

Networks, Phillips Curves, and Monetary Policy

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Abstract

I develop an analytical framework for monetary policy in a multi-sector economy with a general input-output network. I derive the Phillips curve and welfare as a function of the underlying production primitives. Building on these results, I characterize (i) the correct definition of aggregate inflation and (ii) how the optimal policy trades off inflation in different sectors, based on the production structure. Correspondingly, I construct two novel inflation indicators. The first yields a well-specified Phillips curve. Consistent with the theory, this index provides a better fit for Phillips curve regressions than conventional consumer price specifications. The second is an optimal policy target, which captures the tradeoff between stabilizing aggregate output and relative output across sectors. Calibrating the model to the U.S. economy, I find that targeting consumer inflation generates a welfare loss of 0.8% of per-period GDP relative to the optimal policy, while targeting the output gap is close to optimal.

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1 Introduction

The New Keynesian framework informs the central banks’ approach to monetary policy, and constitutes the theoretical foundation underpinning inflation targeting. The baseline New Keynesian model assumes only one sector of production, whereas in reality an economy has multiple and heterogeneous sectors, which trade in intermediate inputs. There are crucial issues that the model is silent about. What is the correct definition of aggregate inflation, based on the production structure? How should central banks trade-off inflation in different sectors, depending on their position in the input-output network?

I extend the New Keynesian framework to account for multiple sectors, arranged in an input-output network. Sectors have arbitrary neoclassical production functions; they face idiosyncratic productivity shocks and heterogeneous pricing frictions. I solve the model analytically, providing an exact counterpart of traditional results in the multi-sector framework.

I derive analytical expressions for the two key objects that constitute the “backbone” of the optimal policy problem: the Phillips curve and the welfare loss function. Building on this result, I construct two novel indicators. The first inherits the positive properties of inflation in the one-sector model, and therefore can be viewed as its natural extension to a multi-sector economy. Specifically, this index yields a well-specified Phillips curve and it is stabilized together with aggregate output (a property which is referred to as the “divine coincidence”). The second indicator instead serves as an optimal policy target.

Traditionally, consumer price inflation has been taken as the relevant real-world counterpart of inflation in the one-sector model: it is universally used in Phillips curve regressions and as a policy target.¹ This choice, however, has no theoretical backing.² Importantly, I argue that in the multi-sector framework no single statistic inherits all the properties of inflation in the one-sector model. The “divine coincidence” in-

¹Statistical agencies release several different measures of consumer prices: in the US they are the consumer price index (CPI), personal consumption expenditures (PCE), their core versions (excluding sectors with very volatile prices, such as food and energy) and the GDP deflator. Central banks look at all of these measures, and various others (such as wage inflation, commodity prices, import prices, exchange rates...), but they lack a theoretical framework to aggregate them into a proxy for the output gap or into an interest rate target.

²In addition, Gali and Monacelli (2005) and Gali (2008) show that for small open economies the relevant statistic for the Phillips curve and monetary policy is producer price inflation.

dex preserves the positive properties, while the optimal policy target maintains the normative ones. These two indicators are distinct, and they are both different from consumer prices.

Correspondingly, I present two sets of analytical results, positive and normative, where I study the Phillips curve and welfare and construct the relevant indicators. I then calibrate the model to the US economy. My representation of production is fully general, and can match any input-output structure. The evolution of the economy is characterized by three variables (the output gap, sectoral inflation and productivity) and a set of steady-state parameters which depend on the production structure and sectoral pricing frictions. I construct time series of these variables and calibrate the parameters for the US economy. The analysis shows that taking into account the disaggregated structure of the economy is important, not just from a theoretical but also from a quantitative point of view.

In the positive section I provide a general expression for the Phillips curves associated with any given inflation index. The Phillips curve describes the joint evolution of inflation (π) and the output gap (\tilde{y}):

$$\pi_t = \rho \mathbb{E} \pi_{t+1} + \kappa \tilde{y}_t + u_t \quad (1)$$

where ρ is the discount factor, κ is the slope and u_t is a residual. In a multi-sector economy one can construct different measures of aggregate inflation, depending on the weighting of sectoral inflation rates. The slope and residual of the Phillips curve depend on the inflation index π_t on the left-hand-side, and on the production structure. I derive κ and u_t for a generic choice of π_t . I show that in general these Phillips curves are misspecified, because the residual u_t has an endogenous component which depends on sectoral productivity shocks. Notably, this is also true of the traditional Phillips curve specification with consumer prices on the left-hand-side. I also show that the slope of the consumer price Phillips curve is decreasing in the amount of input-output flows, and approximating the multi-sector economy with a one-sector model always leads to overestimating it. I then construct a novel inflation measure (the “divine coincidence” index) which instead yields a well-specified Phillips curve, with no endogenous residual and a slope that is independent of the production structure.

To build to these results, I first relate sectoral inflation rates to the output gap and

productivity. I then show that the slope of the Phillips curve aggregates sector-level elasticities with respect to the output gap, while the residual aggregates sector-level elasticities with respect to productivity.

The output gap is positive whenever aggregate demand is above the efficient level. Labor supply must then increase to accommodate the raise in demand, and this requires higher real wages. While the network structure does not affect the relation between the output gap and real wages, it is crucial for the pass-through of wages into prices. I demonstrate that this pass-through is decreasing in the size of intermediate input flows. Sectors are affected by wage changes directly (if they hire workers) and through intermediate input prices. Because of price rigidities, suppliers do not fully reflect changes in wages into their price, so that price rigidities get “compounded” along the production chain. This reduces the pass-through of wages into sectoral and aggregate prices, thereby flattening the aggregate Phillips curve(s).

The calibration illustrates the quantitative relevance of this result, with a focus on the consumer-price Phillips curve. The network model predicts a slope of around 0.1, consistent with empirical estimates (usually between 0.1 and 0.3). By contrast, the one-sector model implies a slope of about 1. Based on historical input-output tables, the multi-sector model also predicts that the slope has declined by about 30% between 1947 and 2017, a result consistent with empirical estimates.³

The residual of the Phillips curve captures a time-varying wedge between aggregate output and aggregate prices. In the one-sector benchmark the “divine coincidence” tells us that this wedge cannot result from productivity changes. Intuitively, a negative productivity shock increases marginal costs, but this direct effect is counter-balanced by a fall in equilibrium wages (reflecting a lower marginal product of labor). With multiple sectors these two effects no longer offset each other, because sectoral marginal costs are asymmetrically exposed to productivity and wage changes. As a consequence both sector-level and aggregate inflation are not stabilized under zero output gap. I use sectoral TFP shocks measured in the BEA-KLEMS dataset to construct a time series for the endogenous residual in the consumer price Phillips curve.

³See for example Blanchard (2012). Other authors attribute the decline in the slope of the Phillips curve to a different channel (see Blanchard (2016)): with better monetary policy inflation is more stable, therefore firms adjust prices less often. This dampens the response of inflation and reduces the slope of the Phillips curve. I mute this channel by assuming constant frequencies of price adjustment. For many sectors it is impossible to track their evolution over time, due to lack of data. For sectors where data are available, Nakamura and Steinsson (2013) find that the frequency of price adjustment is stable over time.

The series has a standard deviation of 25 basis points, suggesting that endogenous cost-push shocks explain a significant fraction of the variance of consumer inflation.

I derive the (unique) inflation index that restores the “divine coincidence” in the aggregate. This index weights sectoral inflation rates according to sales shares, appropriately discounting more flexible sectors. Intuitively, the importance of each sector is given by its total value added in final consumption, captured by its sales share, and not just by its consumption share. Moreover, the same shock generates a larger inflation response in sectors with more flexible prices, therefore these sectors need to be discounted.⁴

I construct a time series of the “divine coincidence” index for the US economy over the years 1984-2017. I compare Phillips curve regressions with this index to standard specifications with consumer prices. In a baseline OLS regression the R-squared is about 0.05 with consumer prices and about 0.2 with the “divine coincidence” index. Rolling regressions over 20 year windows have a stable coefficient and are always significant with the “divine coincidence” index, versus about 50% of the time with consumer prices.

