPTIMAL MONETARY POLICY in the canonical New Keynesian framework is well known and takes a particularly simple form: as long as there are no missing tax instruments, it is optimal to stabilize the nominal price level. Price stability neutralizes the effects of nominal rigidities, implements flexible-price allocations, and, in the absence of markup shocks, restores productive efficiency. In the language of the New Keynesian literature, the "divine coincidence" holds: price stabilization simultaneously eliminates inflation and the output gap.[1]

The ability of monetary policy to replicate flexible-price allocations in the textbook New Keynesian models, however, relies critically on the assumption that all firms are technologically identical: as long as all firms employ the same production technology, price

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[1]While divine coincidence holds in the absence of markup shocks or when such shocks are neutralized by tax instruments, it may fail more generally when state-contingent tax instruments that may counteract markup shocks are assumed away. In such a case, the monetary authority faces a tradeoff between minimizing the productive inefficiency due to inflation and stabilizing the output gap.

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stabilization implements zero relative price dispersion across firms, and hence achieves productive efficiency, regardless of the extent of nominal rigidities (Correia, Nicolini, and Teles (2008)). But once there are technological differences across firms—say, in a multisector economy with input-output linkages—monetary policy may lose its ability to replicate flexible-price allocations: while productive efficiency would dictate movements in relative quantities across different producers in response to producer-specific shocks, monetary policy may not be able to induce the corresponding relative price movements.

In view of the above, it is not readily obvious what principles should guide the conduct of monetary policy when firms employ heterogenous production technologies, rely on a host of different intermediate goods and services produced by other firms in the economy, and are subject to various degrees of nominal rigidities.

In this paper, we address these questions by studying the optimal conduct of monetary policy in a multisector New Keynesian framework while allowing for intersectoral trade over a production network. We first provide a necessary and sufficient condition for the monetary policy's ability to implement flexible-price equilibria in the presence of nominal rigidities and show that, generically, no monetary policy can implement the first-best allocation. We then characterize the optimal policy in terms of the economy's production network and the extent of nominal rigidities. Our characterization result yields general principles for the optimal conduct of monetary policy in the presence of input-output linkages.

We develop these results in the context of a static multisector general equilibrium model à la Long and Plosser (1983) and Acemoglu, Carvalho, Ozdaglar, and Tahbaz-Salehi (2012) in which firms are linked to one another via input-output linkages and are subject to industry-level productivity shocks.[2] As in the New Keynesian tradition, we assume that firms are subject to nominal rigidities. More specifically, we assume that firms make their nominal pricing decisions under incomplete information about the productivity shocks. As a result, nominal prices respond to changes in productivities only to the extent that such changes are reflected in the firms' information sets. This nominal friction opens the door to potential price distortions throughout the production network, as well as a role for monetary policy in shaping real allocations.

Within this framework, we start by characterizing the entire sets of sticky- and flexible-price equilibria, defined as the sets of allocations that can be implemented as an equilibrium in the presence and absence of nominal rigidities, respectively.[3] We show that while both sets of allocations are characterized by similar sets of conditions relating the marginal rates of substitution between goods and their marginal rates of transformation, the conditions characterizing sticky-price allocations exhibit an additional collection of wedges that depend on the interaction between the conduct of monetary policy and the firms' information sets. Using these characterizations, we then provide the exact conditions on the firms' technologies and information sets under which monetary policy can implement flexible-price equilibria, and hence restore productive efficiency. As an important byproduct of this result, we also show that these conditions are violated for a generic set of information structures, thus concluding that, generically, monetary policy cannot achieve productive efficiency.

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[2]Throughout, we assume that these productivity shocks are the only payoff-relevant shocks in the economy, thus abstracting away from markup shocks.

[3]Our approach is thus similar to Correia, Nicolini, and Teles (2008), Correia, Farhi, Nicolini, and Teles (2013) and Angeletos and La'O (2020), who apply the primal approach to optimal taxation of Atkinson and Stiglitz (2015) and Diamond and Mirrlees (1971) to New Keynesian models.

Having established the failure of monetary policy to implement the first-best allocation, we then turn to the study of optimal monetary policy, that is, the policy that maximizes welfare over the set of all possible sticky-price-implementable allocations. In order to obtain closed-form expressions for the optimal policy, we impose a number of functional form assumptions by assuming that all firms employ Cobb–Douglas production technologies and that all signals are normally distributed.

We establish three sets of results. First, we show that firms' optimal pricing decisions can be recast as a generalized version of a "beauty contest" game à la Morris and Shin (2002), in which firms face heterogenous strategic complementarities in their price-setting decisions due to interdependencies arising from the production network. Second, we demonstrate that monetary policy faces a trade-off between three sources of welfare losses: misallocation due to price dispersion within sectors, misallocation arising from pricing errors across sectors, and output gap volatility. Third, building on our previous results, we derive the monetary policy that optimally trades off these three components.

Our characterization of the optimal policy yields general principles for the conduct of monetary policy in the presence of input-output linkages. In particular, we establish that, all else equal, optimal policy stabilizes a price index with greater weights assigned to (i) larger industries as measured by their sales shares, (ii) stickier industries, (iii) more upstream industries, and (iv) industries with less sticky upstream suppliers but with stickier downstream customers.

We then use our theoretical results to undertake a quantitative exercise and determine the optimal monetary policy for the U.S. economy as implied by the model. Matching input-output tables constructed by the Bureau of Economic Analysis with industry-level data on nominal rigidities, we compute the weights corresponding to the optimal price-stabilization index and quantify the resulting welfare loss due to the presence of nominal rigidities. We find that the optimal policy generates a welfare loss equivalent to 0.65% of quarterly consumption relative to the (unattainable) flexible-price equilibrium, with the overwhelming fraction of this loss arising from misallocation within and across industries. We then provide a comparison between the performance of the optimal policy and four alternative, nonoptimal, price-stabilization policies. We find that, in our calibration, the welfare difference between the optimal policy and a policy that stabilizes the output gap is minuscule, amounting to roughly 0.02 percentage points of quarterly consumption. In contrast, moving from a price-stabilization target based on industries' shares in the household's consumption basket (akin to CPI or PCE) to the optimal price index would result in quantitatively meaningful welfare gains (equal to 1.2 percentage points of quarterly consumption in our baseline calibration).

Related Literature. Our paper is part of the growing literature that studies the role of production networks in macroeconomics. Building on the multisector model of Long and Plosser (1983), Acemoglu et al. (2012) investigate whether input-output linkages can transform microeconomic shocks into aggregate fluctuations.[4] We follow this line of work by focusing on a multisector general equilibrium economy with nominal rigidities and investigating the interaction between monetary policy and the economy's production network. Within this literature, our paper builds on the works of Jones (2013), Bigio

[4]Other papers in this line of work include Carvalho (2010), Foerster, Sarte, and Watson (2011), Acemoglu, Akcigit, and Kerr (2016), Acemoglu, Ozdaglar, and Tahbaz-Salehi (2017), and Atalay (2017). See Carvalho (2014) and Carvalho and Tahbaz-Salehi (2019) for surveys of the theoretical and empirical literature on production networks.

and La'O (2020), and Baqaee and Farhi (2020), who study misallocation in economies with nontrivial production networks. However, in contrast to these papers, which treat markups and wedges as exogenously-given model primitives, we focus on an economy in which wedges are determined endogenously as the result of firms' individually optimal price-setting decisions and monetary policy. We investigate the monetary authority's ability to shape these wedges using available policy instruments, and use this characterization to derive the optimal policy.

In a series of recent papers, Pastén, Schoenle, and Weber (2020a, 2020b), Ozdagli and Weber (2021), and Ghassibe (2021) study the production network's role as a possible transmission mechanism of monetary policy shocks.[5] We differ from these papers by providing a closed-form characterization of the optimal monetary policy as a function of the economy's underlying production network and the extent of nominal rigidities. Also related is the recent work of Wei and Xie (2020), who study the role of monetary policy in the presence of global value chains. Whereas they focus on an open economy in which production occurs over a single production chain, we provide a characterization of optimal policy for a general production network structure in a closed economy.[6]

Our paper also belongs to a small strand of the New Keynesian literature that studies optimal monetary policy in multisector economies. In one of the earliest examples of this line of work, Aoki (2001) shows that in a two-sector economy with one sticky and one fully flexible industry (but no input-output linkages), a policy that stabilizes the price of the sticky industry implements the first-best allocation. Mankiw and Reis (2003), Woodford (2003b, 2010), Benigno (2004), and Eusepi, Hobijn, and Tambalotti (2011) generalize this insight to multisector economies with varying degrees of price stickiness and establish that the monetary authority should stabilize a price index that places greater weights on industries with stickier prices.[7] While most of this literature has abstracted from input-output linkages, Huang and Liu (2005) consider a two-sector economy with a final and an intermediate good and show that it is optimal to stabilize a combination of the price of the two goods. To the best of our knowledge, the prior literature has not studied optimal monetary policy with a general production network.

More closely related to our work is the independent and contemporaneous work of Rubbo (2020), who also studies the implications of input-output linkages in New Keynesian models. While both papers characterize the optimal policy, our work departs from Rubbo's along two dimensions. First, we obtain necessary and sufficient conditions on the economy's disaggregated structure and the nature of nominal rigidities under which monetary policy can implement a given flexible-price allocation. Second, we provide a series of analytical results that distill the role of the various economic forces that shape the optimal policy. Our normative analysis thereby yields general principles for the optimal conduct of monetary policy in the presence of input-output linkages, establishing that monetary policy should stabilize a price index with greater weights assigned to larger, stickier, and more upstream industries, as well as industries with less sticky upstream suppliers but stickier downstream customers.

[5]Also, see Castro (2019), who studies the welfare costs of trend inflation in a quantitative New Keynesian model with sectoral heterogeneity and production networks.

[6]While our focus is squarely on monetary policy, a related strand of literature explores fiscal policy in multisector economies. Cox, Müller, Pastén, Schoenle, and Weber (2021) study the transmission mechanism of fiscal policy in a multisector New Keynesian model with sectoral government spending, whereas Flynn, Patterson, and Sturm (2021) characterize fiscal multipliers in a heterogenous-agent economy with input-output linkages.

[7]This principle of "sticky-price stabilization" was first proposed by Goodfriend and King (1997) and was later formalized in the above mentioned papers. Also, see Erceg, Henderson, and Levin (2000), who study an economy with both nominal price and wage rigidities.

The importance of strategic complementarities in firms' price-setting behavior in the presence of nominal rigidities has a long history. Investigating "in-line" and "roundabout" production structures, Blanchard (1983) and Basu (1995) emphasize the role of intermediate inputs in creating strategic complementarities in firms' price-setting behavior. We build on these papers by providing a closed-form characterization of how strategic complementarities arising from input-output linkages shape equilibrium nominal prices, quantities, and the optimal conduct of monetary policy.

Finally, our approach to modeling nominal rigidities as an informational constraint on the firms' price-setting decisions follows the extensive literature that proposes informational frictions as an appealing substitute to Calvo frictions and menu costs on theoretical (Mankiw and Reis (2002), Woodford (2003a), Mackowiak and Wiederholt (2009), Nimark (2008)) and empirical (Coibion and Gorodnichenko (2012, 2015)) grounds. We follow this approach not only because we find informational frictions to be a priori more plausible than other alternatives, but also because, in the context of our exercise, they lend themselves to a more transparent analysis. Importantly, this modeling feature does not upset the key normative lessons of the New Keynesian paradigm; in particular, price stability remains optimal insofar as monetary policy need not substitute for missing tax instruments (Angeletos and La'O (2020)).

Outline. The rest of the paper is organized as follows. Section 2 sets up the environment and defines the sticky- and flexible-price equilibria in our context. Section 3 characterizes these equilibria and provides necessary and sufficient conditions for the monetary policy's ability to implement the first-best allocation. Section 4 contains our closed-form characterization of the optimal policy in terms of the economy's production network and the extent of nominal rigidities. We present a quantitative analysis of the model in Section 5. The Appendix contains additional theoretical results. All proofs and some additional technical details are presented in the Online Supplementary Material (La'O and Tahbaz-Salehi (2022)).

2. FRAMEWORK

Consider a static economy consisting of n industries indexed by $i \in I = \{1, 2, \dots, n\}$. Each industry consists of two types of firms: (i) a unit mass of monopolistically-competitive firms, indexed by $k \in [0, 1]$, producing differentiated goods and (ii) a competitive producer whose sole purpose is to aggregate the industry's differentiated goods into a single sectoral output. The output of each industry can be either consumed by the households or used as an intermediate input for production by firms in other industries. In addition to the firms, the economy consists of a representative household as well as a government with the ability to levy industry-specific taxes and control nominal aggregate demand.

The monopolistically-competitive firms within each industry use a common constant-returns-to-scale technology to transform labor and intermediate inputs into their differentiated products. More specifically, the production function of firm $k \in [0, 1]$ in industry i is given by

$$y_{ik} = z_i F_i(l_{ik}, x_{i1,k}, \dots, x_{in,k}),$$

where y_{ik} is the firm's output, l_{ik} is its labor input, $x_{ij,k}$ is the amount of sectoral commodity j purchased by the firm, z_i is an industry-specific productivity shock, and F_i is a homogenous function of degree one. Throughout, we assume that labor is an essential input for the production technology of all goods, in the sense that $F_i(0, x_{i1,k}, \ldots, x_{in,k}) = 0$ and that $\partial F_i/\partial l_{ik} > 0$ whenever all other inputs are used in positive amounts. Unless otherwise noted—and without much loss of generality—we also assume that $\partial F_i/\partial x_{ij,k} > 0$ for all pairs of industries i and j.

The nominal profits of firm k in industry i are given by

$$\pi_{ik} = (1 - \tau_i) p_{ik} y_{ik} - w l_{ik} - \sum_{j=1}^{n} p_j x_{ij,k}, \tag{1}$$

where p_{ik} is the nominal price charged by the firm, p_j is nominal price of industry j's sectoral output, w denotes the nominal wage, and τ_i is an industry-specific revenue tax (or subsidy) levied by the government.

The competitive producer in industry i transforms the differentiated products produced by the unit mass of firms in that industry into a sectoral good using a constant-elasticity-of-substitution (CES) production technology with elasticity of substitution $\theta_i > 1$:

$$y_i = \left(\int_0^1 y_{ik}^{(\theta_i - 1)/\theta_i} \, \mathrm{d}k \right)^{\theta_i/(\theta_i - 1)}.$$

This producer's profits are thus given by $\pi_i = p_i y_i - \int_0^1 p_{ik} y_{ik} \, \mathrm{d}k$, where p_i is the price of the aggregated good produced by industry i. We include this producer—which has zero value added and makes zero profits in equilibrium—to ensure that a homogenous good is produced by each industry, while at the same time allowing for monopolistic competition among firms within the industry.

The preferences of the representative household are given by

$$W(C, L) = U(C) - V(L), \tag{2}$$

where C and L denote the household's final consumption basket and total labor supply, respectively. We impose the typical regularity conditions on U and V: they are strictly increasing, twice differentiable, and satisfy $U'' < 0$, $V'' > 0$, and the Inada conditions. The final consumption basket of the household is given by $C = \mathcal{C}(c_1, \ldots, c_n)$, where c_i is the household's consumption of the good produced by industry i and $\mathcal{C}$ is a homogenous function of degree one.[8] The representative household's budget constraint is thus given by

$$PC = \sum_{j=1}^{n} p_j c_j \leq wL + \sum_{i=1}^{n} \int_0^1 \pi_{ik} \, \mathrm{d}k + T,$$

where $P = \mathcal{P}(p_1, \ldots, p_n)$ is the nominal price of the household's consumption bundle. The left-hand side of the above inequality is the household's nominal expenditure, whereas the right-hand side is equal to the household's total nominal income, consisting of labor income, dividends from owning firms, and lump-sum transfers from the government.

In addition to the firms and the household, the economy also consists of a government with the ability to set fiscal and monetary policies. The government's fiscal instrument is

[8] Unless otherwise noted, and without much loss of generality, we assume that $\partial \mathcal{C}/\partial c_i > 0$ for all i.

a collection of industry-specific taxes (or subsidies) on the firms, with the resulting revenue then rebated to the household as a lump-sum transfer. Therefore, the government's budget constraint is given by

$$T=\sum_{i=1}^{n}\tau_i\int_0^1 p_{ik}y_{ik}\,\mathrm{d}k,$$

where τ_i is the revenue tax imposed on firms in industry i and T is the net transfer to the representative household. Finally, to model monetary policy, we sidestep the microfoundations of money and, instead, impose the following cash-in-advance constraint on the household's total expenditure:

$$PC=m, \tag{3}$$

where we assume that m—which can be interpreted as either money supply or nominal aggregate demand—is set directly by the monetary authority.

2.1. *Nominal Rigidities and Information Frictions*

We model nominal rigidities by assuming that firms do not observe the realized productivity shocks $z=(z_1,\dots,z_n)$ and, instead, make their nominal pricing decisions under incomplete information. This assumption implies that nominal prices respond to changes in productivities only to the extent that such changes are reflected in the firms' information sets.

Formally, we assume that each firm k in industry i receives a signal $\omega_{ik}\in\Omega_{ik}$ about the economy's aggregate state. The aggregate state includes not only the vector of realized productivity shocks, but also the realization of all signals, that is,

$$s=(z,\omega)\in\mathbb{R}_+^n\times\Omega=S,$$

where $\omega=(\omega_1,\dots,\omega_n)\in\Omega$ denotes the cross-sectional profile of realized signals in the economy and $\omega_i=(\omega_{ik})_{k\in[0,1]}\in\Omega_i$ denotes the cross-sectional profile of realized signals in industry i.

Since ω_{ik} is the only component of state s that is observable to firm k in industry i, the nominal price set by this firm can be contingent on ω_{ik}, but not on the aggregate state, s. We capture this measurability constraint by denoting the firm's nominal price by $p_{ik}(\omega_{ik})$. Similarly, we write $p_i(\omega_i)$ and $P(\omega)$ to capture the fact that the nominal prices of sectoral good i and the consumption bundle can be contingent only on the profiles of signals in industry i and in the entire economy, respectively (but not on the agggregate state, s).[9] Throughout, we assume that, prior to receiving their private signals, all firms share a common prior belief.

A few remarks are in order. First, note that the above formulation implies that state $s=(z,\omega)$ not only contains all payoff-relevant shocks, but also contains shocks to the aggregate profile of beliefs. Therefore, our framework can accommodate the possibility of higher-order uncertainty, as ω_{ik} may contain information about other firms' (first- or higher-order) beliefs, as in Angeletos and La'O (2013). Second, our framework is flexible

[9]Note that the CES technology of sectoral good producers implies that $p_i(\omega_i)=(\int_0^1 p_{ik}^{1-\theta_i}(\omega_{ik})\,\mathrm{d}k)^{1/(1-\theta_i)}$. Similarly, the consumption good's price index is given by $P(\omega)=\mathcal{P}(p_1(\omega_1),\dots,p_n(\omega_n))$.

enough to nest models with "sticky information" (Mankiw and Reis (2002)) as a special case by assuming that a fraction of firms in industry i set their nominal prices under complete information ($\omega_{ik} = z$), whereas the rest of the firms in that industry observe no informative signals ($\omega_{ik} = \emptyset$), and hence set their nominal prices based only on their prior beliefs. Finally, note that the information structure in our framework is exogenous: while firm-level signals can depend on the exogenous productivity shocks $(z_1, \dots, z_n)$, they do not depend on the endogenous objects in the economy (such as prices). This means that our formulation rules out the possibility that a firm can set a nominal price that is contingent on prices set by other firms in the economy.

In summary, we can represent the economy's price system by the collection of nominal prices and nominal wage at any given state:[10]

$$\varrho = \left\{\left(\left(p_{ik}(\omega_{ik})\right)_{k\in[0,1]}, p_i(\omega_i)\right)_{i\in I}, P(\omega), w(s)\right\}_{s\in S}.$$

While nominal prices are set under incomplete information, we assume that firms and the household make their quantity decisions after observing the prices and the realization of productivities. As a result, quantities may depend on the entire state, s. We thus represent an allocation in this economy by

$$\xi = \left\{\left(\left(y_{ik}(s), l_{ik}(s), x_{ik}(s)\right)_{k\in[0,1]}, y_i(s), c_i(s)\right)_{i\in I}, C(s), L(s)\right\}_{s\in S},$$

where $l_{ik}(s)$, $x_{ik}(s) = (x_{i1,k}(s), \dots, x_{in,k}(s))$, and $y_{ik}(s)$ denote, respectively, the labor input, material inputs, and output of firm k in industry i, $y_i(s)$ is the output of industry i, $c_i(s)$ is the household's consumption of sectoral good i, and $C(s)$ and $L(s)$ are the household's consumption and labor supply, respectively.

We conclude this discussion by specifying how government policy depends on the economy's aggregate state. Recall from equations (1) and (3) that the fiscal and monetary authorities can, respectively, levy taxes and control the nominal aggregate demand. We assume that while the fiscal authority has the ability to levy industry-specific taxes τ_i, these taxes cannot be contingent on the economy's aggregate state. In contrast, the monetary authority can set the nominal demand as an arbitrary function $m(s)$ of the economy's aggregate state, s. This is equivalent to assuming that the monetary authority has the ability to commit, ex ante, to a policy that can, in principle, depend on the realized productivities and the profile of beliefs throughout the economy. Government policy can thus be summarized as

$$\upsilon = \left\{(\tau_1, \dots, \tau_n), m(s)\right\}_{s\in S}. \tag{4}$$

Note that, as in the standard New Keynesian literature, our formulation of the government's policy instruments in (4) allows for noncontingent taxes to undo steady-state distortions due to monopolistic markups, while ruling out state-contingent taxes.[11] We also remark that while it may be far-fetched to assume that the monetary authority can

[10] This formulation assumes that the nominal wage, w, can depend on the entire state, s. While this assumption simplifies the exposition, it is without loss of generality: in our multisector framework, one can incorporate nominal wage rigidities by introducing a pseudo-industry that transforms, one-for-one, the labor supplied by the representative household into labor services sold to the rest of the industries in the economy. The information sets of firms in this pseudo-industry then determine the extent and nature of nominal wage rigidity.

[11] It is well understood that with a sufficiently rich set of state-contingent tax instruments, one can undo the real effects of nominal rigidities and implement the first-best allocation under any monetary policy (see, e.g., Correia et al. (2013)).

commit to a policy that is contingent not just on the payoff-relevant shocks, z, but also on the entire profile of beliefs, ω, we nonetheless make this assumption to illustrate the limit to monetary policy's ability to implement allocations even under maximum policy flexibility.

2.2. *Equilibrium Definition*

We now define our notions of sticky- and flexible-price equilibria. To this end, first note that the market-clearing conditions for labor and commodity markets are given by

$$L(s) = \sum_{i=1}^{n} \int_0^1 l_{ik}(s)\,\mathrm{d}k, \tag{5}$$

$$y_i(s) = c_i(s) + \sum_{j=1}^{n} \int_0^1 x_{ji,k}(s)\,\mathrm{d}k = \left(\int_0^1 y_{ik}(s)^{(\theta_i-1)/\theta_i}\,\mathrm{d}k \right)^{\theta_i/(\theta_i-1)} \tag{6}$$

for all industries i and all states s, whereas the production technology of firm k in industry i requires that

$$y_{ik}(s) = z_i F_i\big(l_{ik}(s), x_{i1,k}(s), \dots, x_{in,k}(s)\big) \tag{7}$$

for all states s. Given the above, the definition of a sticky-price equilibrium is straightforward.

DEFINITION 1: A *sticky-price equilibrium* is a triplet (ξ, ϱ, υ) of allocations, prices, and policies such that:

(i) the monopolistically-competitive firms in each industry set prices $p_{ik}(\omega_{ik})$ to maximize expected real value of profits given their information and optimally choose inputs to meet realized demand;
(ii) the competitive producer in each industry chooses inputs to maximize its profits given prices;
(iii) the representative household chooses consumption and labor supply to maximize utility subject to its budget constraint;
(iv) the government budget constraint is satisfied;
(v) all markets clear.

We next define our notion of flexible-price equilibria by dropping the measurability constraint on prices imposed on sticky-price equilibria in Definition 1. More specifically, we assume that, in a flexible-price equilibrium, firms make their nominal pricing decisions based on complete information about the aggregate state. We can capture this scenario in our framework by simply considering the special case in which all firm-level prices can be contingent on the aggregate state, s. Accordingly, we adjust our notation for the nominal prices of firm-level goods, sectoral goods, and the consumption bundle by expressing them as $p_{ik}(s)$, $p_i(s)$, and $P(s)$, respectively.

DEFINITION 2: A *flexible-price equilibrium* is a triplet (ξ, ϱ, υ) of allocations, prices, and policies that satisfy the same conditions as those stated in Definition 1, except that all prices can be contingent on the aggregate state, s.

While not the main focus of our study, the set of flexible-price-implementable allocations serves as a benchmark to which we will contrast equilibria in the presence of nominal rigidities. We conclude with one additional definition, whose meaning is self-evident.

DEFINITION 3: An allocation ξ is *feasible* if it satisfies resource constraints (5), (6), and (7).

3. STICKY- AND FLEXIBLE-PRICE EQUILIBRIA AND THE POWER OF MONETARY POLICY

In this section, we provide a characterization of the set of all allocations that can be implemented as part of flexible- and sticky-price equilibria. We then use our characterization results to establish that, except for a nongeneric set of specifications, the two sets of allocations never intersect, thus implying that, in our multisector framework, monetary policy cannot undo the effects of nominal rigidities.

3.1. *First-Best Allocation*

We start by focusing on the first-best allocation that maximizes household welfare (2), state-by-state, among all feasible allocations. Note that, by symmetry, a planner who maximizes social welfare dictates that all firms within an industry choose the same intermediate input, labor, and output quantities. We can therefore drop the firm index k. The equations characterizing the planner's optimum are straightforward and are summarized in the following lemma.

LEMMA 1: *The first-best optimal allocation is a feasible allocation that satisfies*

$$V'\big(L(s)\big) = U'\big(C(s)\big)\frac{\partial \mathcal{C}}{\partial c_i}(s) z_i \frac{\partial F_i}{\partial l_i}(s), \tag{8}$$

$$\frac{\partial \mathcal{C}/\partial c_j}{\partial \mathcal{C}/\partial c_i}(s) = z_i \frac{\partial F_i}{\partial x_{ij}}(s) \tag{9}$$

for all pairs of industries i and j and all states s.

Equation (8) states that, for any good, it is optimal to equate the marginal rate of substitution between consumption of that good and labor with the marginal rate of transformation. In particular, the planner equates the household's marginal disutility of labor on the left-hand side of (8) with its marginal social benefit on the right-hand side, which itself consists of three multiplicative components: the marginal product of labor in the production of commodity i, the marginal product of good i in the production of the final good, and the marginal utility of consumption of the final good.

The second condition, (9), similarly indicates that the planner finds it optimal to equate the marginal rate of substitution between two goods to their marginal rate of transformation. The marginal rate of substitution on the left-hand side of equation (9) is the ratio of marginal utilities from consumption of the two goods, whereas the marginal rate of transformation is simply the marginal product of good j in the production of good i, as shown on the right-hand side of this condition.

3.2. *Flexible-Price Equilibrium*

We now turn to the set of allocations that are implementable as flexible-price equilibria. Since the tax instruments $(\tau_1, \dots, \tau_n)$ are industry-specific and, in any flexible-price equilibrium, all firms in the same industry have identical information sets, we can once again drop the firm index k.

PROPOSITION 1: *A feasible allocation is part of a flexible-price equilibrium if and only if there exists a set of positive scalars* $(\chi_1^f, \dots, \chi_n^f)$ *such that*

$$V'\big(L(s)\big) = \chi_i^f U'\big(C(s)\big) \frac{\partial \mathcal{C}}{\partial c_i}(s) z_i \frac{\partial F_i}{\partial l_i}(s), \tag{10}$$

$$\frac{\partial \mathcal{C}/\partial c_j}{\partial \mathcal{C}/\partial c_i}(s) = \chi_i^f z_i \frac{\partial F_i}{\partial x_{ij}}(s) \tag{11}$$

for all pairs of industries i and j and all states s.

The conditions in Proposition 1 are identical to those characterizing the first-best allocation in Lemma 1, aside from the set of scalars $(\chi_1^f, \dots, \chi_n^f)$. The first condition (10) indicates that for any good, the marginal rate of substitution between consumption and labor is equal to the marginal rate of transformation, modulo a noncontingent wedge, χ_i^f. Similarly, the second condition equates the marginal rate of substitution between two goods to their marginal rate of transformation, again subject to the wedge χ_i^f. This nonstochastic wedge, which is given by

$$\chi_i^f = (1 - \tau_i) \frac{\theta_i - 1}{\theta_i}, \tag{12}$$

consists of two terms: the tax or subsidy levied by the government and the markup that arises due to monopolistic competition among firms within each industry. As a result, the scalars $(\chi_1^f, \dots, \chi_n^f)$ parameterize the power of the fiscal authority. In particular, with sectoral taxes or subsidies, the fiscal authority can influence the allocation through the wedges in conditions (10) and (11).

Another immediate consequence of Proposition 1 is that the first-best allocation is implementable as a flexible-price equilibrium. This follows from the observation that equations (10) and (11) reduce to (8) and (9) whenever $\chi_i^f = 1$ for all i. Consequently, the first-best allocation can be implemented as a flexible-price equilibrium with industry-specific subsidies $\tau_i = 1/(1 - \theta_i)$. This, of course, is not surprising: the only distortion in the economy without nominal rigidities arises from monopolistic competition. Therefore, the government can implement the first-best allocation by setting industry-specific subsidies that are invariant to the economy's aggregate state and undo the monopolistic markups.

3.3. *Sticky-Price Equilibrium*

With the above preliminary results in hand, we are now ready to characterize the set of equilibrium allocations in the presence of nominal rigidities.