The normative analysis focuses on the central bank’s problem. I derive welfare as a function of the output gap and sectoral inflation rates, solve for optimal monetary policy, and construct the inflation target which implements this policy. Targeting the “divine coincidence” index closes the output gap, but this does not implement the optimal policy. While the output gap captures distortions in aggregate demand, with multiple sectors there are also distortions in relative demand across firms and sectors. Relative demand distortions cannot be fully eliminated, and monetary policy cannot replicate the efficient equilibrium that emerges under flexible prices. These distortions however can be alleviated, at the cost of deviating from the optimal aggregate demand. Closing the output gap therefore is not constrained optimal. In this sense the “divine coincidence” does not hold from a normative point of view, unlike in the baseline model.

Monetary policy has only one instrument (interest rates or money supply), therefore it needs to trade off aggregate demand against allocative efficiency. We argued

⁴Interestingly, in the calibrated model the “divine coincidence” index assigns the highest weight (of 18%) to wage inflation. This is because labor has the highest sales share, and wages are quite rigid. Previous contributions (Mankiw and Reis (2006), Blanchard and Gali (2007), Blanchard (2016)) also suggest using wage inflation as an indicator. I provide a formal argument, and characterize the correct weight for wages relative to other sectors.

before that the “divine coincidence” inflation index moves one-to-one with the aggregate output gap. I show that the welfare cost of distortions in relative demand across firms and sectors is also fully captured by sectoral inflation rates. The size of these distortions depends on how shocks propagate through the input-output network, and their welfare effect depends on the response of quantities demanded, which is governed by the relevant elasticities of substitution in production and consumption. The optimal policy therefore can still be implemented via inflation targeting.

Targeting consumer inflation, as prescribed by the baseline model, leads to a welfare loss of 1.12% of per-period GDP with respect to a world without pricing frictions. Switching to the optimal policy brings this loss down to 0.28%, but does not fully eliminate it. Closing the output gap instead is almost optimal. Intuitively, the output gap is a good target because monetary policy is a blunt instrument to correct misallocation (being one-dimensional). Therefore the cost of distorting aggregate demand is larger than the gain in allocative efficiency, and in practice the optimal output gap is close to zero.

Related literature My framework is closely related with the literature on markup distortions, aggregate output and welfare in production networks (Baqae and Farhi (2019, 2020)). The distinctive feature of my setup is that markup changes are not exogenous, but result from productivity shocks and price rigidities.

A large literature extends the one-sector New Keynesian model to incorporate realistic elements of the production structure, both analytically and quantitatively. Earlier papers maintain the analytical approach of the baseline model, focusing on simpler extensions (Aoki (2001), Woodford (2003), Benigno (2004), Blanchard and Gali (2007), Gali (2008), Gali and Monacelli (2008)). More recent works allow for richer input-output structures, but restrict themselves to a mostly quantitative approach (Basu (1995), Carvalho (2006), Carvalho and Nechio (2011), Nakamura and Steinsson (2013) and Pasten, Schoenle and Weber (2016, 2017), Castro-Cienfuegos (2019), Höynck (2019)). I combine the two approaches, providing a full analytical solution and quantitative results with a general production structure.

My paper is also related with previous works deriving optimal indicators, based on theoretical (Benigno (2004), Gali and Monacelli (2005)) or quantitative arguments (Mankiw and Reis (2003), Eusepi, Hobbijn and Tambalotti (2011)). I consider a more general input-output structure, and my optimal inflation target is based on a

microfounded objective function. My analytical approach allows a clear interpretation of sectoral weights based on production primitives.

In parallel and independent work, La’O and Tahbaz-Salehi (2019) perform a similar “normative” analysis. A key difference is that in their setup price rigidities are microfounded as arising from incomplete information, while production functions are restricted to be Cobb-Douglass. Because of these modeling differences, sectoral weights have different determinants in the optimal targeting rule (the information structure versus substitution elasticities).

A large empirical literature documents the limitations of consumer price inflation for Phillips curve regressions and forecasting (Orphanides and Van Norden (2002), Mavroeidis, Plagborg-Muller and Stock (2014)). Many studies seek to construct indicators with better statistical properties (Stock and Watson (1999), Bernanke and Boivin (2003), Stock and Watson (2015)). I show that Phillips curve regressions with the “divine coincidence” index which I construct yield stable and significant estimates over time and across specifications.

2 Setup

This section lays out the key elements of the network model and the assumptions about preferences, timing and policy instruments. Section 2.5 introduces the equilibrium concept, which is designed to account for the endogenous evolution of markups under price rigidities.

2.1 Timing and policy instruments

In the main text I consider a one-period model. The dynamic version is presented in online Appendix D.

The timing is as follows: before the world begins, firms set prices based on their expectations of productivity and money supply; then sectoral productivities are realized, and the central bank sets money supply; some firms have the possibility to adjust their price after observing the realized productivity and money supply, while others do not; the world ends after production and consumption take place. Inflation is defined as the change in prices with respect to the pre-set ones.

In the static setup money supply is the only policy instrument (to be replaced

with interest rates in the dynamic version). I impose that nominal consumption expenditure cannot exceed the aggregate money supply M , so that with incomplete price adjustment an increase in M raises aggregate demand and output.

2.2 Preferences

Consumers derive utility from consumption and leisure, with utility function

$$U = \frac{C^{1-\gamma}}{1-\gamma} - \frac{L^{1+\varphi}}{1+\varphi}$$

L is labor supply. There are N goods produced in the economy, and agents have homothetic preferences over all of these goods. C is their utility from consumption, defined over bundles (c_1, \dots, c_N) :

$$C = C(c_1, \dots, c_N)$$

Consumers maximize utility subject to the budget constraint

$$PC \leq wL + \Pi - T$$

where P is the price index of the consumption bundle, w is the nominal wage, Π are firm profits (rebated to households) and T is a lump-sum transfer from the government.

In addition, nominal consumption expenditure PC cannot exceed the aggregate money supply M :

$$PC \leq M$$

2.3 Production

There are N sectors in the economy (indexed by $i \in \{1, \dots, N\}$). Within each sector there is a continuum of firms, producing differentiated varieties.

All firms f in sector i have the same constant returns to scale production function

$$Y_{if} = A_i F_i(L_{if}, \{x_{ijf}\})$$

where L_{if} is the amount of labor hired by firm f in sector i , x_{ijf} is the quantity of

good j that it uses as input, and A_i is a Hicks-neutral, sector-specific productivity shock.⁵ Labor is freely mobile across sectors.

Customers buy a CES bundle of the differentiated varieties. Sectoral outputs are given by

$$Y_i = \left(\int Y_{if}^{\frac{\epsilon_i-1}{\epsilon_i}} df \right)^{\frac{\epsilon_i}{\epsilon_i-1}}$$

where ϵ_i is the elasticity of substitution between varieties within sector i .

Cost minimization and markups All producers in sector i solve the cost-minimization problem

$$C_i = \min_{\{x_{ij}\}, L_i} wL_i + \sum_j p_j x_{ij} \quad s.t. \quad A_i F_i(L_i, \{x_{ij}\}) = \bar{y}$$

Under constant returns to scale marginal costs are the same for all firms, and they use inputs in the same proportions.

Before the world begins, all firms set their price optimally based on their expected marginal cost. They solve

$$\max_{p_i} \mathbb{E} D_i(p_i - (1 - \tau_i) mc_i) \left(\frac{p_i}{P_i} \right)^{-\epsilon_i}$$

where D_i and P_i are the sector-level demand and price index, and τ_i is an input subsidy provided by the government. The subsidies τ_i are set in order to eliminate the distortions that arise under the CES demand structure, where firms have constant desired markup given by

$$\mu_i^* = \frac{\epsilon_i}{\epsilon_i - 1} > 1$$

This is inefficient, since there are no fixed costs. The optimal subsidies satisfy

$$1 - \tau_i = \frac{\epsilon_i - 1}{\epsilon_i}$$

They are set so that the resulting markup over pre-subsidy marginal costs is 1, and firms charge price

$$p_i^* = \mathbb{E} mc_i \tag{2}$$

⁵Note that this is without loss of generality: factor-biased productivity shocks can be modeled by introducing an additional sector which simply purchases and sells the factor, and letting a Hicks-neutral shock hit this sector.

Input subsidies cannot change in response to shocks, and are constrained to be the same for all firms within the same sector.

After productivity and money supply are realized, firms in the same sector end up charging different prices. Those who can adjust their price keep a constant markup equal to the desired one. All other firms need to keep constant prices, and must accept a change in markup given by

$$d \log \mu_{if}^{NA} = -d \log mc_i$$

2.4 Government

The government provides input subsidies to firms, financing them through lump-sum taxes on consumers. It runs a balanced budget, so that the lump-sum transfer must equal total input subsidies:

$$T = \sum_i \tau_i mc_i$$

2.5 Equilibrium

The equilibrium concept adapts the definition in Baqaee and Farhi (2020) to account for the endogenous determination of markups given pricing frictions and shocks. For given sectoral markups I impose market clearing, and further require that the evolution of markups is consistent with the realization of productivity and monetary shocks.

For given output gap, sectoral probabilities of price adjustment δ_i and sectoral productivity shifters, general equilibrium is given by a vector of firm-level markups, a vector of prices p_i , a nominal wage w , labor supply L , a vector of sectoral outputs y_i , a matrix of intermediate input quantities x_{ij} , and a vector of final demands c_i , such that: a fraction δ_i of firms in each sector i adjust their price; markups are optimally chosen by adjusting firms, while they are such that prices stay constant for the non-adjusting firms; consumers maximize utility subject to the budget and cash-in-advance constraint; producers in each sector i minimize costs and charge the relevant markup; and markets for all goods and labor clear.

3 Definitions

I approximate the model by solving for first and second order log-deviations from an equilibrium where productivity and money supply are equal to their expected value. The Phillips curve and welfare are fully characterized by three variables (the output gap, the vector of sectoral inflation rates and the vector of sectoral productivity shifters), and a set of equilibrium parameters, which capture the input-output structure and sector-level pricing frictions. These variables and parameters are defined below.

3.1 Variables

3.1.1 Aggregate output gap

Definition 1. The aggregate output gap \tilde{y} is the log-difference between realized output y and efficient output y_{nat} :

$$\tilde{y} = y - y_{nat}$$

online Appendix A3 in the Supplemental Materials derives natural output as a function of productivity.

3.1.2 Sectoral inflation rates

The $N \times 1$ vector of inflation rates is denoted by

$$\pi = \begin{pmatrix} \pi_1 \\ \dots \\ \pi_N \end{pmatrix}$$

Remark 1. While the output gap captures distortions in aggregate demand, Proposition 4 in Section 5.1 shows that the welfare cost of relative demand distortions across sectors (which is related with sectoral output gaps) can be written as a function of sectoral inflation rates.

3.2 Steady-state parameters

3.2.1 Price rigidity parameters

To model price rigidities, I assume that only a fraction δ_i of the firms in each sector i can adjust their price after observing money supply and productivity. I collect these price adjustment parameters into a diagonal matrix Δ .

Remark 2. This Calvo-style assumption, together with the firms' optimal pricing equation (2), yields a mapping between inflation, marginal costs and markups. The fraction δ_i of firms in each sector i who can adjust prices fully passes-through changes in sectoral marginal costs $d \log mc_i$ into their price.⁶ The remaining fraction $1 - \delta_i$ is constrained to keep its price fixed, therefore it fully absorbs cost changes into its markup. At the sector level, this implies a markup response equal to $d \log \mu_i = -(1 - \delta_i) d \log mc_i$, and a change in price given by $\pi_i = \delta_i d \log mc_i$. Therefore, the following relation holds:

$$\pi = \Delta d \log mc = -\Delta (I - \Delta)^{-1} d \log \mu \quad (3)$$

where $d \log mc$ is the vector of sectoral marginal cost changes, and $d \log \mu$ is the vector of sectoral markups.

Remark 3. Wage rigidities can be easily incorporated into this setup, by adding a labor sector which collects labor services and sells them to all the other sectors. While there still is a flexible underlying wage (paid by the labor sector to workers), the market wage, defined as the price charged by the labor sector, is sticky.

3.2.2 Input-output definitions

The input-output structure is characterized by steady-state consumption, labor and input-output shares. We also introduce two useful derived objects, the Leontief inverse and the vector of sales shares, constructed from the input-output matrix and the vector of consumption shares.

⁶Remember that desired markups are constant under the CES assumption (see Section 2.3).

Consumption shares The $N \times 1$ vector β denotes sectoral expenditure shares in total consumption, and has components

$$\beta_i = \frac{p_i c_i}{PC}$$

Labor shares Sector-level labor shares in total sales are encoded in the $N \times 1$ vector α , with components

$$\alpha_i = \frac{w L_i}{p_i y_i}$$

Input-output matrix The input-output matrix Ω is an $N \times N$ matrix, with elements $\omega_{i,j}$ given by the expenditure share on input j in i 's total sales:

$$\omega_{ij} = \frac{p_j x_{ij}}{p_i y_i}$$

Leontief inverse The Leontief inverse of the input-output matrix Ω is the matrix $(I - \Omega)^{-1}$.

While ω_{ij} is the fraction of sector i revenues directly spent on goods from sector j , the Leontief inverse captures the total (direct and indirect) expenditure of sector i on goods from sector j (again as a share of i 's revenues). The indirect component comes from the fact that j 's product can be embedded in i 's intermediate inputs, if i 's suppliers, or i 's suppliers' suppliers, etc., use good j in production.

“Adjusted” Leontief inverse The “adjusted” Leontief inverse is the matrix $(I - \Omega\Delta)^{-1}$. The (i, j) element of this matrix is the elasticity of i 's marginal cost with respect to j 's marginal cost. With price rigidities it is different from the Leontief inverse, because marginal cost changes are not fully passed-through into prices. In this case the “direct” elasticity of i 's marginal cost with respect to j 's is $\omega_{ij}\delta_j$, which discounts the input share ω_{ij} by the fraction δ_j of producers in j that adjust their price. The total (direct plus indirect) elasticity is then given by $(I - \Omega\Delta)_{ij}^{-1}$.

Sales shares The vector λ of sectoral sales shares in total GDP has components

$$\lambda_i = \frac{P_i Y_i}{PC}$$

It is a well known result that

$$\lambda^T = \beta^T (I - \Omega)^{-1}$$

Elasticities of substitution The log-linearized model only depends on the input and consumption shares introduced above. Elasticities of substitution in production and consumption instead matter for the second-order welfare loss derived in Section 5. I denote the elasticity of substitution between varieties from sector i by ϵ_i , the elasticity of substitution between goods i and j in the production of good k by θ_{ij}^k , and their elasticity of substitution in consumption by σ_{ij}^C ; the elasticity of substitution between good i and labor in the production of good k is denoted by θ_{iL}^k .