PROPOSITION 2: *A feasible allocation is implementable as a sticky-price equilibrium if and only if there exist positive scalars* $(\chi_1^s, \dots, \chi_n^s)$, *a monetary policy function* $m(s)$, *and firm-level wedges* $\varepsilon_{ik}(s)$ *such that*:

(i) *the allocation, the scalars* $(\chi_1^s, \dots, \chi_n^s)$, *and firm-level wedges* $\varepsilon_{ik}(s)$ *jointly satisfy*

$$V'\big(L(s)\big) = \chi_i^s \varepsilon_{ik}(s) U'\big(C(s)\big) \frac{\partial \mathcal{C}}{\partial c_i}(s) z_i \frac{\partial F_i}{\partial l_i}(s) \left(\frac{y_{ik}(s)}{y_i(s)}\right)^{-1/\theta_i}, \tag{13}$$

$$\frac{\partial \mathcal{C}/\partial c_j}{\partial \mathcal{C}/\partial c_i}(s) = \chi_i^s \varepsilon_{ik}(s) z_i \frac{\partial F_i}{\partial x_{ij}}(s) \left(\frac{y_{ik}(s)}{y_i(s)}\right)^{-1/\theta_i} \tag{14}$$

for all firms k, *all pairs of industries* i *and* j, *and all states* s;

(ii) *the monetary policy function* $m(s)$ *induces firm-level wedges* $\varepsilon_{ik}(s)$ *given by*

$$\varepsilon_{ik}(s) = \frac{\mathrm{mc}_i(s) \mathbb{E}_{ik}\big[v_{ik}(s)\big]}{\mathbb{E}_{ik}\big[\mathrm{mc}_i(s) v_{ik}(s)\big]} \tag{15}$$

for all firms k, *all industries* i, *and all states* s, *where* $\mathbb{E}_{ik}[\cdot]$ *denotes the expectation with respect to the information set of firm* k *in industry* i,

$$\mathrm{mc}_i(s) = m(s) \frac{V'\big(L(s)\big)}{C\big((s)\big)U'\big(C(s)\big)} \left(z_i \frac{\partial F_i}{\partial l_i}(s)\right)^{-1} \tag{16}$$

is the nominal marginal cost of firms in industry i, *and*

$$v_{ik}(s) = U'\big(C(s)\big) \frac{\partial \mathcal{C}}{\partial c_i}(s) y_i(s) \left(\frac{y_{ik}(s)}{y_i(s)}\right)^{(\theta_i - 1)/\theta_i}. \tag{17}$$

Proposition 2 provides a characterization of the set of sticky-price implementable allocations in terms of model primitives and the monetary policy instrument, $m(s)$. It is straightforward to see that conditions (13) and (14) are identical to their flexible-price counterparts (10) and (11) in Proposition 1, except for a new wedge, $\varepsilon_{ik}(s)$. Also, as in Proposition 1, industry-specific wedges $(\chi_1^s, \dots, \chi_n^s)$ are given by (12) and capture the fiscal authority's ability to influence allocations via tax instruments.

The new wedge $\varepsilon_{ik}(s)$ in equations (13) and (14), which is firm-specific and depends on the economy's aggregate state, represents an additional control variable for the government, one that encapsulates the power of monetary policy over real allocations in the presence of nominal rigidities. Similar to the fiscal authority's ability to influence the allocation by setting taxes, the monetary authority can implement different allocations by moving the wedges $\varepsilon_{ik}(s)$ in (13) and (14). This power is nontrivial, but it is also constrained by conditions (15) and (16): unlike the fiscal authority's full control over $(\chi_1^s, \dots, \chi_n^s)$, the monetary authority's choice of the single policy instrument $m(s)$ pins down all wedges $\varepsilon_{ik}(s)$ at the same time.

The constraint on the monetary policy's ability in shaping real allocations can also be seen by the fact that equation (15) implies $\mathbb{E}_{ik}[v_{ik}(s)(\varepsilon_{ik}(s) - 1)] = 0$. This means the wedge $\varepsilon_{ik}(s)$ cannot be moved around in an unconstrained manner, as it has to be equal to 1 in expectation irrespective of the policy. This is because these wedges arise only due to "mistakes" by the sticky-price firms in setting their nominal prices. But since firms set their prices optimally given their information sets, they do not make any pricing errors in expectation.

As a final remark, we note that, in sticky-price equilibria, firms are uncertain not only about their marginal costs, but also about the demand they face from their downstream customers, as well as the household's marginal utility of consumption. As a result, firm k in industry i sets its nominal price to $p_{ik}(\omega_{ik}) = (1/\chi_i^s)\mathbb{E}_{ik}[\text{mc}_i(s)v_{ik}(s)]/\mathbb{E}_{ik}[v_{ik}(s)]$, where $v_{ik}(s)$ is given by (17) and is proportional to the product of the stochastic discount factor and the demand $y_{ik}(s)$ faced by the firm.[12]

3.4. *The Power of Monetary Policy*

As illustrated in Proposition 2, the monetary authority can use monetary policy to implement different allocations by moving around the wedge $\varepsilon_{ik}(s)$ as a function of the economy's aggregate state. This leads to the natural question of whether monetary policy can fully undo the effect of nominal rigidities. Our first main result provides an answer to this question by characterizing the set of flexible-price allocations that can be implemented as sticky-price equilibria.

To state this result, let $\sigma(\omega_{ik})$ denote the σ-field generated by the signal ω_{ik}. Also, let $g_i(z_1, \dots, z_n)$ denote the marginal product of labor in the production of commodity i (as a function of productivity shocks) under the first-best allocation. Note that g_i only depends on the firms' production technologies and is independent of household preferences, policy, and the economy's information structure. We have the following result.

THEOREM 1: *A flexible-price allocation indexed by $(\chi_1^f, \dots, \chi_n^f)$ is implementable as a sticky-price equilibrium if and only if there exists a nominal wage function $w(s)$ such that*

$$w(s)/g_i\big(\chi_1^f z_1, \dots, \chi_n^f z_n\big) \in \sigma(\omega_{ik}) \tag{18}$$

for all firms $k \in [0, 1]$ in all industries i, where $w(s)$ is pinned down by the monetary policy via $w(s) = m(s)V'(L(s))/C(s)U'(C(s))$.

This theorem provides a joint restriction on the technology, information structure, and monetary policy under which a flexible-price allocation can be implemented as a sticky-price equilibrium. It establishes that monetary policy can implement a given flexible-price allocation if and only if there exists a policy-induced function $w(s)$ that can make the expression $w(s)/g_i(\chi_1^f z_1, \dots, \chi_n^f z_n)$ measurable with respect to the information sets of all firms in industry i, simultaneously for all industries. To see the intuition underlying this result, note that the left-hand side of (18) coincides with the nominal marginal cost of firms in industry i under complete information. Therefore, Theorem 1 states that the monetary authority can implement flexible-price allocations and neutralize the effect of nominal rigidities if and only if there exists a policy that makes all firms' nominal marginal costs measurable with respect to their corresponding information sets. This guarantees that all firms set their nominal prices as if they had complete information about their nominal marginal costs.

We can now use the characterization in Theorem 1 to obtain the following corollary.

COROLLARY 1: *Let $\mathcal{A}^f$ and $\mathcal{A}^s$ denote the sets of allocations that are implementable as flexible-price and sticky-price equilibria, respectively. Then $\mathcal{A}^f \cap \mathcal{A}^s = \emptyset$ for a generic set of information structures.*

[12]This observation also illustrates that $\varepsilon_{ik}(s)$ is the reciprocal of the firm-level markup arising due to nominal rigidities. Specifically, it implies that $p_{ik}(\omega_{ik}) = \frac{1}{\chi_i^s \varepsilon_{ik}(s)}\text{mc}_i(s)$.

That is, in general, any allocation implementable as an equilibrium under flexible prices cannot be implemented as an equilibrium under sticky prices with any monetary policy. Interpreted through the lens of Theorem 1, the above result is an immediate consequence of the observation that, in general, it is impossible to satisfy condition (18) for all firms simultaneously. The following result is then immediate.

COROLLARY 2: *In a multisector economy with given preferences and technologies*, *the first-best allocation is not implementable as a sticky-price equilibrium for a generic set of information structures*.

The intuition behind Corollary 2 is straightforward. Consider the planner's optimal allocation which can itself be implemented as a flexible-price equilibrium with appropriate industry-level subsidies. The planner would like relative quantities across industries to move efficiently with productivity shocks, while at the same time ensuring that all firms within each industry produce the same quantity. In order to implement this under flexible prices, relative prices across industries should move with relative productivities, while prices across firms within each industry should be identical. This specific pattern of price movements with productivity shocks is necessary for flexible-price allocations and in particular for implementing the first-best allocation.

However, inducing this pattern of price movements is in general impossible under sticky prices in a multisector economy. In order to ensure that prices are uniform within a particular industry, the monetary authority must target price stability for that industry. This is the typical first-best policy in one-sector New Keynesian models as it implements zero price dispersion, and hence productive efficiency within that particular industry. But when there are multiple industries, if monetary policy is used to achieve price stability within one particular industry, it cannot, in general, be used to target price stability in any other industry. That is, monetary policy cannot stabilize prices in all industries at once. And even if it could—for example, because the information structure is such that all firms in any given industry set the same exact price—it is still not sufficient for achieving the first best: in general, no monetary policy can induce relative prices of all pairs of industries to move with their corresponding productivity shocks.

Another consequence of condition (18) and Corollaries 1 and 2 is that monetary policy may not be able to implement the first-best allocation even if all firms in the economy have perfect information about their own productivities: incomplete information about productivity shocks to other industries can also make flexible-price allocations not implementable as sticky-price equilibria.[13]

That the single instrument of monetary policy cannot eliminate multiple distortions simultaneously is in line with Erceg, Henderson, and Levin (2000) and Woodford (2003b), who obtain similar results for, respectively, an economy with price and wage rigidities and a two-sector economy with no input-output linkages. Theorem 1 extends these findings and provides a characterization of conditions on model primitives under which monetary policy can neutralize the effect of nominal rigidities and implement flexible-price allocations.

While Corollaries 1 and 2 illustrate the limitation of monetary policy in a generic multisector economy, there are some nongeneric, yet important, special cases in which the monetary authority can implement the first-best allocation.

[13]However, (18) implies that a sufficient condition for sticky-price implementability of flexible-price allocations is that firms in industry i have complete information about productivity shocks to all their (direct and indirect) upstream industries.

COROLLARY 3: *If there is a single sticky-price industry* i, *any flexible-price allocation can be implemented as a sticky-price equilibrium with a monetary policy that stabilizes industry* i*'s price*.

This result is an immediate consequence of Theorem 1: if there is a single sticky-price industry i, then setting $w(s) = Mg_i(\chi_1^f z_1, \dots, \chi_n^f z_n)$ for any constant $M > 0$ ensures that the left-hand side of (18) is measurable with respect to the information set of all firms in industry i. Importantly, such a policy stabilizes the nominal marginal cost, and hence the nominal price of firms in the sticky-price industry: $\text{mc}_i(s) = M$ and $p_{ik}(\omega_{ik}) = M/\chi_i^f$, both of which are independent of the economy's aggregate state.

Though focused on a nongeneric class of economies, Corollary 3 nests two important economies as special cases. The first special case is the textbook single-sector New Keynesian model with no markup shocks. As is well known (and in line with Corollary 3), the first-best allocation can always be implemented by a combination of (i) price stabilization and (ii) an industry-level subsidy that eliminates monopolistic markups. Importantly, the above result establishes that such a policy mix is optimal irrespective of the nature and extent of information frictions, thus generalizing the insights of Correia, Nicolini, and Teles (2008) to a broad class of nominal rigidities. The second special case is the two-sector model of Aoki (2001), who considers an economy consisting of one flexible industry and one sticky industry subject to Calvo frictions and shows that stabilizing the price of the sticky industry can implement the first-best allocation. Corollary 3 establishes that, as long as there is a single sticky-price industry, Aoki's result generalizes to a multisector economy with input-output linkages and an arbitrary form of pricing friction.

COROLLARY 4: *If firms have complete information about all shocks except for an aggregate labor-augmenting shock*, *then any flexible-price allocation can be implemented as a sticky-price equilibrium*.

This result is a consequence of the fact that in an economy with constant returns and a single factor of production (labor), the marginal products of labor of all industries in the first-best allocation move one-for-one with aggregate labor-augmenting shocks. As a result, a monetary policy that implements a nominal wage function, $w(s)$, that also moves one-for-one with the shock ensures that the left-hand side of (18) is invariant to the shock, and hence is measurable with respect to all firms' information sets. Importantly, the same argument does not apply to aggregate TFP shocks: in general, monetary policy cannot neutralize the impact of nominal rigidities that are due to incomplete information about aggregate TFP shocks. This disparity highlights the fact that, in our multisector economy, whether the single instrument of monetary policy can implement the first-best allocation depends not only on the number of (unobservable) shocks, but also on how relative prices of different industries respond to those shocks.

3.5. *Cobb–Douglas Economies*

We conclude this section by studying the implications of Theorem 1 for the benchmark class of Cobb–Douglas economies. The log-linearity of production technologies in this class of economies allows us to obtain explicit conditions on the economy's production network and information structure under which monetary policy is able to implement flexible-price equilibria.

Let the production technology of firm k in industry i be given by

$$y_{ik} = z_i F_i(l_{ik}, x_{i1,k}, \dots, x_{in,k}) = z_i \zeta_i l_{ik}^{\alpha_i} \prod_{j=1}^{n} x_{ij,k}^{a_{ij}}, \tag{19}$$

where $\alpha_i \geq 0$ denotes the share of labor in industry i's production technology, $a_{ij} \geq 0$ parameterizes the importance of good j in the production technology of firms in industry i, and ζ_i is a normalization constant, the value of which only depends on model parameters and is independent of the shocks.[14] Input-output linkages in this economy can thus be summarized by matrix $\mathbf{A} = [a_{ij}]$, which with some abuse of terminology, we refer to as the economy's *input-output matrix*. We also define the economy's *Leontief inverse* as $\mathbf{L} = (\mathbf{I} - \mathbf{A})^{-1}$, whose (i, j) element captures the role of industry j as a direct or indirect intermediate input supplier to industry i.

The consumption basket is also a Cobb–Douglas aggregator of the sectoral goods given by

$$\mathcal{C}(c_1, \dots, c_n) = \prod_{i=1}^{n} (c_i/\beta_i)^{\beta_i}, \tag{20}$$

where c_i is the amount of good i consumed and $(\beta_1, \dots, \beta_n)$ are nonnegative constants that measure various goods' shares in the household's consumption basket, normalized such that $\sum_{i=1}^{n} \beta_i = 1$. We have the following result.

PROPOSITION 3: *In a Cobb–Douglas economy with Leontief inverse* $\mathbf{L}$,

(a) *the monetary authority can implement the first-best allocation using a price-stabilization policy if and only if there exists a substochastic vector* $\psi = (\psi_1, \dots, \psi_n)'$ *such that*[15]

$$(\psi' - u_i')\mathbf{L}\mathbf{V}_{ik} = 0 \quad \textit{for all firms } k \textit{ in all industries } i, \tag{21}$$

where u_i *is the ith unit vector and* $\mathbf{V}_{ik} = \operatorname{var}_{ik}(\log z)$ *denotes the covariance matrix of log productivity shocks conditional on the information set of firm k in industry i.*

(b) *If (21) is satisfied, the first-best allocation can be implemented by stabilizing a price index that assigns weight* ψ_i *to the price of industry i, that is,* $\sum_{i=1}^{n} \psi_i \log p_i + (1 - \sum_{i=1}^{n} \psi_i) \log w = 0$.