4 The Phillips curve

The Phillips curve describes the joint evolution of aggregate inflation π^{AGG} and the output gap \tilde{y} . The standard New-Keynesian Phillips curve is given by (see for example Galí (2008)):

$$\pi_t^{AGG} = \rho \mathbb{E} \pi_{t+1}^{AGG} + \kappa \tilde{y}_t + u_t \quad (4)$$

where $\mathbb{E} \pi_{t+1}^{AGG}$ is expected future inflation, κ is the slope, ρ is the discount factor and u_t is a residual. In the main text I focus on a one-period model, where the Phillips curve has no forward-looking term:⁷

$$\pi_t^{AGG} = \kappa \tilde{y}_t + u_t \quad (5)$$

The slope κ captures the percentage change in prices when output raises by 1% above the efficient level. Intuitively, if output is above the efficient level labor demand also raises. This puts upwards pressure on wages, so that marginal costs and prices increase ($\kappa > 0$). The residual u_t captures a time-varying wedge between output and prices. In the one-sector model this wedge cannot arise endogenously from productivity fluctuations. This is a key result, referred to as the “divine coincidence” (see Blanchard and Galí (2007)). In the one sector model therefore there is no endogenous tradeoff between stabilizing output and prices. The only way to generate such

⁷The dynamic version of the model is derived in online Appendix D2.

a tradeoff is via an exogenous shock to producers' desired markups (a “cost-push” shock).

It is widely recognized however that shocks to certain sectors, such as the oil sector, raise inflation even if output is stabilized. The stylized representation of oil shocks as an increase in producers' desired markups is not suitable to study the optimal policy response. The multi-sector model provides a much more convincing representation of the inflationary effect of oil shocks, and of productivity shocks in general.

With multiple sectors there are several possible ways to define aggregate inflation, depending on the weighting of sectoral inflation rates. Accordingly, the slope and residual of the Phillips curve change with the aggregate inflation index π^{AGG} on the left-hand-side of (5). Below, I address two questions. Section 4.1 derives the slope and residual of the Phillips curve corresponding to any given aggregate inflation index, as a function of the production structure. I show that the “divine coincidence” fails for a generic inflation index, resulting in an endogenous tradeoff between stabilizing (consumer) prices and output. Section 4.3 constructs the unique inflation index which preserves the “divine coincidence” and inherits all the “positive” properties of inflation in the one sector model.

4.1 Phillips curve for a generic inflation index

4.1.1 Notation and aggregation

I first derive the response of prices to productivity and monetary shocks at the sector level, and then combine them into the aggregate Phillips curve(s). All changes in productivity, marginal costs and prices are relative to the flex-price equilibrium where productivity and money supply are equal to their expected value.

Sectoral prices respond to marginal cost shocks according to equation (3):

$$\pi = \Delta d \log mc \tag{6}$$

Equation (6) shows that the change in sector-level prices is proportional to the change in marginal costs, times the fraction of adjusting firms. Intuitively, firms would like to fully pass-through changes in marginal costs into their prices, but only a fraction Δ of them has the opportunity to do so.

Marginal costs depend on wages and productivity, either directly, or indirectly

through input prices. While productivity shocks are exogenous, wage changes are determined in equilibrium as a result of productivity and monetary shocks. Propositions 1 and 2 below solve for the marginal cost change in (6) as a function of these underlying shocks. Monetary shocks in turn are fully captured by the output gap, which is related one-to-one with the money supply (see Remark 5 below).

This allows us to express the vector π of sector-level inflation rates as a function of productivity shocks ($d \log A$) and the output gap (\tilde{y}):

$$\underbrace{\pi}_{N \times 1} = \underbrace{\mathcal{B}}_{N \times 1} \tilde{y} + \underbrace{\mathcal{V}}_{N \times N} \underbrace{d \log A}_{N \times 1} \quad (7)$$

Here I denote by \mathcal{B} the $N \times 1$ vector whose components \mathcal{B}_i are the elasticities of sector i 's price with respect to the output gap, and by \mathcal{V} the $N \times N$ matrix whose elements \mathcal{V}_{ij} are the elasticities of sector i 's price with respect to a productivity shock to sector j . The elasticities \mathcal{B} and \mathcal{V} are derived in Propositions 1 and 2.

For a given inflation index, the corresponding Phillips curve is obtained by aggregating both sides of Equation (7). An inflation index π^{AGG} is characterized by the vector of weights ϕ that it assigns to sectoral inflation rates:

$$\pi^{AGG} \equiv \phi^T \pi = \sum_i \phi_i \pi_i$$

Weighting both sides of Equation (7) according to ϕ we obtain the Phillips curve:

$$\pi^{AGG} = \underbrace{\phi^T \mathcal{B}}_{\text{slope}} \tilde{y} + \underbrace{\phi^T \mathcal{V} d \log A}_{\text{residual}} \quad (8)$$

The slope is the aggregate elasticity with respect to the output gap, while the residual is the aggregate elasticity with respect to productivity. Consumer inflation π^C is a special case, obtained by weighting sectoral inflation rates according to consumption shares ($\phi = \beta$).

Sections 4.1.2 and 4.1.3 below characterize the elasticities \mathcal{B} and \mathcal{V} , and derive the slope and residual of the consumer-price Phillips curve as a corollary.⁸

⁸Propositions 1 and 2 can be seen as an application of Proposition 10 in Baqaee and Farhi (2017), recast in terms of sectoral probabilities of price adjustment and in the special case of an efficient initial equilibrium.

4.1.2 Slope of the Phillips curve

Proposition 1 derives the elasticities of prices with respect to the output gap sector-by-sector. Corollary 1 aggregates them into the slope of the consumer-price Phillips curve.

Proposition 1. *The elasticity of sectoral prices with respect to the output gap is*

$$\mathcal{B} = \frac{\Delta \left((I - \Omega \Delta)^{-1} \alpha \right)}{1 - \bar{\delta}_w} (\gamma + \varphi) \quad (9)$$

where

$$\bar{\delta}_w \equiv \beta^T \Delta (I - \Omega \Delta)^{-1} \alpha \quad (10)$$

is the pass-through of nominal wages into consumer prices.

Proof. See online Appendix A1 □

Corollary 1. *The slope κ^C of the consumer-price Phillips curve is given by*

$$\kappa^C = \frac{\bar{\delta}_w}{1 - \bar{\delta}_w} (\gamma + \varphi) \quad (11)$$

Proof. The result follows immediately from Proposition 1 and Equation 8. □

The vector \mathcal{B} and the slope κ^C are the elasticities of sectoral and consumer prices with respect to the output gap. Intuitively, if output is above potential then labor demand must increase. This puts upwards pressure on wages and prices. The term $(\gamma + \varphi)$ on the right hand side of (9) and (11) is the effect on real wages. It is governed by the parameters of the labor supply curve, and does not depend on the production structure.

The pass-through of real wages into prices (the remaining component in (9) and (11)) instead depends on the input-output network. It can be further decomposed into the nominal wage pass-through (given by $\Delta \left((I - \Omega \Delta)^{-1} \alpha \right)$ for sectoral inflation rates and by $\bar{\delta}_w$ for consumer prices) and a general equilibrium multiplier $1 - \bar{\delta}_w$ (which maps changes in real wages into changes in nominal wages, through the equilibrium response of consumer prices).

The nominal wage pass-through $\bar{\delta}_w$ is the key object. With no intermediate inputs ($\Omega = \mathbb{O}$, $\alpha = 1$), as in benchmark model, marginal costs have unit elasticity with

respect to wages. From Equation (3), the price pass-through is simply given by the adjustment frequency $diag(\Delta)$, and we have $\bar{\delta}_w = \mathbb{E}_\beta(\delta)$. With input-output linkages instead this pass-through is dampened, as stated in Corollary 2.