This result restates the measurability condition in (18) as an explicit algebraic condition on the interaction between the production network (as summarized by the Leontief inverse, $\mathbf{L}$) and the economy's information structure (as captured by conditional covariance matrices, $\mathbf{V}_{ik}$) under which monetary policy can neutralize the impact of nominal rigidities and implement the first-best allocation. It also characterizes the policies that do so.

The characterization in Proposition 3 illustrates our earlier result that the monetary policy's ability to implement the first-best allocation is limited to a nongeneric class of information structures: all it takes to violate (21) is for a nonzero fraction of firms in

[14]In what follows, we set the value of this constant to $\zeta_i = \alpha_i^{-\alpha_i} \prod_{j=1}^{n} a_{ij}^{-a_{ij}}$. This choice has no bearing on the results, as the sole purpose of this constant is to simplify the analytical expressions. Also, note that our assumption that all technologies exhibit constant returns requires that $\alpha_i + \sum_{j=1}^{n} a_{ij} = 1$ for all i.

[15]Vector $\psi \in \mathbb{R}^n$ is *substochastic* if $\psi_i \geq 0$ for all i and $\sum_{i=1}^{n} \psi_i \leq 1$.

two industries to have an arbitrarily small idiosyncratic uncertainty about productivity shocks.[16] At the other extreme, (21) is trivially satisfied when all firms know the exact realizations of all shocks (in which case, $\mathbf{V}_{ik} = 0$).

4. OPTIMAL MONETARY POLICY

Our results in Section 3 establish that, in general, monetary policy cannot implement the first-best allocation as a sticky-price equilibrium. In view of these results, we now turn to the study of optimal monetary policy, that is, the policy that maximizes household welfare over the set of all possible sticky-price implementable allocations.

In order to obtain closed-form expressions for the optimal policy, we impose a number of functional form assumptions on preferences, technologies, and the nature of nominal rigidities in the economy. More specifically, we focus on the class of Cobb–Douglas economies in Section 3.5 by assuming that the production technology of firms in industry i and the household consumption bundle are given by (19) and (20), respectively. In addition, we assume that the representative household's preferences (2) are given by

$$U(C) = \frac{C^{1-\gamma}}{1-\gamma}, \qquad V(L) = \frac{L^{1+1/\eta}}{1+1/\eta},$$

where C and L denote the household's consumption and labor supply, respectively. We also assume that sector-specific taxes/subsidies in (1) are set to $\tau_i = 1/(1-\theta_i)$ for all i. As discussed in Section 3, this choice undoes the effect of monopolistic markups and guarantees that the flexible-price equilibrium is efficient.

To specify firms' information sets and the resulting nominal rigidities, we assume all productivity shocks are drawn independently from a log-normal distribution:

$$\log z_i \sim \mathcal{N}\big(0, \delta^2\sigma_z^2\big). \tag{22}$$

Each firm k in industry i then receives a collection of private signals $\omega_{ik} = (\omega_{i1,k}, \dots, \omega_{in,k})$ about the realized productivities given by

$$\omega_{ij,k} = \log z_j + \epsilon_{ij,k}, \qquad \epsilon_{ij,k} \sim \mathcal{N}\big(0, \delta^2\sigma_{ik}^2\big), \tag{23}$$

where the noise terms $\epsilon_{ij,k}$ are independent from one another and the productivity shocks. In this formulation, $\delta > 0$ is a normalization constant, σ_z^2 measures firms' (common) prior uncertainty about the shocks, and σ_{ik}^2 parametrizes the quality of information available to firm k in industry i.[17] Hence, an increase in σ_{ik}^2/σ_z^2 corresponds to an increase in the extent of nominal rigidity faced by firm k in industry i. In contrast, the extreme case that $\sigma_{ik}^2 = 0$ for all k and all i corresponds to an economy with fully flexible prices. More generally, it

[16]More generally, (21) is violated if a nonzero fraction of firms in industries i and j face some uncertainty about all linear combinations of log productivity shocks. In that case, the corresponding covariance matrices $\mathbf{V}_{ik}$ and $\mathbf{V}_{jk}$ are positive definite, and as a result, (21) is satisfied only if $\psi = u_i = u_j$, which is impossible.

[17]The formulation in (22) assumes that log productivity shocks are independent with identical volatilities. We consider the case with heteroskedastic and correlated shocks in Appendix A.2. Also, note that the formulation in (23) allows for potential heterogeneity in the degrees of price flexibility, not only across industries, but also among firms within the same industry. See Weber (2015) and Gorodnichenko and Weber (2016) for evidence of substantial heterogeneity in the frequency of price adjustments within narrowly defined industries.

is straightforward to verify that

$$\begin{aligned} \mathbb{E}_{ik}[\log z_j] &= \phi_{ik}\omega_{ij,k}, \\ \text{var}_{ik}(\log z_j) &= (1-\phi_{ik})\text{var}(\log z_j), \end{aligned} \tag{24}$$

where

$$\phi_{ik} = \sigma_z^2/\big(\sigma_z^2 + \sigma_{ik}^2\big). \tag{25}$$

Equation (24) indicates that an increase in ϕ_{ik} corresponds to a reduction in the firm's uncertainty about the payoff-relevant productivity shocks. We thus refer to $\phi_{ik} \in [0, 1]$ as the *degree of price flexibility of firm k* in industry i. Similarly, we define the *degree of price flexibility of industry i* as

$$\phi_i = \int_0^1 \phi_{ik}\,\mathrm{d}k.$$

Note that in the special case that $\sigma_{ik}^2 \in \{0, \infty\}$ for all firms, $\phi_{ik} \in \{1, 0\}$ for all i and k, in which case our framework reduces to an economy that is subject to sticky information pricing frictions similar to Mankiw and Reis (2002): firms in each industry can either set their prices flexibly with no frictions or face full nominal rigidity.[18]

To keep the analysis tractable, we work with the log-linearization of the above economy as $\delta \to 0$, where recall from equations (22) and (23) that $\delta > 0$ simultaneously parametrizes the firms' prior uncertainty about (log) productivity shocks and the noise in their private signals. This specific parametrization leads to two desirable features. First, the fact that $\text{var}(\log z_i) = \delta^2\sigma_z^2$ means that our small-δ approximation is akin to focusing on small departures from the economy's steady state, as is typical in the New Keynesian literature. Second, scaling $\text{var}(\epsilon_{ij,k})$ with δ^2 ensures that the degree of price flexibility ϕ_{ik} in equation (25) remains independent of δ.

As a final remark, we note that, under this information structure, monetary policy can implement the first-best allocation only if there is at most one industry with firms that receive imperfect signals. To see this, note that equation (24) implies that the covariance matrix of the vector of log productivity shocks conditional on the information set of firm k in industry i is given by $\mathbf{V}_{ik} = \delta^2\sigma_z^2(1-\phi_{ik})\mathbf{I}$, where $\mathbf{I}$ denotes the identity matrix. As a result, condition (21) in Proposition 3 is violated unless $\phi_i = 1$ for at least $n-1$ industries. This means that monetary policy cannot neutralize the impact of nominal rigidities and implement the first-best allocation as long as $\phi_i, \phi_j < 1$ for $i \neq j$.

4.1. *Strategic Complementarities and Monetary Nonneutrality*

In this subsection, we use Proposition 2 to obtain a set of preliminary results that will serve as the basis of our characterization of the optimal policy. We first illustrate the central role of strategic complementarities in firms' price-setting decisions in our production network economy. We then show how the interaction of such strategic complementarities with nominal rigidities impacts nominal prices and marginal costs and shapes the extent of monetary nonneutrality.

[18]This special case is also isomorphic to the static variant of the Calvo friction, in which fraction ϕ_i of firms in industry i can set their nominal prices with no restrictions, whereas the remaining $1-\phi_i$ fraction have fully rigid nominal prices.

LEMMA 2: *The nominal price set by firm k in industry i satisfies*

$$\log p_{ik} = \mathbb{E}_{ik}[\log \mathrm{mc}_i] + o(\delta) \tag{26}$$

$$= \alpha_i \mathbb{E}_{ik}[\log w] - \mathbb{E}_{ik}[\log z_i] + \sum_{j=1}^{n} a_{ij} \mathbb{E}_{ik}[\log p_j] + o(\delta) \tag{27}$$

to a first-order approximation as $\delta \to 0$.

Equation (26), which is a consequence of Proposition 2, establishes that, to a first-order approximation, each firm sets its log nominal price equal to its expected log marginal cost, given its information set. This is a consequence of monopolistic competition and the assumption that sector-specific taxes/subsidies are set to $\tau_i = 1/(1 - \theta_i)$ to eliminate monopolistic markups.

Lemma 2 also illustrates that our multisector New Keynesian model is isomorphic to a "beauty contest" game over the production network (Bergemann, Heumann, and Morris (2017)). In particular, equation (27) is identical to the first-order conditions of a network game of incomplete information in which firms in industry i choose their log nominal prices to match an industry-specific "fundamental" (given by $\alpha_i \log w - \log z_i$), while simultaneously coordinating with a linear combination of the (log) prices set by their supplier industries (given by $\sum_{j=1}^{n} a_{ij} \log p_j$).[19] This coordination motive is the consequence of strategic complementarities in firms' price-setting behavior in the presence of input-output linkages: all else equal, an increase in the price set by firms in an industry increases the incentive of its downstream customers to also raise their prices.

To capture the implications of the interaction between such strategic complementarities and nominal rigidities, we next define the following concept.

DEFINITION 4: The *upstream (price) flexibility* of industry i is given by

$$\rho_i = 1 - \sum_{j=1}^{n} a_{ij}(1 - \phi_j \rho_j), \tag{28}$$

where ϕ_j is the degree of price flexibility of industry j.

A few observations are in order. First, note that while the definition in (28) is recursive, the vector of upstream flexibilities has a simple closed-form representation given by $\rho = (\mathbf{I} - \mathbf{A}\mathbf{\Phi})^{-1}\alpha$, where $\mathbf{\Phi} = \mathrm{diag}(\phi_1, \dots, \phi_n)$ is the diagonal matrix of (own) price flexibilities and $\alpha = (\alpha_1, \dots, \alpha_n)'$ is the vector of industry labor shares. Second, it is straightforward to verify that $\rho_i \in [0, 1]$ for all i. Third, and more importantly, the recursive nature of (28) implies that upstream flexibility of industry i is increasing in the own (ϕ_j) and upstream (ρ_j) price flexibilities of any of i's supplier industries j, with these terms weighted by the importance of j in i's production technology, a_{ij}. As a result, ρ_i decreases if any of i's direct or indirect upstream suppliers are subject to more pricing frictions, whereas ρ_i takes its maximum value of 1 if none of i's direct and indirect upstream suppliers are subject to any pricing friction. This observation clarifies the sense in which ρ_i serves as a summary statistic for the extent of nominal rigidities in industries upstream to i.

[19]More specifically, (27) coincides with the first-order condition of a quadratic-payoff game in which the payoff of firms in industry i is given by $u_{ik} = -(\log p_{ik} - (\alpha_i \log w - \log z_i))^2 - (\log p_{ik} - \sum_{j=1}^{n} a_{ij} \log p_j)^2$.

We now use Definition 4 and Lemma 2 to characterize equilibrium nominal prices and marginal costs as a function of model primitives and the nominal wage.

PROPOSITION 4: *Equilibrium log nominal marginal costs and prices are given by*

$$\log \mathrm{mc}_i = \rho_i \log w - \sum_{j=1}^{n} h_{ij} \log z_j + o(\delta), \tag{29}$$

$$\log p_i = \phi_i \rho_i \log w - \phi_i \sum_{j=1}^{n} h_{ij} \log z_j + o(\delta) \tag{30}$$

to a first-order approximation as $\delta \to 0$, *where* h_{ij} *is the* (i, j) *element of* $\mathbf{H} = (\mathbf{I} - \mathbf{A}\mathbf{\Phi})^{-1}$.

Proposition 4 illustrates that the interaction between nominal rigidities and the strategic complementarities that arise from the economy's production network amplifies the sluggishness of the response of nominal variables to real and monetary shocks. In particular, it is immediate from (29) and (30) that the pass-through of changes in the nominal wage to i's nominal marginal cost and nominal price are given by

$$\frac{\mathrm{d}\log \mathrm{mc}_i}{\mathrm{d}\log w} = \rho_i \quad \text{and} \quad \frac{\mathrm{d}\log p_i}{\mathrm{d}\log w} = \phi_i \rho_i, \tag{31}$$

respectively, both of which are increasing in industry i's upstream flexibility, ρ_i. This is in line with Blanchard (1983), Basu (1995), and Christiano (2016) who, in simpler settings, argue that strategic complementarities that arise from the presence of input-output linkages amplify the effect of nominal rigidities and increase the sluggishness of the response of nominal variables to shocks.

We conclude our set of preliminary results by characterizing how the strategic complementarities that arise from the economy's production network shape the extent of monetary nonneutrality. To this end, let

$$\rho_0 = \sum_{j=1}^{n} \beta_j \phi_j \rho_j, \tag{32}$$

where β_j is the share of good j in the household's consumption basket. In view of (31), ρ_0 captures the pass-through of changes in the log nominal wage to the price of the household consumption basket.[20] Recall from our previous discussion that this quantity has a closed-form representation in terms of model primitives given by $\rho_0 = \beta' \mathbf{\Phi}(\mathbf{I} - \mathbf{A}\mathbf{\Phi})^{-1}\alpha$. Furthermore, as expected, ρ_0 is increasing in the extent of price flexibilities $(\phi_1, \ldots, \phi_n)$ of all industries in the economy, regardless of whether they sell directly to the household or not. We have the following result.

PROPOSITION 5: *The degree of monetary nonneutrality is*

$$\Xi = \frac{\mathrm{d}\log C}{\mathrm{d}\log m} = \frac{1 - \rho_0}{1 + (\gamma - 1 + 1/\eta)\rho_0}, \tag{33}$$

where C *is the household's consumption and* m *is the nominal aggregate demand.*

[20]Note that (32) can also be expressed as $\rho_0 = 1 - \sum_{j=1}^{n} \beta_j (1 - \phi_j \rho_j)$. Therefore, in view of (28), ρ_0 can also be interpreted as the degree of (upstream) price flexibility from the household's perspective.

Proposition 5, which generalizes the results of Pastén, Schoenle, and Weber (2020b), characterizes how nominal rigidities interact with the economy's production network to generate monetary nonneutrality. As a first observation, note that Ξ is decreasing in ρ_0, which itself is decreasing in the degree of price stickiness of all industries in the economy. Therefore, as expected, an increase in nominal rigidities anywhere in the economy results in a greater degree of monetary nonneutrality. Furthermore, the recursive nature of equation (28) underscores how strategic complementarities that arise from the economy's production network amplify monetary nonneutrality: an increase in the degree of price stickiness of industry j (i.e., a decrease in ϕ_j) not only decreases ρ_0 directly as is evident from (32), but also does so indirectly by making the marginal cost of any industry i that relies on j more sluggish (thus reducing ρ_0 by reducing ρ_i).

4.2. *Welfare Loss and Policy Objective*

In the remainder of this section, we use our preliminary results in Section 4.1 to obtain a closed-form expression for the optimal monetary policy, which maximizes the expected welfare of the representative household over the set of all sticky-price equilibrium allocations.

We express the household's welfare relative to a benchmark with no nominal rigidities, which corresponds to the first-best allocation. More specifically, let W and W^* denote the representative household's welfare in the presence and absence of nominal rigidities, respectively. Similarly, let $\varrho = (p_{ik}, p_i, w)$ and $\varrho^* = (p^*_{ik}, p^*_i, w^*)$ denote the nominal price systems under the two scenarios. Given the indeterminacy of prices in the flexible-price equilibrium, we normalize the nominal wage such that $w^* = w$. We also use $e_{ik} = \log p_{ik} - \log p^*_{ik}$ to denote the "pricing error" of firm k in industry i in the sticky-price equilibrium relative to the benchmark with no nominal rigidities. The cross-sectional average and dispersion of pricing errors within industry i are thus given by

$$\bar{e}_i = \int_0^1 e_{ik}\,\mathrm{d}k, \tag{34}$$

$$\vartheta_i = \int_0^1 e_{ik}^2\,\mathrm{d}k - \left(\int_0^1 e_{ik}\,\mathrm{d}k\right)^2. \tag{35}$$

Finally, let $\lambda_i = p_i y_i / PC$ denote industry i's *Domar weight*, defined as its sales as a share of GDP. We have the following result.

PROPOSITION 6: *The welfare loss due to the presence of nominal rigidities is given by*

$$W - W^* = -\frac{1}{2}\Bigg[\sum_{i=1}^n \lambda_i\theta_i\vartheta_i + (\gamma + 1/\eta)\Delta^2 + \sum_{i=1}^n \lambda_i \operatorname{xvar}_i(\bar{e}_1, \dots, \bar{e}_n) + \operatorname{xvar}_0(\bar{e}_1, \dots, \bar{e}_n)\Bigg] + o(\delta^2) \tag{36}$$

to a second-order approximation as $\delta \to 0$, *where* ϑ_i *is the cross-sectional dispersion of pricing errors in industry i defined in* (35),

$$\Delta^2 = (\log C - \log C^*)^2 = \frac{1}{(\gamma + 1/\eta)^2}\left(\sum_{j=1}^{n} \beta_j \bar{e}_j\right)^2 + o(\delta^2) \tag{37}$$

is the volatility of output gap, *and*

$$\begin{aligned} \text{xvar}_i(\bar{e}_1, \ldots, \bar{e}_n) &= \sum_{j=1}^{n} a_{ij}\bar{e}_j^2 - \left(\sum_{j=1}^{n} a_{ij}\bar{e}_j\right)^2, \\ \text{xvar}_0(\bar{e}_1, \ldots, \bar{e}_n) &= \sum_{j=1}^{n} \beta_j\bar{e}_j^2 - \left(\sum_{j=1}^{n} \beta_j\bar{e}_j\right)^2 \end{aligned} \tag{38}$$

are the interindustry cross-sectional dispersions of pricing errors from the perspectives of industry i and the household, *respectively*.

Proposition 6 generalizes the well-known expression for welfare loss in single-sector New Keynesian models (e.g., Galí (2008)) as well as the corresponding expressions in Woodford (2003b, 2010) and Huang and Liu (2005) for two-sector economies. Additionally, equation (36) illustrates that the loss in welfare due to the presence of nominal rigidities in our multisector economy with input-output linkages manifests itself via four separate terms.[21]

The first term, $\lambda_i \theta_i \vartheta_i$, measures welfare losses due to price dispersion *within* each industry *i* and is the counterpart to welfare loss due to inflation in the textbook New Keynesian models: price dispersion ϑ_i in industry *i* translates into output dispersion, and hence misallocation of resources, with the extent of this misallocation increasing in the elasticity of substitution θ_i between firms in that industry. This term vanishes if all firms in industry *i* make their nominal pricing decisions under the same information. Not surprisingly, the loss due to price dispersion in industry *i* is weighted by the industry's Domar weight, λ_i.

The second term on the right-hand side of (36) is proportional to the volatility of output gap, $\Delta^2 = (\log C - \log C^*)^2$. This term, which is also present in the textbook New Keynesian models and vanishes as the Frisch elasticity of labor supply $\eta \to 0$, captures loss of welfare due to inefficient supply of labor by the household, that is, the aggregate labor wedge. Equation (37) then characterizes how output gap volatility relates to industry-level pricing errors in our multisector economy.

In contrast to the first two terms, the third and fourth terms on the right-hand side of (36) only appear in multisector economies and correspond to welfare losses arising from misallocation of resources *across* industries. To see this, consider the expression $\text{xvar}_i(\bar{e}_1, \ldots, \bar{e}_n)$ in equation (38). This term measures the cross-sectional dispersion in the average pricing error of *i*'s supplier industries, with greater weights assigned to industries

[21]Note that the second-order approximation for welfare loss in (36) holds not just for the information structure specified by (22) and (23), but for any information structure. This expression is also related to Proposition 5 of Baqaee and Farhi (2020), which provides a second-order approximation to aggregate output in terms of sectoral markups. However, note that (36) is in terms of cross-sectional mean and dispersion of pricing errors defined in (34) and (35) as opposed to markups.

that are more important input suppliers to i. To be even more specific, suppose industry i has two suppliers indexed j and r such that $a_{ij} + a_{ir} = 1$. In this case, it is immediate that

$$\text{xvar}_i(\bar{e}_j, \bar{e}_r) = a_{ij}a_{ir}(\bar{e}_j - \bar{e}_r)^2 = a_{ij}a_{ir}\big(\log(p_j/p_r) - \log(p_j^*/p_r^*)\big)^2$$

simply measures the extent to which nominal relative prices of i's inputs diverge from the relative prices that would have prevailed under the flexible-price (and hence efficient) allocation. Finally, note that $\text{xvar}_i(\bar{e}_1, \dots, \bar{e}_n) = 0$ whenever industry i has only a single input supplier j with $a_{ij} = 1$, as this corresponds to a scenario in which there is no room for misallocation between i's input suppliers.[22]

In summary, Proposition 6 indicates that, in a multisector economy, the monetary authority faces an inherent trade-off between minimizing the various losses captured by equation (36). Importantly, as we already established in Corollaries 1 and 2, this trade-off cannot be circumvented, in the sense that, generically, there is no policy that can simultaneously eliminate all forms of welfare loss. Finally, note that, unlike the textbook New Keynesian models, the various trade-offs faced by the monetary authority arise from the structural properties of the economy's production network as opposed to exogenous markup shocks.

4.3. *Optimal Monetary Policy*

We are now ready to present our main result of this section, which characterizes the optimal policy as a function of the economy's production network and the extent of nominal rigidities.

THEOREM 2: *The optimal monetary policy is a price-stabilization policy of the form* $\sum_{i=1}^n \psi_i^* \log p_i = 0$, *with the weight assigned to industry i in the target price index given by*

$$\psi_i^* = \psi_i^{\text{o.g.}} + \psi_i^{\text{within}} + \psi_i^{\text{across}}, \tag{39}$$

where

$$\psi_i^{\text{o.g.}} = (1/\phi_i - 1)\lambda_i\left(\frac{1-\rho_0}{\gamma + 1/\eta}\right), \tag{40}$$

$$\psi_i^{\text{within}} = (1-\phi_i)\lambda_i\theta_i\rho_i, \tag{41}$$

$$\psi_i^{\text{across}} = (1/\phi_i - 1)\left[(\rho_0 - \rho_i)\lambda_i + \sum_{j=1}^n (1-\phi_j)\lambda_j\rho_j\ell_{ji}\right], \tag{42}$$

ϕ_i *is degree of price flexibility of industry i*, ρ_i *is i's degree of upstream price flexibility in* (28), λ_i *is the i's Domar weight*, *and* $\mathbf{L} = [\ell_{ij}]$ *is the economy's Leontief inverse*.

Theorem 2 provides a characterization of the optimal policy in terms of model primitives, with each term on the right-hand side of (39) aimed at minimizing a specific source of welfare loss in (36). Recall from Section 4.2 that the monetary authority faces a trade-off between minimizing the various sources of allocational inefficiencies due to nominal

[22]The interpretation for the term $\text{xvar}_0(\bar{e}_1, \dots, \bar{e}_n)$ in equation (36) is identical, with the household replacing industry i as purchaser of various goods.

rigidities. Not surprisingly then, the optimal policy in (39) consists of three different terms corresponding to the relative importance of each of these misallocations for household welfare: the first term on the right-hand side of (39) aims to minimize the welfare loss induced by the labor wedge (or equivalently, output gap volatility), the second term arises due to the policymaker's concern about within-industry price dispersion, and the last term is in response to misallocation across industries.[23] Note that the three terms constituting the optimal policy in (39) are in general not proportional to one another, thus indicating that the monetary authority faces a real trade-off between the corresponding sources of welfare loss.

The above result also illustrates that the optimal policy is shaped by how nominal rigidities interact with the economy's production network. In particular, the weight ψ_i^* assigned to any given industry i in the optimal policy depends not just on that industry's size (as measured by its Domar weight) and price flexibility (as parametrized by ϕ_i), but also on i's position in the production network and the nominal rigidities faced by other industries in the economy.

As a final remark, we note that in deriving the above result, we did not restrict our attention to the class of price-stabilization policies to begin with. In particular, the monetary authority can choose the nominal aggregate demand, m, as an arbitrary function of productivities in an unrestricted manner, including policies that do not stabilize any specific price index. Nonetheless, Theorem 2 establishes that the optimal policy fully stabilizes the price index $\sum_{s=1}^n \psi_s^* \log p_s$ with weights given by (39). This reflects the fact that the underlying flexible-price economy is efficient: even though our multisector economy gives rise to an endogenous output gap, the absence of cost-push shocks means that there are no forces driving optimal policy away from price stabilization.[24]

4.4. *Comparative Statics*

In what follows, we present a series of comparative static results to distill the role of the various forces that shape the optimal policy (39) in a transparent manner. These results allow us to obtain general insights on how optimal policy depends on the production network and the distribution of pricing frictions throughout the economy. In particular, we establish that, all else equal, optimal policy stabilizes a price index with greater weights assigned to (i) stickier industries, (ii) industries with less sticky upstream suppliers, (iii) industries with stickier downstream customers, (iv) industries whose customers exhibit greater upstream flexibilities, and (v) more upstream industries.

We start with a definition.

DEFINITION 5: Industries i and j are *upstream symmetric* if $a_{ir} = a_{jr}$ for all industries r. They are *downstream symmetric* if $a_{ri} = a_{rj}$ for all industries r and $\beta_i = \beta_j$.

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[23]Alternatively, the expressions in (40), (41), and (42) correspond to the optimal price-stabilization policies of a planner who only intends to minimize welfare losses arising from output gap volatility, within-industry price dispersion, and interindustry misallocation, respectively.

[24]The fact that full stabilization of the price index with weights given by (39) is feasible is a consequence of the assumption that the monetary authority can set nominal aggregate demand, m, as a function of productivity shocks in an unrestricted manner. Fully stabilizing such a price index may no longer be feasible when nominal aggregate demand cannot be contingent on the shocks' realizations, for example, because the monetary authority is also subject to information frictions. As we show in Appendix A.3, in that case, the optimal policy minimizes the volatility of the target price index $\sum_{i=1}^n \psi_i^* \log p_i$, where ψ_i^* is given by (39).

While upstream symmetry means that i and j have the same production technology, downstream symmetry means that the two industries take identical roles as input suppliers of other firms in the economy as well as in household preferences. Consequently, if i and j are upstream symmetric, then they have the same degree of upstream flexibilities ($\rho_i = \rho_j$), whereas if they are downstream symmetric, they have the same steady-state Domar weights ($\lambda_i = \lambda_j$). We have the following result.

PROPOSITION 7: *Suppose industries i and j are upstream and downstream symmetric. Also suppose $\theta_i = \theta_j$. Then $\psi_i^* > \psi_j^*$ in the optimal policy if and only if $\phi_i < \phi_j$.*

This result thus extends what Eusepi, Hobijn, and Tambalotti (2011) refer to as the "stickiness principle" to our multisector economy with input-output linkages: all else equal, the monetary authority should stabilize a price index that places larger weights on producers with stickier prices.

To see the intuition underlying Proposition 7, consider a policy that treats industries i and j symmetrically. Since i and j are upstream symmetric, under such a policy, mc_i and mc_j have the same ex ante distribution. Yet, firms in the stickier of the two industries respond more sluggishly to changes in their realized marginal costs. Therefore, altering the policy to target the industry that is subject to more nominal rigidities for price stabilization reduces the need for price adjustments by firms in that industry, and thus reduces the overall level of welfare loss due to within-industry price dispersion. Indeed, consistent with this argument, equation (41) in Theorem 2 implies that, due to upstream symmetry, if $\phi_i < \phi_j$, then $\psi_i^{\text{within}} > \psi_j^{\text{within}}$. At the same time, the downstream symmetry assumption implies that a policy that targets the stickier industry more also reduces output gap volatility and the interindustry price dispersion faced by i and j's common customers: from (40) and (42), it is easy to see that whenever $\phi_i < \phi_j$, it must be the case that $\psi_i^{\text{o.g.}} > \psi_j^{\text{o.g.}}$ and $\psi_i^{\text{across}} > \psi_i^{\text{across}}$. Putting these inequalities together then guarantees that $\psi_i^* > \psi_j^*$.

By assuming that i and j take symmetric positions in the production network, Proposition 7 effectively assumes away how differences in input-output linkages may matter for optimal policy. In our subsequent results, we instead assume that the two industries are equally sticky and focus on the role of network connections in shaping the optimal policy.

PROPOSITION 8: *Suppose i and j are downstream symmetric. Also, suppose $\phi_i = \phi_j < 1$ and $\theta_i = \theta_j$. Then $\psi_i^* > \psi_j^*$ if and only if $\rho_i > \rho_j$.*

This result encapsulates the second general principle that emerges from our characterization of optimal policy: all else equal, the optimal target price index places a larger weight on the industry with less sticky upstream suppliers, as summarized by a greater degree of upstream flexibility ρ.

The intuition underlying Proposition 8 is straightforward. Since i and j are downstream symmetric, stabilizing the price of either industry would have the same exact effect on the labor wedge and the extent of interindustry relative price distortions perceived by their (direct and indirect) customers. As a result, any differential treatment of i and j by the optimal policy is solely driven by concerns for within-industry misallocation. At the same time, the fact that $\rho_i > \rho_j$ means that industry j's marginal cost responds more sluggishly to shocks, making the lack of complete information about the realized shocks less material for price-setting by firms in j compared to those in i. As a result, all else equal, the within-industry price dispersion would be lower in j than in i, despite the fact that both industries are equally sticky. Not surprisingly then, the optimal price-stabilization target assigns a smaller weight to the industry with stickier suppliers, which has an already more stabilized marginal cost.

PROPOSITION 9: *Suppose industries i and j are upstream symmetric. Also, suppose $\phi_i = \phi_j < 1$, $\theta_i = \theta_j$, and $\lambda_i = \lambda_j$. Then $\psi_i^* > \psi_j^*$ if and only if*

$$\sum_{s=1}^{n}(1-\phi_s)\lambda_s\rho_s(\ell_{si}-\ell_{sj}) > 0, \tag{43}$$

where ρ is the degree of upstream price flexibility in (28) and $\mathbf{L} = [\ell_{ij}]$ is the economy's Leontief inverse.