Corollary 2. *As long as some sector uses an intermediate input with sticky prices, the pass-through of wages into marginal costs is less than one:*

$$\exists i, j \text{ such that } \omega_{ij}\delta_j < \omega_{ij} \Rightarrow (I - \Omega\Delta)^{-1} \alpha < \mathbf{1} \quad (12)$$

As a result, sectoral price pass-throughs are smaller than the corresponding adjustment frequencies, and the aggregate price pass-through $\bar{\delta}_w$ is less than the average price rigidity $\mathbb{E}_\beta(\delta)$:

$$\exists i, j \text{ such that } \omega_{ij}\delta_j < \omega_{ij} \Rightarrow \begin{cases} \Delta ((I - \Omega\Delta)^{-1} \alpha) < diag(\Delta) \\ \bar{\delta}_w < \mathbb{E}_\beta(\delta) \end{cases} \quad (13)$$

A reduction in labor shares compensated by a uniform increase in input shares reduces $\bar{\delta}_w$:

$$d\alpha_i < 0, \quad d\omega_{ij} = d\omega_{ik} \quad \forall j, k, \quad \exists j \text{ such that } \omega_{ij}\delta_j < \omega_{ij} \Rightarrow d\bar{\delta}_w < 0 \quad (14)$$

Proof. See online Appendix A1. □

The intuition is as follows. Marginal costs are affected by wages directly, or indirectly through input prices. The direct exposure depends on the own labor share, while the indirect exposure depends on the suppliers' labor share, the suppliers' suppliers labor share, etc. Incomplete price adjustment dampens the indirect component of the pass-through, as stated in Corollary 2. Formally, the “impulse” component of a wage shock is given by the vector α of steady-state labor shares. The propagation is captured by the “adjusted” Leontief inverse $(I - \Omega\Delta)^{-1}$, which discounts rigid sectors. Therefore the overall effect on marginal costs is

$$\frac{d \log mc}{d \log w} = (I - \Omega\Delta)^{-1} \alpha \quad (15)$$

We can then use the pricing equation (3) to translate changes in marginal costs into inflation rates:

$$\frac{d \log p}{d \log w} = \Delta \frac{d \log mc}{d \log w} = \Delta (I - \Omega\Delta)^{-1} \alpha \quad (16)$$

This yields the pass-through of nominal wages into sectoral inflation rates in equation (9). Note that different sectors have different pass-through: it is higher in sectors with a large direct labor share and flexible prices, whose suppliers have a large direct labor share and flexible prices, etc.

To obtain the pass-through into consumer prices $\bar{\delta}_w$ we simply aggregate the sectoral responses in (16) according to consumption shares:

$$\bar{\delta}_w = \beta^T \frac{d \log p}{d \log w} = \beta^T \Delta (I - \Omega \Delta)^{-1} \alpha \quad (17)$$

Corollary 2 implies that in the presence of intermediate inputs $\bar{\delta}_w$ is smaller than the average price rigidity. This in turn lowers the slope of the consumer-price Phillips curve:

$$\kappa^C = (\gamma + \varphi) \frac{\bar{\delta}_w}{1 - \bar{\delta}_w} < (\gamma + \varphi) \frac{\mathbb{E}_\beta(\delta)}{1 - \mathbb{E}_\beta(\delta)} \quad (18)$$

The right hand side of Equation (18) is the slope predicted by standard calibrations, which directly map the one-sector model into the data without accounting for input-output linkages. Quantitatively, the difference between the left and right hand sides of Equation (18) is important. Section 6.3 evaluates it for the US economy, finding that the left hand side is one order of magnitude smaller (~ 0.1 against ~ 1).

4.1.3 Endogenous cost-push shocks

Proposition 2 derives the elasticities of sectoral prices with respect to productivity shocks. Corollary 3 aggregates them into the endogenous residual of the consumer-price Phillips curve.

Proposition 2. *The elasticity of sectoral prices with respect to productivity shocks is given by*

$$\mathcal{V} = \Delta (I - \Omega \Delta)^{-1} \left[\frac{\alpha \lambda^T - \beta^T \Delta (I - \Omega \Delta)^{-1}}{1 - \bar{\delta}_w} - I \right] \quad (19)$$

so that

$$\mathcal{V} d \log A = \Delta (I - \Omega \Delta)^{-1} \left[\frac{1 - \bar{\delta}_A}{1 - \bar{\delta}_w} \alpha \lambda^T - I \right] d \log A \quad (20)$$

where

$$\bar{\delta}_A (d \log A) \equiv \frac{\beta^T \Delta (I - \Omega \Delta)^{-1} d \log A}{\lambda^T d \log A} \quad (21)$$

is the pass-through of the productivity shock into consumer prices, scaled by the aggregate shock.

Proof. See online Appendix A1 □

Corollary 3. *The residual in the consumer-price Phillips curve is given by*

$$u^C = \frac{\bar{\delta}_w - \bar{\delta}_A}{1 - \bar{\delta}_w} \lambda^T d \log A \quad (22)$$

Proof. The result follows immediately from Proposition 2 and Equation 8. □

The elasticity \mathcal{V} captures a direct and an indirect effect of productivity shocks on marginal costs. If aggregate productivity falls, marginal costs increase (direct effect). However wages fall in equilibrium (indirect effect), thereby reducing marginal costs. In the flex-price economy real wages are equal to aggregate productivity $\lambda^T d \log A$, which is also the marginal product of labor. In the sticky-price economy real wages are the same as in the efficient equilibrium if output is at the efficient level ($\tilde{y} = 0$).⁹

In the one-sector model the direct and indirect effect exactly offset each other when output is at the efficient level. This is the key intuition behind the “divine coincidence”. With multiple sectors instead marginal costs are asymmetrically exposed to wages and productivity. Formally, the direct effect of productivity on sectoral prices is given by the second term in (20):

$$\text{direct component} = -\Delta \underbrace{(I - \Omega \Delta)^{-1}}_{\text{marginal cost}} d \log A \quad (23)$$

The adjusted Leontief inverse captures the shock propagation, following the same intuition as in Section 4.1.2. The price response is obtained by multiplying the change in marginal costs times the adjustment probability Δ , according to the pricing Equation (16).

The indirect effect through wages is given by the first term in Equation (20):

$$\text{wage component} = \underbrace{\Delta (I - \Omega \Delta)^{-1} \alpha}_{\text{pass-through}} \underbrace{\frac{1 - \bar{\delta}_A}{1 - \bar{\delta}_w}}_{\text{GE multiplier}} \underbrace{\lambda^T d \log A}_{\text{real wages}}$$

⁹This result is derived in the proof of Proposition 2.

The term $\lambda^T d \log A$ is the change in real wages, which equals the aggregate productivity shock. The general equilibrium multiplier $\frac{1-\bar{\delta}_A}{1-\bar{\delta}_w}$ maps real wages into nominal wages. The term $\Delta (I - \Omega \Delta)^{-1} \alpha$ is the pass-through of nominal wages into sectoral prices, which we derived in Section 4.1.2. Note that, while the direct component depends on the full distribution of sectoral productivity shocks, the wage component only depends on the aggregate shock.

In general, at the sector level the wage and productivity pass-through are different. Section 4.2 provides illustrative examples. As a result inflation is not stabilized sector-by-sector, even if the output gap is closed. Corollary 3 shows that consumer inflation is not stabilized either. Its response depends on the relative pass-through of wages and productivity into consumer prices, given by the difference $\bar{\delta}_w - \bar{\delta}_A$.

The productivity pass-through $\bar{\delta}_A$ is defined in Equation (21), mirroring the wage pass-through $\bar{\delta}_w$ introduced in Section 4.1.2. Note that $\bar{\delta}_A$ is scaled by the aggregate shock, and it depends on the full distribution of sectoral productivity shocks (while $\bar{\delta}_w$ is a constant). From Equation (22) we see that following a negative shock ($\lambda^T d \log A < 0$) consumer inflation is positive if and only if the productivity pass-through is larger than the wage pass-through ($\bar{\delta}_A > \bar{\delta}_w$). This is the case whenever downstream or flexible sectors are hit by a “worse” shock than the average, as the examples in Section 4.2 illustrate.

A natural question at this point is whether there are shocks after which prices are stabilized sector-by-sector under zero output gap. Corollary 4 shows that the only shock with this property is an aggregate labor augmenting shock, which in this setup is equivalent to a TFP shock proportional to sectoral labor shares α .

Corollary 4. *It holds that $\mathcal{V}\alpha = \mathbf{0}$, and α is the only vector with this property.*

Proof. See the complements to Appendix A1 in the Supplemental Material. \square

A consequence of Corollary 4 is that perfect stabilization is impossible not only in the presence of asymmetric sector-level shocks, but also after an aggregate TFP shock - except in the horizontal economy,¹⁰ where aggregate TFP shocks and labor augmenting shocks coincide. Quantitatively, aggregate TFP shocks generate a significant inflation-output tradeoff. In the calibrated model a 1% negative shock increases consumer inflation by 0.26% under zero output gap.

¹⁰That is, an economy without intermediate inputs.

4.2 Examples

The three examples in this section illustrate the main channels through which the “divine coincidence” fails in the multi-sector model. The vertical chain isolates the effect of input-output linkages, while the horizontal economy highlights the role of heterogeneous adjustment frequencies and idiosyncratic shocks. The oil economy combines the two. This last example rationalizes the common wisdom that oil shocks generate a tradeoff between stabilizing output and consumer prices (an endogenous “cost-push” shock). The Example highlights the crucial role of wage rigidities and heterogeneous adjustment probabilities in generating this outcome.

Example 1. Vertical chain

Consider an economy made of two sectors, which we label U (for “upstream”) and D (for “downstream”), as in Figure 1. Both sectors use labor, and D also uses U as an intermediate input. Only D sells to final consumers.

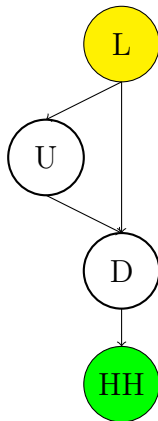


Figure 1: Vertical chain

Let’s verify that in general consumer prices are not stabilized under zero output gap (the “divine coincidence” fails). In this example consumer prices coincide with the price of the downstream sector D , because this is the only consumption good. Consider first a negative productivity shock to D , $d \log A_D < 0$. The corresponding price responses are given by $\mathcal{V}_{UD} d \log A_D$ and $\mathcal{V}_{DD} d \log A_D$, where \mathcal{V}_{UD} and \mathcal{V}_{DD} can

be derived from Proposition 2:

$$\mathcal{V}_{UD} d \log A_D = \underbrace{\delta_U}_{\text{pass-through}} \underbrace{\frac{1 - \delta_D}{1 - \bar{\delta}_w}}_{\text{multiplier}} d \log A_D < 0 \quad (24)$$

$$\mathcal{V}_{DD} d \log A_D = \left[\underbrace{\bar{\delta}_w}_{\text{pass-through}} \underbrace{\frac{1 - \delta_D}{1 - \bar{\delta}_w}}_{\text{multiplier}} - \underbrace{\delta_D}_{\text{productivity}} \right] d \log A_D > 0 \quad (25)$$

where

$$\bar{\delta}_w = \delta_D \left(\underbrace{\alpha_D}_{\text{direct pass-through}} + \underbrace{(1 - \alpha_D) \delta_U}_{\text{through } U} \right)$$

From Equation (24) we see that inflation is negative in the upstream sector under zero output gap. This is because real wages fall to compensate the change in D 's productivity, thereby reducing U 's marginal cost. The downstream sector D instead experiences positive inflation (see Equation (25)), so that consumer inflation is also positive. In D the productivity shock has both a direct effect (lower productivity increases marginal costs), and an indirect effect through lower wages and input prices. As long as there is some price stickiness in U , input prices do not fully reflect the change in wages. The overall wage pass-through into D 's marginal cost is given by

$$\alpha_D + (1 - \alpha_D) \delta_U$$

which is less than 1 whenever $\delta_U < 1$. In this case the direct effect dominates.

In this example the “divine coincidence” fails because of input-output linkages. This is not merely a result of the asymmetric nature of the shock (it hits only one sector), as it is immediate to show that inflation is not stabilized after an aggregate Hicks-neutral shock either. The issue is that consumer inflation focuses only on the last stage of the chain. Indeed, given that inflation has opposite sign in the two sectors it is possible to construct a weighted average which is stabilized. Proposition 3 below shows that this is a general result, and the correct sectoral weights do not depend on the underlying productivity shock.

Example 2. Horizontal economy

Consider the horizontal economy in Figure (2): there are N sectors, $\{1, \dots, N\}$, with consumption shares β_1, \dots, β_N and adjustment probabilities $\delta_1, \dots, \delta_N$. There are no input-output linkages, but sectors face idiosyncratic shocks and heterogeneous pricing frictions.

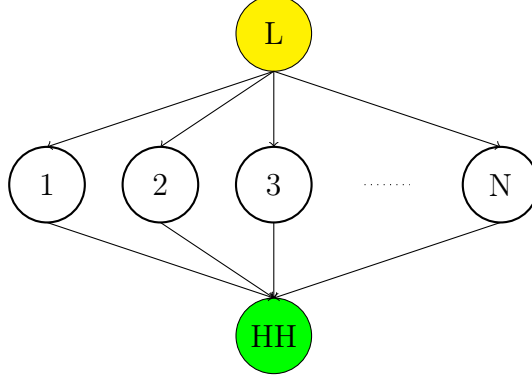


Figure 2: Horizontal economy

Under zero output gap wages adjust to reflect the “average” change in productivity $\mathbb{E}_\beta(d \log A)$. Sectors are equally exposed to wage changes, but they face different productivity shocks. Therefore marginal costs and prices cannot be stabilized everywhere. From Proposition 2, inflation in each sector i satisfies

$$\pi_i = \delta_i \left(\underbrace{\frac{1 - \bar{\delta}_A}{1 - \bar{\delta}_w}}_{\text{wage}} \underbrace{\mathbb{E}_\beta(d \log A)}_{\text{real wage}} - \underbrace{d \log A_i}_{\text{productivity}} \right) \quad (26)$$

where

$$\begin{aligned} \bar{\delta}_w &= \mathbb{E}_\beta(\delta) \\ \bar{\delta}_A &= \frac{\mathbb{E}_\beta(\delta d \log A)}{\mathbb{E}_\beta(d \log A)} \end{aligned}$$

We see from (26) that inflation increases in sectors which received a worse shock than the average ($d \log A_i < \frac{1 - \bar{\delta}_A}{1 - \bar{\delta}_w} \mathbb{E}_\beta(d \log A)$), and vice versa. Consumer inflation is not stabilized either, because it overrepresents flexible sectors. It is negative if these

sectors received a better shock, and vice versa:

$$\pi^C = -\frac{\text{Cov}_\beta(\delta, d \log A)}{1 - \mathbb{E}_\beta(\delta)} \quad (27)$$

As in the vertical chain, it would be possible to weight sectoral inflation rates in such a way that the average is stabilized. In the horizontal economy this can be achieved by discounting flexible sectors. Proposition 3 shows that this is a general results, and the correct sectoral weights do not depend on the underlying productivity shock.

Example 3. Oil shocks and consumer inflation

This example presents a stylized “oil economy”, showing that negative oil shocks lead to positive consumer inflation under zero output gap. Section 6 evaluates the quantitative importance of the channels highlighted here for the US economy. It finds that a 10% negative shock raises consumer prices by 0.22% under zero output gap.

Consider the production network in Figure 3. We can interpret our economy as a vertical chain where the upstream sector is labor, with sticky wages.¹¹ Then comes oil, and finally the last stage is broken down into multiple sectors, like a horizontal economy. Final sectors have heterogeneous consumption shares (β_i), oil input shares ($\omega_{i,oil}$) and adjustment frequencies (δ_i).