The above result highlights yet another important dimension along which the production network structure shapes the optimal policy. It establishes that, all else equal, industry i receives a larger weight in the optimal price-stabilization index if (i) it is a more important supplier to stickier industries and (ii) its customers have a greater degree of upstream flexibility. To see these from inequality (43), recall that expression $\ell_{si} - \ell_{sj}$ captures the differential importance of i and j as direct or indirect input suppliers to any industry s. Therefore, the left-hand side of (43) is positive if, relative to j, industry i is a more important supplier of industries with lower degree of price flexibility, ϕ_s, but greater degree of upstream price flexibility, ρ_s.

Why is it optimal to stabilize the price of the industry with stickier downstream customers? This is because such a policy would reduce the need for the firms in the customer industry to adjust their nominal price. Therefore, the stickier are those customers, the larger is the welfare gain of stabilizing their marginal cost by assigning a larger weight on their suppliers in the target price-stabilization index.

The argument for why optimal policy places a larger weight on the industry whose customers have a greater degree of upstream flexibility is also similar. Recall that, all else equal, a higher degree of upstream flexibility, ρ_s, means that firms in industry s face a more volatile nominal marginal cost, and hence, on average, have to adjust their nominal prices by more. Therefore, stabilizing the price of one of their inputs, i, would reduce the need for such price adjustments, and hence reduce the welfare loss arising from nominal rigidities.

PROPOSITION 10: *Suppose j is the sole supplier of i and i is the sole customer of j. Also, suppose $\phi_i = \phi_j < 1$ and $\theta_i = \theta_j$. Then $\psi_i^* < \psi_j^*$.*

The assumption that i and j are, respectively, each other's only customer and supplier and have identical stickiness and substitution elasticities is meant to ensure that the difference between the two industries is solely in their respective positions in the chain of production, with industry j taking an unambiguously upstream position in relation to industry i. As such, Proposition 10 establishes that, all else equal, the optimal policy assigns a larger weight to more upstream industries. The differential treatment of the two industries by the optimal policy is driven purely by concerns about within-industry misallocation.

Taken together, our results presented as Propositions 7–10 yield general principles for the optimal conduct of monetary policy in the presence of input-output linkages. In particular, they establish that, all else equal, optimal policy stabilizes a price index with larger weights assigned to industries that are stickier (Proposition 7), have more flexible upstream suppliers (Proposition 8) but more sticky downstream customers (Proposition 9), have downstream customers with higher degrees of upstream flexibility (Proposition 9), and are themselves more upstream (Proposition 10). Last but not least, the characterization in Theorem 2 also implies that the optimal policy assigns a greater weight on larger industries, as measured by their Domar weights.

4.5. *Examples*

We conclude this section by providing a series of examples to further clarify the dependence of optimal policy on model primitives.

EXAMPLE 1: Consider the vertical production network depicted in Figure 1(a), in which each industry $i \neq n$ depends on the output of a single other industry as its input for production ($a_{i,i+1} = 1$), industry n only uses labor ($\alpha_n = 1$), and the household, labeled as vertex 0 in the figure, only consumes the good produced by industry 1 ($\beta_1 = 1$ and $\beta_i = 0$ for all $i \neq 1$).

Given the vertical nature of production, it is immediate that in this economy—a variant of which is studied by Huang and Liu (2005) and Wei and Xie (2020)—there is no room for interindustry misallocation. Indeed, the expressions in (38) corresponding to welfare losses arising from interindustry misallocation are equal to zero, irrespective of the extent of nominal rigidities. It is therefore not surprising that this source of welfare loss is immaterial for the design of optimal policy: equation (42) in Theorem 2 implies that $\psi_i^{\text{across}} = 0$ for all i.

There is, however, room for within-industry misallocation, as firms' incomplete information about productivity shocks may result in a nontrivial price dispersion within each industry. Indeed, equation (41) implies that the corresponding component of optimal policy is nonzero and is given by

$$\psi_i^{\text{within}} = (1 - \phi_i)\theta_i\rho_i,$$

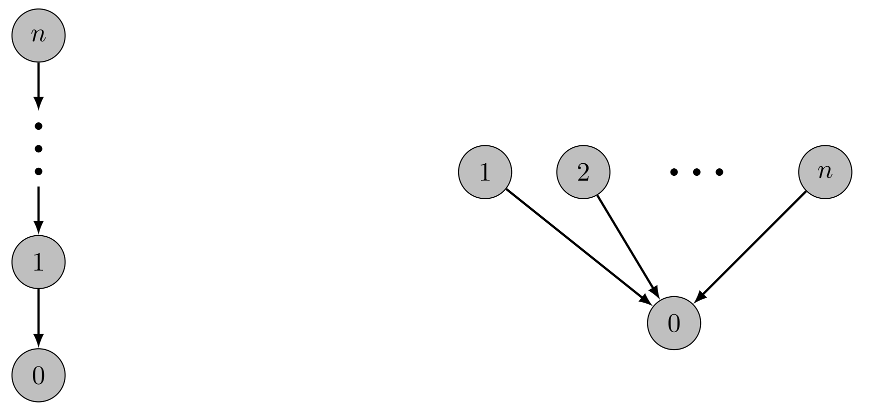
where $\rho_i = \phi_{i+1}\phi_{i+2} \dots \phi_n$ is the degree of upstream flexibility of industry i. Note that due to the presence of strategic complementarities, ρ_i is smaller for industries further downstream: $\rho_i \leq \rho_{i+1}$.

Combining the above with equation (40)—which captures the component of optimal policy that aims at reducing welfare losses arising from the labor wedge—implies that the optimal price-stabilization target is given by

$$\psi_i^* = \psi_i^{\text{within}} + \psi_i^{\text{o.g.}} = (1 - \phi_i)\theta_i\phi_{i+1}\phi_{i+2} \dots \phi_n + (1/\phi_i - 1)\frac{1 - \phi_1\phi_2 \dots \phi_n}{\gamma + 1/\eta}.$$

Consequently, the optimal policy assigns a larger weight to (i) industries with higher degrees of price stickiness (i.e., lower ϕ_i), (ii) those with greater elasticities of substitution θ_i, and (iii) more upstream industries. This latter observation is of course consistent with the prescription of Proposition 10.

EXAMPLE 2: Consider the horizontal production network depicted in Figure 1(b), in which all industries only rely on labor as their input for production, that is, $\alpha_i = 1$ for all i.



(a) vertical production network (b) horizontal production network

FIGURE 1.—Each vertex corresponds to an industry, with a directed edge present from one vertex to another if the former is an input supplier to the latter. The vertex indexed 0 represents the household.

This economy is therefore similar to the multisector economies with no input-output linkages that were studied in the prior literature, such as Mankiw and Reis (2003), Benigno (2004), and Woodford (2010).

Unlike the economy in Example 1, nominal rigidities in the horizontal economy result in misallocation not only within but also across industries: while efficiency requires relative prices across industries to move with corresponding productivities, such movements are in general not possible. This observation means that the component of optimal policy that targets interindustry misallocation losses is nonzero. In particular, equation (42) in Theorem 2 implies that

$$\psi_i^{\text{across}} = (1/\phi_i - 1)\beta_i \sum_{j=1}^{n} \beta_j(\phi_j - \phi_i).$$

Next, note that all industries in this economy are upstream symmetric, and in fact, since no industry has a sticky-price supplier, $\rho_i = 1$ for all i. As a result, (41) reduces to

$$\psi_i^{\text{within}} = (1 - \phi_i)\beta_i\theta_i,$$

whereas (40) implies that

$$\psi_i^{\text{o.g.}} = (1/\phi_i - 1)\beta_i \left(\frac{1 - \sum_{j=1}^{n} \beta_j\phi_j}{\gamma + 1/\eta} \right).$$

Taken together, the above expressions imply that, consistent with the results of Benigno (2004) and Woodford (2010), industries with (i) higher levels of price stickiness and (ii) larger shares in the household's consumption basket receive a larger weight in the optimal price-stabilization policy.

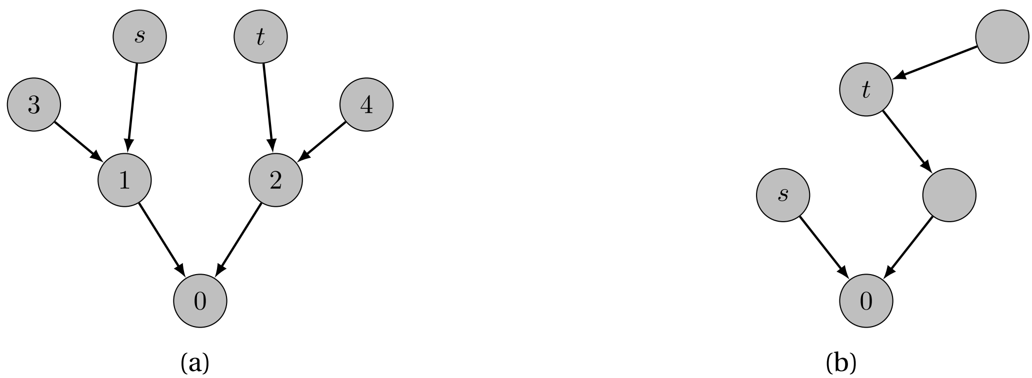


FIGURE 2.—Each vertex corresponds to an industry, with a directed edge present from one vertex to another if the former is an input supplier to the latter. The vertex indexed 0 represents the household.

EXAMPLE 3: Next, consider the economy depicted in Figure 2(a), in which industries s and t only rely on labor as their input for production ($\alpha_s = \alpha_t = 1$) and are in turn input suppliers to industries 1 and 2, with $a_{1s} = a_{2t} < 1$. To isolate the role of the network structure, we in addition impose the symmetry assumptions that $\phi_s = \phi_t$ and $\theta_s = \theta_t$ and that s and t have the same steady-state Domar weight, that is, $\lambda_s = \lambda_t$. Therefore, any heterogeneity across s and t only comes from the stickiness of their respective customers, 1 and 2, and the latter firms' other suppliers, 3 and 4.

As a first observation, note that since the two industries are identical in size and stickiness and are upstream symmetric, they contribute equally to welfare losses arising from output gap volatility and within-industry misallocation. Not surprisingly then equations (40) and (41) imply that the weights in the optimal policy corresponding to output gap and within-industry misallocation losses are also equal, that is, $\psi_s^{\text{o.g.}} = \psi_t^{\text{o.g.}}$ and $\psi_s^{\text{within}} = \psi_t^{\text{within}}$.

The contributions of s and t to across-industry misallocation, on the other hand, depend on their downstream supply chains, which are not necessarily identical. In particular, an immediate application of equation (42) in Theorem 2 implies that $\psi_s^{\text{across}} > \psi_t^{\text{across}}$ if and only if

$$(1 - \phi_1)\rho_1 > (1 - \phi_2)\rho_2.$$

To further clarify the nature of optimal policy, suppose that industries 3 and 4 are equally sticky, so that $\rho_1 = \rho_2$. In such a case, the above inequality implies that $\psi_s^* > \psi_t^*$ if and only if $\phi_1 < \phi_2$. In other words, all else equal, the optimal policy places a larger weight on the industry whose downstream customer is stickier, as prescribed by Proposition 9. This is because by stabilizing the industry with the stickier customer, the policy can reduce the need for the firms in the customer industry to adjust their nominal price, thus effectively reducing the variance of pricing errors by more. A similar argument also illustrates that if firms in industry 1 and 2 are equally sticky (so that $\phi_1 = \phi_2$), then $\psi_s^* > \psi_t^*$ if and only if $\phi_3 > \phi_4$, which guarantees that $\rho_1 > \rho_2$.

EXAMPLE 4: Finally, consider the simple economy depicted in Figure 2(b) and suppose that s and t are the only industries that are subject to nominal rigidities. To isolate the role of the network structure, we once again impose the symmetry assumptions that $\phi_s = \phi_t$ and $\theta_s = \theta_t$. Additionally, assume that s only uses labor as an input for production ($\alpha_s = 1$), whereas t solely relies on intermediate inputs ($\alpha_t = 0$). Under these assumptions, it is immediate that, compared to t, industry s has a larger value added share as well as a greater share in the household's consumption basket. Nonetheless, an immediate application of Theorem 2 implies that industry t receives a larger weight in the optimal policy whenever it has a larger Domar weight ($\lambda_t > \lambda_s$), highlighting the fact that, as far as size is concerned, what matters for the optimal policy is an industry's sales share as opposed to its value added or consumption shares.

5. QUANTITATIVE ANALYSIS

In this section, we use our results in Section 4 to determine the optimal monetary policy for the U.S. economy as implied by the model.

Our analysis relies on three sources of data. As our first source, we use the 2019 input-output tables constructed by the Bureau of Economic Analysis (BEA) to determine the intermediate input expenditure by various industries. The BEA tables also detail total compensation of employees for each industry as well as each industry's contribution to final uses.

The second source of data is provided to us by Pastén, Schoenle, and Weber (2020b), who use the confidential microdata underlying the Bureau of Labor Statistics (BLS) producer price index (PPI) to calculate the frequency of price adjustments at the industry level. They construct this measure as the ratio of the number of price changes to the number of sample months. We use this data set to obtain proxies for each industry's degree of price flexibility.

Our third and final source of data is the March 2021 release of the BEA/BLS Integrated Industry-Level Production Account (ILPA). This data set contains estimates of industry-level productivities over the 1987–2019 period.

We merge the BEA input-output data at the summary level with price-adjustment data at the 3-digit North American Industry Classification System (NAICS) level, while excluding industries corresponding to federal, state, and local governments. This results in a matched data set consisting of 66 industries. The mean and median price change frequency across industries are 23.0% and 21.9%, respectively, while the implied cross-sectional mean and median of expected price durations are 5.26 and 4.56 months, respectively. These durations are in line with prior estimates of price adjustment frequencies and durations produced by Bils and Klenow (2004) and Klenow and Kryvtsov (2008).[25] We then merge the resulting dataset with the ILPA data to obtain a measure of productivity shocks for each of the 66 industries.[26]

Calibration. We interpret each period as a quarter. We calibrate the input-output matrix, $\mathbf{A}$, and labor expenditure shares, α, so as to match the intermediate good expenditure shares and compensation of employees by industry in the BEA input-output data, respectively. We similarly construct the vector of consumption shares, β, to match the share of final uses of each industry's output.

[25] In particular, Bils and Klenow (2004) report a median duration of prices across all categories to be 4.3 months for posted prices and 5.5 months for regular prices. For posted prices, Klenow and Kryvtsov (2008) report the mean and the median to be 6.8 and 3.7 months, respectively.

[26] The ILPA data set is slightly more aggregated than the BEA input-output data. Whenever there is a mismatch between the two data sets, we attribute the productivity of the more aggregated industry to its more disaggregated components. Specifically, we attribute the productivity series of "Retail trade" in the ILPA data set to "Motor vehicle and parts dealers," "Food and beverage stores," "General merchandise stores," and "Other retail"; that of "Real estate" to "Housing" and "Other real estate"; and that of "Hospitals and nursing and residential care facilities" to "Hospitals" and "Nursing and residential care facilities."