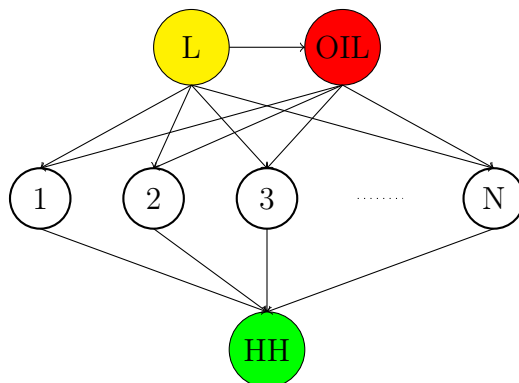


Figure 3: Oil economy

Two channels determine the response of consumer inflation to oil shocks. First, since oil prices are very flexible, oil shocks are (almost) fully passed-through to the final goods sector. These shocks therefore act like downstream shocks, in spite of

¹¹See Remark 3 in Section 3.2.1 for a discussion of how I model wage rigidities.

the role of oil as an intermediate input. We know from Example 1 that consumer prices increase in response to negative downstream shocks. Second, oil input shares and adjustment frequencies are positively correlated in the data. Consistent with the intuition from the horizontal economy in Example 2, this further increases the pressure on consumer prices.

Formally, if $\delta_{oil} = 1$ and wages adjust with probability δ_L , under zero output gap consumer inflation is given by

$$\pi^C = - \frac{\overbrace{Cov_\beta(\delta, \omega_{oil})}^{\text{horizontal}} + \overbrace{(1 - \delta_L) \mathbb{E}_\beta(\delta) \mathbb{E}_\beta(\omega_{oil})}^{\text{vertical}}}{1 - \delta_L \mathbb{E}_\beta(\delta)} d \log A_{oil} \quad (28)$$

For $d \log A_{oil} < 0$, consumer inflation π_C increases with wage stickiness $1 - \delta_L$ and with the covariance between oil shares and adjustment frequencies.

Table 2 in Section 6.4.1 reports the calibrated response of inflation to an oil shock in the US network, under different assumptions about δ_L and $Cov_\beta(\delta, \omega_{oil})$. The comparative statics are consistent with our discussion, even if the full network is much more complex than the stylized economy in this example.

4.3 The “divine coincidence” inflation index

Section 4.1.3 shows that productivity fluctuations generate endogenous “cost-push” shocks in the consumer-price Phillips curve, and its slope changes with the input-output structure. Proposition 3 constructs an inflation index which eliminates both of these issues.

Proposition 3. *Assume that no sector has fully rigid prices ($\delta_i \neq 0 \forall i$). Then the inflation statistic*

$$DC \equiv \lambda^T (I - \Delta) \Delta^{-1} \pi$$

satisfies

$$DC = (\gamma + \varphi) \tilde{y} \quad (29)$$

Unless prices are fully flexible in all sectors ($\Delta = I$), DC is the only aggregate inflation statistic that yields a Phillips curve with no endogenous cost-push term.

Proof. The pricing equation (2) allows to infer markup changes from inflation rates

and price adjustment probabilities:

$$-d \log \mu = (I - \Delta) \Delta^{-1} \pi \quad (30)$$

Lemma 1 then relates the output gap with sector-level markups.

Lemma 1. *The output gap is proportional to a notion of “aggregate” markup, which weights sector level markups according to sales shares:*

$$(\gamma + \varphi) \tilde{y} = -\lambda^T d \log \mu \quad (31)$$

Proof. See online Appendix A2. □

Together, Equations (31) and (30) yield the sales-weighted Phillips curve:

$$\lambda^T (I - \Delta) \Delta^{-1} \pi = -\lambda^T d \log \mu = (\gamma + \varphi) \tilde{y}$$

Lemma 2 implies that $DC = \lambda^T (I - \Delta) \Delta^{-1} \pi$ is the only aggregate inflation statistic which yields a Phillips curve with no endogenous cost-push term.

Lemma 2. *If $\Delta \neq I$ then $\lambda^T (I - \Delta) \Delta^{-1}$ is the only vector ν that satisfies*

$$\nu^T \mathcal{V} = 0$$

Proof. See the complements to Appendix A2 in the Supplemental Material. □

□

Remark 4. The weights in DC are all positive. Therefore we can have $\lambda^T (I - \Delta) \Delta^{-1} \pi = 0$ only if π_i is positive in some sectors and negative in others. This implies that under zero output gap there are always sectors where inflation is positive and sectors where it is negative.¹²

Lemma 1 shows that the output gap is inversely proportional to a sales-weighted sum of sectoral markups.¹³ Intuitively, aggregate demand is lower when markups are high, resulting in a negative output gap. Remark 2 allows to infer changes in

¹²We know from Lemma 4 that in general π_i cannot be zero in every sector.

¹³This argument is closely related to Proposition 3 in Baqaee and Farhi (2017).

sector-level markups from inflation rates, by appropriately discounting them for the relevant adjustment probabilities.

Remark 4 extends the intuition from Examples 1 and 2 to the general case. Even though consumer prices are not stabilized under zero output gap, prices move in different directions across sectors, therefore we can expect an appropriate “average” to be stabilized. The weighting in consumer prices is not the correct one because it does not capture the contribution of upstream sectors to value added, and it fails to account for the fact that flexible sectors respond more to a given cost shock.

While the relation between the output gap and markups derived in Lemma 1 does not rely on the specific pricing assumptions (ex. Calvo), the mapping between markups and inflation rates in equation (30) does depend on the Calvo assumption and on the CES demand structure within sectors.¹⁴ Nonetheless, the Calvo-CES benchmark highlights important forces that are at play also in richer setups. The empirical results in Section 7 show that the “divine coincidence” index based on this model provides a good fit in Phillips curve regressions, much better than consumer price inflation.

5 Welfare function and optimal policy

The presence of pricing frictions determines three types of distortions. First, the output gap captures deviations from the efficient level of aggregate output. Second, adjusting and non-adjusting firms within each sector charge different prices, even though they face the same marginal cost. Customers inefficiently substitute towards the cheaper varieties, resulting in distortions in their relative output. Third, sectoral prices do not fully adjust to reflect their relative productivities, so that relative output across sectors is also distorted.¹⁵ These three channels are captured by the welfare function derived in Proposition 4.

¹⁴Crucially, in the Calvo-CES framework the wedge between changes in prices and markups is exogenous and constant (it is given by $(I - \Delta) \Delta^{-1}$). This is no longer true under different pricing models, either because the share of adjusting firms is endogenous (as for example in menu cost models), or because the desired pass-through from marginal costs into prices is endogenous (this happens with fixed menu costs, variable adjustment costs or non-CES demand). In general there is no closed form solution for this endogenous wedge.

¹⁵The second and third channel are conceptually the same. If we considered a fully disaggregated model, where sectors are identified with individual firms, they could be unified into the cross-sector component. For expositional purposes however it is useful to keep them distinct, to facilitate the comparison with the one-sector benchmark.

In the one sector benchmark there are no cross-sector distortions. The “divine coincidence” implies that stabilizing aggregate output also eliminates within-sector distortions, thereby replicating the efficient allocation. This result no longer holds in the multi-sector model. Even though the “divine coincidence” inflation index is stabilized together with aggregate output, inflation is not stabilized sector-by-sector, and relative prices within and across sectors are distorted.¹⁶ Monetary policy has one instrument (money supply or interest rates) to address all three types of distortions, therefore it cannot replicate the first-best. In this sense the “divine coincidence” fails from a normative point of view.