We then use the ILPA data to calibrate the distribution of productivity shocks in the model. Specifically, we assume that log productivity shocks $(\log z_1, \ldots, \log z_n)$ in the model are jointly normally distributed, with a variance-covariance matrix set equal to the empirical variance-covariance matrix of linearly detrended productivity series for the 66 industries.

To calibrate the model's vector of price flexibilities $(\phi_1, \ldots, \phi_n)$, we assume that firms in each industry are subject to sticky information pricing frictions à la Mankiw and Reis (2002). Specifically, we assume that firms in each industry receive a perfectly informative signal about the vector of realized productivity shocks according to a Poisson process with a constant rate. This implies that, in our quarterly calibration, a fraction $\phi_i = 1 - e^{-3\times\text{FPA}_i}$ of firms in industry i receive a perfectly informative signal about the realized productivities, where FPA_i is industry i's monthly frequency of price adjustment as measured by Pastén, Schoenle, and Weber (2020b). On the other hand, a fraction $1 - \phi_i$ of firms in industry i receive no signals during a given quarter.[27] To introduce nominal wage rigidities, we add a pseudo-industry that transforms, one-for-one, the labor supplied by the representative household into labor services, which are then sold to the rest of the industries in the economy. We calibrate the extent of nominal wage rigidity according to the estimates of Beraja, Hurst, and Ospina (2019) and set the degree of price flexibility of this pseudo-industry to $\phi_w = 0.30$.[28]

We set the within-industry elasticity of substitution, θ, equal to 6. This number is consistent with values commonly used in the New Keynesian literature, typically set to match steady-state levels of markups. For example, Coibion, Gorodnichenko, and Wieland (2012) set the elasticity of substitution equal to 7 in order to match steady-state markups of 17% as estimated by Burnside (1996) and Basu and Fernald (1997). Similarly, McKay, Nakamura, and Steinsson (2016) and Christiano, Eichenbaum, and Rebelo (2011) set the elasticity of substitution equal to 6, consistent with steady-state markups of 20%. While we allow for a subsidy in our model that eliminates all steady-state markups, we keep the value of this elasticity in line with the rest of the literature.

Finally, the preference parameters η and γ are chosen as follows. We set the Frisch elasticity of labor supply to $\eta = 2$; this value is consistent with "macro" elasticities of labor supply (Hall (2009)). As for γ, note that intertemporal substitution plays no role in our setting as all choices are static. Nonetheless, γ still controls the household's wealth effect on labor supply. We thus set $\gamma = 0.1$; this value essentially minimizes the income effect on labor supply, similar to using GHH preferences (Greenwood, Hercowitz, and Huffman (1988)). In Appendix C of the Online Supplementary Material, we provide a series of robustness checks with respect to these parameter values.

Optimal Monetary Policy. With the calibrated model in hand, we use equation (39) to obtain the optimal monetary policy implied by the model as well as the associated welfare loss (measured as a percentage of steady-state consumption).[29] We calculate the expected welfare loss due to the presence of nominal rigidities in two different ways. First, we

[27]In the notation of Section 4, this is equivalent to assuming that $\sigma_{ik} = 0$ for a fraction $\phi_i = 1 - e^{-3\times\text{FPA}_i}$ of firms industry i and $\sigma_{ik} = \infty$ for the rest of the firms in that industry. As discussed in footnote 18, this pricing friction can also be interpreted as the static variant of the Calvo friction.

[28]Beraja, Hurst, and Ospina (2019) estimate that 76% of wages adjust during a given year. The implied quarterly degree of wage flexibility is thus $\phi_w = 1 - (0.24)^{1/4} = 0.30$.

[29]While we derived equation (39) in Theorem 2 under the assumption that productivity shocks are independent, we show in Appendix A.2 that the optimal policy's target price index remains unchanged even if one allows for heteroskedastic and correlated shocks.

TABLE I

EXPECTED WELFARE LOSS UNDER VARIOUS POLICIES.

	Optimal Policy (1)	Output-Gap Stabilization (2)	Consumption Weighted (3)	Domar Weighted (4)	Stickiness-Adjusted CPI (5)
Exact model					
Welfare loss	0.65	0.67	1.85	1.59	1.46
Quadratic approximation					
Total welfare loss	0.67	0.68	1.08	0.87	0.89
Within-industry misallocation	0.53	0.54	0.73	0.64	0.65
Across-industry misallocation	0.14	0.14	0.15	0.14	0.14
Output gap volatility	10^{-5}	0	0.20	0.08	0.10
Cosine similarity to optimal policy	1	0.99	0.12	0.16	0.14

Note: The table reports the expected welfare loss due to the presence of nominal rigidities under various monetary policies as a percentage of steady-state consumption. The expected welfare loss for the exact model is calculated using 10,000 draws. The quadratic approximation of welfare loss and its various components are obtained in accordance with the decomposition in equation (36). The last row reports the cosine similarity between each policy and the optimal policy.

simulate the exact model and calculate the resulting average welfare loss relative to the flexible-price economy for 10,000 draws of the vector of productivity shocks. Second, we rely on the closed-form expression in equation (36) to obtain the welfare loss under the model's quadratic approximation. While the former allows us to calculate the welfare loss taking into account all nonlinearities in the model, the latter provides us with a transparent decomposition of the welfare loss in terms of the various sources of misallocation as well as the labor wedge.

The first column of Table I reports the results. We find that the optimal policy generates an expected welfare loss equivalent to a 0.65% loss in quarterly consumption relative to the (unattainable) flexible-price equilibrium. This estimate remains virtually unchanged if instead one uses the quadratic approximation of the model, which predicts a loss equal to 0.67% of consumption under the optimal policy. The largest component of this welfare loss is due to misallocation within industries, accounting for 0.53 percentage points of loss in consumption. The second largest component is due to misallocation across industries, which accounts for another 0.14 percentage points loss in consumption. Finally, as the table indicates, under the optimal policy, there is nearly zero welfare loss due to the third component: volatility of the output gap.

Table I also provides a comparison between the performance of the optimal policy and four alternative, nonoptimal, price-stabilization policies. The first of these is the policy that minimizes the volatility of output gap. Recall from equation (40) that such a policy weighs industries solely based on their size and stickiness. Specifically, it stabilizes a price index with weights given by $\psi_i^{\text{o.g.}} \propto (1/\phi_i - 1)\lambda_i$ for all i, where ϕ_i is the degree of price flexibility of industry i and λ_i is the corresponding Domar weight. As the second column of the table indicates, the policy that stabilizes the output gap generates a welfare loss that is equivalent to a 0.67% fall in quarterly consumption (0.68% under the quadratic approximation). This welfare loss is incredibly similar to that under the optimal policy both in magnitude as well as in composition.

The third and fourth columns of Table I present welfare losses corresponding to two policies that weigh industries by size. The first of these policies, which is akin to targeting CPI or PCE, stabilizes the household's consumption price index, with weights that are equal to consumption shares: $\psi_i^{\text{cons}} = \beta_i$. The second policy weighs industries not by consumption shares but by their sales shares: $\psi_i^{\text{Domar}} \propto \lambda_i$. As is evident from the table, and in contrast to the output-gap-stabilization policy, these policies result in materially larger welfare losses compared to the optimal policy: consumption-weight-based price stabilization leads to a welfare loss equivalent to a 1.85% fall in quarterly consumption, while the Domar-weights-based price stabilization results in a welfare loss equivalent to a 1.59% reduction in quarterly consumption.[30]

Finally, the last column of Table I reports the expected welfare loss under a policy that targets a price index that would have been optimal in a counterfactual economy with no input-output linkages (akin to the horizontal economy in Figure 1(b)). Unlike the purely size-weighted policies in the third and fourth columns, such a policy takes the degree of price stickiness of different industries into account: as in Benigno (2004) and Eusepi, Hobijn, and Tambalotti (2011), it assigns greater weights to stickier industries and those with a larger share in the household's consumption basket, while disregarding input-output linkages. We thus refer to the target price index of this policy as the stickiness-adjusted CPI. We find that while such a policy outperforms the policy that targets the household's consumption price index, it still generates a significantly larger welfare loss compared to the optimal policy (1.46% instead of 0.65% of quarterly consumption).

Approximate Optimality of Output-Gap Stabilization. As already discussed, the welfare difference between the optimal and output-gap-stabilization policies in our calibration is minuscule, amounting to roughly 0.02 percentage points of quarterly consumption. Crucially, the industry-specific weights in the implied target price indices of the two policies are also similar. This similarity can be seen from Figure 3, which plots the weights corresponding to the two policies side by side (aggregated to sectoral level and normalized such that the weights in each policy add up to one).

To quantify the similarity between various policies, the last row of Table I reports the cosine similarities between the optimal policy and each of the four alternative policies. According to this measure—which is equal to the cosine of the angle between the two vectors representing the weights in the policies' corresponding target price indices—the optimal and the output-gap-stabilization policies are very similar, with a cosine similarity that exceeds 99%.[31] It is thereby no surprise that the difference in welfare between the two is negligible. For comparison, the cosine similarity between the optimal policy and any of the other three policies does not exceed 17%.

It is important to note that, while the optimal and output-gap-stabilization policies result in nearly identical expected welfare losses, this does not mean that losses due to misallocation are immaterial. In fact, as Table I illustrates, the bulk of the loss under either policy is due to price dispersion within industries. Rather, the similarity between the optimal and output-gap-stabilization policies is driven by the fact that, in our calibration, the components of optimal policy aimed at minimizing the losses from output gap volatility and misallocation are more or less aligned with one another. This, in turn, is due to two

[30]Unlike the optimal and output-gap-stabilization policies—for which the estimates obtained using the quadratic approximation are very close to the those obtained by simulating the exact model—the quadratic approximation underestimates the expected welfare loss under the consumption- and Domar-weights-based stabilization policies.

[31]Specifically, if ψ and $\hat{\psi}$ denote the vectors representing the weights in two policies' corresponding target price indices, the cosine similarity between the two policies is given by $\cos(\psi, \hat{\psi}) = \psi'\hat{\psi}/\|\psi\|_2\|\hat{\psi}\|_2$. When ψ and $\hat{\psi}$ are elementwise non-negative, $\cos(\psi, \hat{\psi})$ is always between 0 and 1, and reaches its maximum value of 1 if and only if ψ and $\hat{\psi}$ are proportional.

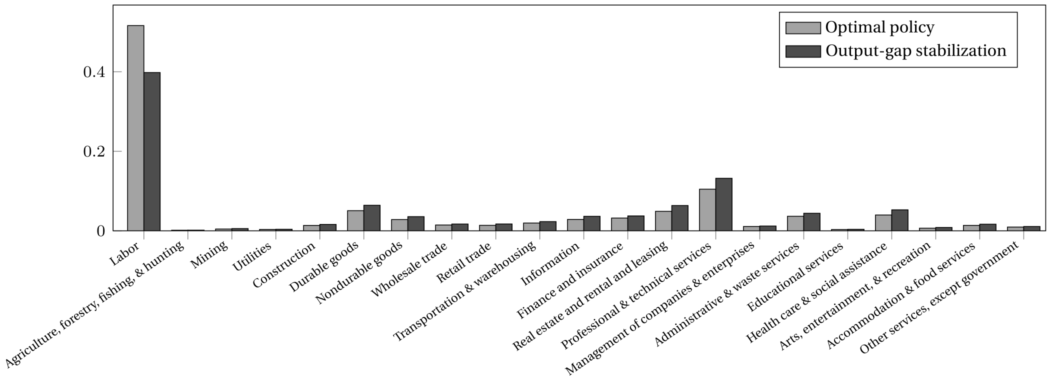


FIGURE 3.—Industry weights under optimal and output-gap-stabilization policies. The weights for each policy are aggregated to sectoral level and are normalized such that they add up to 1.

features of our calibration. First, the fact that the within-industry elasticity of substitution, $\theta = 6$, is larger than the unit elasticity of substitution across industries (because of Cobb–Douglas technologies) means that losses due to across-industry misallocation are quantitatively less important than those due to within-industry misallocation.[32] Second, the fact that all within-industry elasticities of substitution are assumed to be identical implies that the component of optimal policy aimed at minimizing within-industry price dispersion (i.e., ψ^{within} in (41)) does not discriminate across industries based on these elasticities and instead ends up weighing industries based on their size and stickiness—similar to $\psi^{\text{o.g.}}$. As a result, even though ψ^{within} and $\psi^{\text{o.g.}}$ are not identical, they both assign greater weights to larger and stickier industries, making the two major components of optimal policy more or less aligned with one another, with a cosine similarity of $\cos(\psi^{\text{o.g.}}, \psi^{\text{within}}) = 97\%$.

We conclude by noting that, as indicated by Figure 3, the target price indices under both the optimal and the output-gap-stabilization policies place the greatest weight on the nominal wage. This reflects the facts that (i) labor has the largest Domar weight (equal to 1) and (ii) in our calibration, the nominal wage is stickier than most industries' prices. The large weight assigned to the nominal wage by the optimal and the output-gap-stabilization policies is one of the key differences between these policies and the policy that stabilizes the household's consumption price index (which assigns no weight on the nominal wage).[33]

Aside from the nominal wage, the optimal and the output-gap-stabilization policies also assign large weights on certain service industries ("Miscellaneous professional, scientific, and technical services" and "Administrative and support services") as well as health care ("Hospitals") and real estate ("Other real estate"). The reason these particular industries command such large weights is due to the fact that they exhibit large Domar weights but low price flexibility. The service and health care sectors in particular comprise a generous

[32] This is also reflected in the fact that while, on average, the term corresponding to within-industry misallocation (ψ^{within}) accounts for 36.8% of the optimal weight ψ^*, the term corresponding to across-industry misallocation (ψ^{across}) is, on average, responsible for only 3.4% of the optimal weight.

[33] That the optimal policy assigns even a larger weight on the nominal wage than the output-gap-stabilization policy is in turn a consequence of the fact that labor is upstream to all other industries (consistent with Proposition 10) and does not rely on any sticky upstream suppliers (Proposition 8).

portion of the economy but are relatively sticky.[34] In contrast, the optimal policy assigns relatively small weights to industries such as "Apparel," "Printing," and "Waste Management," which, despite being relatively sticky, do not exhibit large Domar weights, making them less of a priority for stabilization.

6. CONCLUSION

In this paper, we study the optimal conduct of monetary policy in a multisector economy in which firms buy and sell intermediate goods over a production network. We introduce nominal rigidities into a rather canonical multisector, input-output model along the lines of Long and Plosser (1983) and Acemoglu et al. (2012) by assuming that firms make nominal pricing decisions under incomplete information about the aggregate state.

Within the context of this model, we make two theoretical contributions. First, we obtain necessary and sufficient conditions on the economy's disaggregated production structure and the nature of nominal rigidities under which monetary policy can implement flexible-price equilibria, and hence restore productive efficiency. As an important byproduct of this result, we also show that these conditions are violated for a generic set of information structures, thus concluding that, in general, monetary policy cannot achieve productive efficiency. This is in stark contrast to the canonical one-sector New Keynesian model in which, in the absence of markup shocks, the efficient allocation can be implemented with price stability.

Given that the first-best allocation is generically unattainable, our second theoretical contribution is thereby to characterize the optimal policy and to provide general principles for the optimal conduct of monetary policy in the presence of input-output linkages. In particular, we show that the optimal policy faces a trade-off between three components of welfare loss: misallocation across industries, misallocation within industries, and volatility of the output gap. We find that the optimal monetary policy is a price-index-stabilization policy with greater weights assigned to larger, stickier, and more upstream industries, as well as industries with less sticky upstream suppliers but stickier downstream customers.

Finally, in a quantitative application of our framework, we determine the optimal price index for the U.S. economy and find that moving from a policy that targets the household's consumption price index (i.e., a policy that is akin to targeting CPI or PCE) to the optimal price index can result in significant welfare gains. At the same time, we also find that, in our calibration, the difference in welfare loss under the optimal policy and under the policy that stabilizes the output gap is rather negligible.

Our theoretical and quantitative results can inform the policy debate around the appropriate price index the central bank should target (Mishkin (2007), Bullard (2011), Thornton (2011)). There are numerous measures of the aggregate price level; the indices most often considered by policymakers are overall measures of consumer prices (the CPI or the PCE), measures of consumer prices that exclude food and energy categories (core CPI or core PCE), as well as measures of producer prices (the PPI). On the theoretical side, our results provide a formal framework to account for the disaggregated nature of production in designing the proper target index. On the quantitative side, the near optimality of the output-gap-stabilization policy indicates that inflation measures that discount flexible-price sectors but also weigh sectors by their sales shares are desirable stabilization targets.

[34] See Bils and Klenow (2004), Dhyne et al. (2006), and Gorodnichenko and Weber (2016) for more evidence on the stickiness of health care and service sectors in the cross-section (both in the U.S. and in Europe).

We view our paper as a step toward exploring the implications of the disaggregated nature of production for the transmission and the optimal conduct of monetary policy. Several important issues, however, remain open for future research. First, as emphasized throughout the paper, we assumed that the underlying flexible-price allocation in our economy is efficient. While this was a conscious modeling decision made in order to isolate how the multisector, input-output feature of our economy fundamentally changes the policy prescriptions of one-sector New Keynesian models, the role of monetary policy would be more complicated in an economy with an inefficient steady state, as the monetary policy faces an additional trade-off between stabilizing prices and substituting for missing tax instruments. Exploring the implications of such a trade-off for the conduct of monetary policy would be a natural next step.

Second, a growing empirical literature has documented the propagation of various kinds of shocks—such as natural disasters (Carvalho, Nirei, Saito, and Tahbaz-Salehi (2021)), trade shocks (Huneeus (2020)), and demand shocks (Acemoglu, Akcigit, and Kerr (2016))—over input-output linkages. Similar empirical investigations on the production network's role as a monetary transmission mechanism, along the lines of Ozdagli and Weber (2021), would shed further light on how monetary policy can shape real economic outcomes.

APPENDIX A

A.1. *Propagation of Productivity and Monetary Shocks*

In this Appendix, we characterize the propagation of real and monetary shocks over the economy's production network under a general specification of nominal rigidities modeled as information frictions. As in Section 4, we focus our analysis on the class of Cobb–Douglas economies by assuming that the production technology of firms in industry i and the household consumption bundle are given by (19) and (20), respectively. We also assume logarithmic utility ($\gamma = 1$) and a fully elastic labor supply ($\eta \to \infty$). In contrast to Section 4, however, we do not impose any restrictions on the information structure. Finally, as is standard, we consider the log-linearization of the economy as $\delta \to 0$, where δ parameterizes the standard deviation of productivity shocks. Specifically, we assume that $\text{var}_{ik}(\log z) = O(\delta^2)$ for all firms in the economy.

We start with a definition. Denote the economy's input-output matrix by $\mathbf{A}$ and let $\mathbb{E}_{ik}[\cdot]$ denote the expectation with respect to the information set of firm k in industry i. For any vector $t = (t_1, \dots, t_n)'$ and any integer $r \geq 1$, define

$$\bar{\mathbb{E}}_i^{(r+1)}[t] = \sum_{j=1}^{n} a_{ij} \int_0^1 \mathbb{E}_{ik} \bar{\mathbb{E}}_j^{(r)}[t]\, \mathrm{d}k, \tag{A.1}$$

with the initial condition $\bar{\mathbb{E}}_i^{(1)}[t] = \int_0^1 \mathbb{E}_{ik}[t_i]\, \mathrm{d}k$. In words, $\bar{\mathbb{E}}_i^{(r+1)}[\cdot]$ is the cross-sectional average expectation of firms in industry i of their suppliers' expectations in the previous iteration, $\bar{\mathbb{E}}_j^{(r)}[\cdot]$, with weights given by expenditure shares, a_{ij}. The expression in (A.1), which is similar to the iterated expectations operator of Golub and Morris (2018), captures firms' higher-order average expectations, with a larger r corresponding to a higher order of iterated expectations. As is evident from (A.1), these expectations depend on the interaction between the production network and the information structure.[35] We have the following result.

PROPOSITION A.1: *Aggregate output satisfies*

$$\log C=\sum_{r=1}^{\infty}\sum_{i=1}^{n}\beta_i\bar{\mathbb{E}}_i^{(r)}[\log z]+\sum_{i=1}^{n}\beta_i\left(\log m-\sum_{r=1}^{\infty}\bar{\mathbb{E}}_i^{(r)}[\alpha\log m]\right)+o(\delta), \tag{A.2}$$

where $\bar{\mathbb{E}}_i^{(r)}[\cdot]$ *denotes the rth order average expectations of firms in industry i as defined in* (A.1).

This result expresses (log) aggregate output in terms of the economy's production network and information structure. It also characterizes the impact of real and monetary shocks on output: the first term on the right-hand side of (A.2) captures the aggregate impact of productivity shocks, whereas the second term captures the impact of monetary shocks (and hence, the degree of monetary nonneutrality). The key observation is that both terms depend not only on firms' first-order expectations, but also on their higher-order expectations (and in particular, on firms' expectations of their suppliers' expectations, firms' expectations of their suppliers' expectations of their suppliers' expectations, and so on). The dependence on these iterated expectations reflects the strategic complementarities in firms' price-setting behavior discussed in Section 4.1: firms set their nominal prices based on their expectations of their nominal marginal costs, which in turn depends on their suppliers' expectations.

To see the implications of Proposition A.1, it is instructive to consider the two stylized production networks depicted in Figure 1. For simplicity, we assume that all firms within each industry have access to the same information. Starting with the horizontal production network in Example 2, it follows from (A.2) that aggregate output is given by

$$\log C=\sum_{i=1}^{n}\beta_i\mathbb{E}_i[\log z_i]+\sum_{i=1}^{n}\beta_i\big(\log m-\mathbb{E}_i[\log m]\big)+o(\delta), \tag{A.3}$$

where β_i is the share of good i in the household's consumption bundle (which is also equal to i's steady-state Domar weight). A few observations are immediate. First, since there are no input-output linkages in the horizontal economy, aggregate output only depends on the firms' first-order expectations. Second, the aggregate impact of idiosyncratic productivity shocks to industry i depends not only on i's Domar weight—as would have been the case in the absence of nominal rigidities—but also on i's uncertainty about the shocks' realizations: regressing $\log C$ on $\log z_i$ results in a slope coefficient that is equal to $\beta_i\,\mathrm{var}[\mathbb{E}_i(\log z_i)]/\mathrm{var}(\log z_i)$.[36] Finally, (A.3) indicates that a monetary shock would have a greater impact on aggregate output the more uncertain the firms are about its realiza-

[35]For example, in the special case that the economy's information structure is given by (22) and (23), the vector of average iterated expectations of order r of log productivity shocks is equal to $\bar{\mathbb{E}}^{(r)}[\log z]=\mathbf{\Phi}(\mathbf{A}\mathbf{\Phi})^{r-1}\log z$, where $\mathbf{\Phi}=\mathrm{diag}(\phi_1,\dots,\phi_n)$ is the diagonal matrix of price flexibilities.

[36]Due to the law of total variance, this coefficient is always less than or equal to industry i's Domar weight (β_i) and is equal to it only when firms in industry i face no uncertainty about the realization of shocks to i (i.e., when $\mathrm{var}_i(\log z_i)=0$).

tion. This can be seen by regressing $\log C$ on $\log m$, which results in a slope coefficient that is equal to $\sum_{i=1}^n \beta_i \mathbb{E}[\text{var}_i(\log m)]/\text{var}(\log m)$.[37]

Next, consider the vertical economy in Example 1. In this case, (A.2) implies that

$$\log C = \sum_{i=1}^n \mathbb{E}_1\mathbb{E}_2 \dots \mathbb{E}_i[\log z_i] + \big(\log m - \mathbb{E}_1\mathbb{E}_2 \dots \mathbb{E}_n[\log m]\big) + o(\delta).$$

In contrast to the horizontal economy, the aggregate impacts of productivity and monetary shocks in this economy also depend on firms' higher-order expectations. This, of course, is a consequence of the presence of input-output linkages in the vertical economy and the resulting strategic complementarities in firms' price-setting behavior. Furthermore, as discussed in Section 4.1, they translate into more sluggish adjustments in nominal prices and an increase in the degree of monetary nonneutrality.

PROPOSITION A.2: *The vector of industry-level log outputs is given by*

$$\log y = \log y^* - \big(\mathbf{A} + \mathbf{\Lambda}^{-1}\mathbf{L}'\mathbf{\Lambda}(\mathbf{I} - \mathbf{A})\big)\left(\mathbf{L}\log z - \sum_{r=1}^{\infty} \bar{\mathbb{E}}^{(r)}[\log z]\right)$$
$$+ \big(\mathbf{A} + \mathbf{\Lambda}^{-1}\mathbf{L}'\mathbf{\Lambda}(\mathbf{I} - \mathbf{A})\big)\left(\mathbf{1}\log m - \sum_{r=1}^{\infty} \bar{\mathbb{E}}^{(r)}[\alpha \log m]\right) + o(\delta), \qquad \text{(A.4)}$$

where $\log y^*$ *denotes the vector of log outputs under flexible prices*, $\mathbf{\Lambda} = \text{diag}(\lambda_1, \dots, \lambda_n)$ *is the diagonal matrix of Domar weights, and* $\bar{\mathbb{E}}^{(r)}[t]$ *is a vector whose ith element is given by* $\bar{\mathbb{E}}_i^{(r)}[t]$.

This result, which is the industry-level counterpart to Proposition A.1, characterizes the impact of real and monetary shocks on sectoral output in the presence of nominal rigidities. Specifically, the second term on the right-hand side of (A.4) captures how nominal rigidities distort the propagation of productivity shocks compared to the flexible-price economy, whereas the third term captures the extent to which monetary shocks propagate over the production network. As in (A.2), both terms in general depend not only on firms' first-order expectations, but also on their expectations of higher orders.

A.2. *Heteroskedastic and Correlated Shocks*

In Section 4, we assumed that productivity shocks $(z_1, \dots, z_n)$ are independent and identically distributed. In this Appendix, we derive the optimal monetary policy while allowing for heteroskedastic and correlated shocks. In particular, we generalize (22) by assuming that log productivity shocks are jointly normally distributed according to

$$\log z \sim \mathcal{N}(0, \delta^2 \mathbf{\Sigma}), \qquad \text{(A.5)}$$

[37]This coefficient is always in the unit interval, and is equal to zero if and only if all firms have perfect information about the realization of the monetary shock. More generally, the slope coefficient of the regression of $\log C$ on $\log m$ extends the measure of monetary nonneutrality in (33) to economies with arbitrary information structures.

where $\delta > 0$ is a normalization constant and $\boldsymbol{\Sigma}$ is an $n \times n$ positive definite matrix that parameterizes the variance-covariance matrix of the shocks. The assumption that $\boldsymbol{\Sigma}$ is positive definite is trivially satisfied if the productivity shock to each industry has some idiosyncratic component. In order to keep the analysis tractable, we focus on sticky information pricing frictions similar to Mankiw and Reis (2002), according to which firms in each industry can either set their prices flexibly with no frictions or face full nominal rigidity. More specifically, we assume that fraction ϕ_i of firms in industry i receive perfectly informative signals about the realized productivity shocks, while the remaining $1 - \phi_i$ fraction of firms receive no information. Thus, as in Section 4, ϕ_i captures the degree of price flexibility of industry i. We have the following result.

PROPOSITION A.3: *Suppose productivity shocks are distributed according to* (A.5). *The optimal monetary policy is a price-stabilization policy of the form* $\sum_{s=1}^{n} \psi_s^* \log p_s = 0$, *where* ψ_s^* *is given by* (39).

Proposition A.3 establishes that optimal monetary policy is invariant to the distribution of shocks, as the target price-stabilization index $\sum_{s=1}^{n} \psi_s^* \log p_s$ remains the same as the one in Theorem 2. This is a consequence of the assumption that the monetary authority can set nominal aggregate demand as a function of the realized productivities, $(z_1, \dots, z_n)$. That the policy can be indexed to the aggregate state of the economy means that the monetary authority can minimizes the welfare loss due to the presence of nominal rigidities state-by-state, irrespective of the ex ante distribution of shocks.

A.3. *Information Frictions on the Monetary Authority*

The characterization of the optimal policy in Theorem 2 relies on the assumption that the monetary authority can set nominal aggregate demand as a function of the realized productivity shocks. In this Appendix, we relax this assumption by assuming that the monetary authority only has imperfect information about the shocks' realizations.

Specially, we assume that the monetary authority observes a collection of signal $(\hat{\omega}_1, \dots, \hat{\omega}_n)$ given by

$$\hat{\omega}_i = \log z_i + \hat{\epsilon}_i, \quad \hat{\epsilon}_i \sim \mathcal{N}(0, \delta^2 \hat{\sigma}^2), \tag{A.6}$$

where $\hat{\sigma}$ parameterizes the monetary authority's uncertainty about the shocks' realizations and the noise terms $(\hat{\epsilon}_1, \dots, \hat{\epsilon}_n)$ are independent from one another and the productivity shocks. As in Section 4, we assume that all productivity shocks are drawn independently according to (22), and we characterize the optimal policy to a first-order approximation as $\delta \to 0$. In order to keep the analysis tractable, we once again focus on a pricing friction according to which fraction ϕ_i of firms in each industry i have complete information about the realization of all shocks—and hence can set their prices flexibly with no frictions—while the remaining $1 - \phi_i$ fraction face full nominal rigidity. We also assume logarithmic utility ($\gamma = 1$) and a fully elastic labor supply ($\eta \to \infty$).

PROPOSITION A.4: *Suppose the monetary authority is subject to information frictions and has access to signals given by* (A.6). *The optimal monetary policy minimizes the volatility of the price index* $\sum_{i=1}^{n} \psi_s^* \log p_s$, *where* ψ_s^* *is given by* (39).

When the monetary authority cannot set nominal aggregate demand as a function of the realized productivity shocks, it is no longer able to implement the price-stabilization policy in Theorem 2. Nonetheless, Proposition A.4 establishes that the nature of optimal policy remains unchanged: (i) instead of fully stabilizing a target price index, the optimal policy minimizes the volatility of a target price index and (ii) this target price index is the same as the target in Theorem 2.[38]

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[38]Note that we obtain this result under the assumption that the monetary authority's information set is exogenous, thus ruling out the possibility of implementing a policy that is contingent on objects that are determined endogenously in equilibrium (as would be the case, for example, under the Taylor rule).

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