Specifically, targeting the “divine coincidence” index replicates the efficient aggregate output, but it ignores relative price distortions. Section 5.2 characterizes the optimal monetary policy response to this tradeoff. Section 5.3 shows that the optimal policy can still be implemented by stabilizing an appropriate inflation index, which trades off the “divine coincidence” index against an inflation statistic that captures the effect of monetary policy on relative price distortions.

The three examples from Section 4.2 are revisited in online Appendix C to illustrate the optimal monetary policy.

Remark 5. I derive optimal policy in terms of the aggregate output gap, even though the actual policy instrument is money supply. I can do this because there is a one-to-one mapping between the two, which can be derived from the consumer-price Phillips curve and the cash-in-advance constraint:

$$\begin{aligned} d \log M &= \pi_C + y = \pi_C + \tilde{y} + \underbrace{\frac{1 + \varphi}{\gamma + \varphi} \lambda^T d \log A}_{y_{nat}} = \\ &= (1 + \kappa^C) \tilde{y} + u^C + \frac{1 + \varphi}{\gamma + \varphi} \lambda^T d \log A \end{aligned}$$

5.1 Welfare function

Proposition 4 derives a second-order approximation of the welfare loss relative to the efficient equilibrium with flexible prices. The loss function is quadratic in the output gap (which captures distortions in aggregate output) and inflation (which is

¹⁶Corollary 4 shows that perfect stabilization can be achieved only after an aggregate labor augmenting shock.

associated with distortions in relative output within and across sectors).¹⁷

Proposition 4. *The second-order welfare loss with respect to the flex-price efficient outcome is*

$$\mathbb{W} = \frac{1}{2} \left[(\gamma + \varphi) \tilde{y}^2 + \pi^T \mathcal{D} \pi \right] \quad (32)$$

The matrix \mathcal{D} can be decomposed as $\mathcal{D} = \mathcal{D}_1 + \mathcal{D}_2$, where \mathcal{D}_1 captures the productivity loss from within-sector misallocation and \mathcal{D}_2 captures the productivity loss from cross-sector misallocation. \mathcal{D}_1 is diagonal with elements

$$d_{ii}^1 = \lambda_i \epsilon_i \frac{1 - \delta_i}{\delta_i} \quad (33)$$

\mathcal{D}_2 is positive semidefinite. It can be written as a function of the substitution operators in production and consumption defined below.¹⁸

Definition 2. The substitution operators Φ_t (for sector t) and Φ_C (for final consumption) are symmetric operators from $\mathbb{R}^N \times \mathbb{R}^N$ to \mathbb{R} , defined as

$$\begin{aligned} \Phi_t(X, Y) = & \frac{1}{2} \sum_k \sum_h \omega_{tk} \omega_{th} \theta_{kh}^t (X_k - X_h) (Y_k - Y_h) + \\ & + \alpha_t \sum_k \omega_{tk} \theta_{kL}^t X_k Y_k \end{aligned}$$

and

$$\Phi_C(X, Y) = \frac{1}{2} \sum_k \sum_h \beta_k \beta_h \sigma_{kh}^C (X_k - X_h) (Y_k - Y_h)$$

The elements of \mathcal{D}_2 are given by

$$d_{ij}^2 = \frac{1 - \delta_i}{\delta_i} \frac{1 - \delta_j}{\delta_j} \left(\Phi_C \left((I - \Omega)_{(i)}^{-1}, (I - \Omega)_{(j)}^{-1} \right) + \sum_t \lambda_t \Phi_t \left((I - \Omega)_{(i)}^{-1}, (I - \Omega)_{(j)}^{-1} \right) \right) \quad (34)$$

¹⁷Interestingly, the loss function does not depend on sectoral productivity shocks directly. Intuitively, misallocation is determined by markup distortions. I derive the welfare function around an efficient steady-state, therefore there is no interaction between the productivity shock and initial misallocation (the envelope theorem holds). The welfare loss is entirely driven by the change in markups induced by the shock, which we can infer from sectoral inflation rates (see equation (30)).

¹⁸ Φ_C and Φ_t are the same as in Baqaee and Farhi (2018). They apply these operators to sector-level price changes and labor shares around a distorted steady-state, to derive the first-order change in allocative efficiency. I work around an efficient steady-state where markup shocks have no first-order effect on allocative efficiency, while the substitution operators applied to sector level price changes characterize the second-order loss.

Proof. See online Appendix B1 □

In the baseline one-sector model the welfare loss is given by

$$\mathbb{W} = \frac{1}{2} \left[(\gamma + \varphi) \tilde{y}^2 + \frac{1-\delta}{\delta} \epsilon \pi^2 \right] \quad (35)$$

Here inflation only captures within-sector distortions. For a given price distortion, quantities respond more if the elasticity of substitution ϵ is higher. Therefore the welfare cost in Equation (35) is increasing in ϵ . In the network model instead the welfare loss associated with inflation comes from both cross-sector and within-sector price distortions, and the latter need to be appropriately aggregated.

From equation (33) we see that the price dispersion loss within each sector is $\epsilon_i \pi_i^2$, the same as in the one-sector model. Sector-level losses are then aggregated by sales shares, discounting flexible sectors. The intuition is the same as for the “divine coincidence” index in Proposition 3. Overall, the within-sector component of the total welfare loss is given by

$$\pi^T \mathcal{D}_1 \pi = \sum_i \lambda_i \frac{1 - \delta_i}{\delta_i} \epsilon_i \pi_i^2$$

The welfare loss from cross-sector misallocation in Equation (34) can be expressed as a weighted sum of sector-level productivity losses:

$$\pi^T \mathcal{D}_2 \pi = \sum_t \underbrace{\lambda_t}_{\text{aggregation}} \underbrace{\sum_{i,j} \Phi_t(i,j)}_{\text{productivity loss in sector } t} \quad (36)$$

Here we treated final consumption as an additional sector with $\lambda_C = 1$, and with some abuse of notation we defined

$$\Phi_t(i,j) \equiv \Phi_t \left((I - \Omega)_{(i)}^{-1} \frac{1 - \delta_i}{\delta_i} \pi_i, (I - \Omega)_{(j)}^{-1} \frac{1 - \delta_j}{\delta_j} \pi_j \right)$$

Intuitively, relative price distortions induce producers in each sector t to substitute towards the inputs whose relative price is lower than in the efficient equilibrium. The welfare consequence of this misallocation is equivalent to a negative TFP shock for sector t . The total loss is obtained by aggregating sector-level contributions according to sales shares, as in Hulten’s formula.

To derive the productivity loss for each sector t we proceed in two steps. First, we isolate the distortionary component of sectoral inflation rates and track its propagation across the network, which results in relative price distortions across t 's inputs. Second, we translate price distortions into t 's productivity loss, resulting from inefficient substitution. This is captured by the substitution operators.

Let's start with the first step. Intuitively, inflation is associated with a distortion because it mirrors an inefficient change in the markup of non-adjusting firms. We want to map inflation rates into markup distortions, and study their effect on the relative price of t 's inputs given how they propagate through the network. I define relative prices with respect to nominal wages. Lemma 3 provides the mapping between inflation rates and relative price distortions.

Lemma 3. *The distortion in sectoral relative prices with respect to the flex-price outcome is given by*

$$d \log p - d \log w = (I - \Omega)^{-1} (I - \Delta) \Delta^{-1} \pi \quad (37)$$

Proof. See online Appendix B1 □

From Equation (37) we see that relative price distortions can be decomposed into a direct and a propagation effect:

$$d \log p - d \log w = \underbrace{(I - \Omega)^{-1}}_{\text{propagation}} \underbrace{(I - \Delta) \Delta^{-1} \pi}_{\text{direct (markup)}}$$

Here is the intuition. A distortion in the relative price of a sector k can come either directly from a change in k 's markup, or indirectly from a change in the markup of some of its inputs. The direct ("impulse") effect is simply given by the change in markups. From Remark 2, we can back-out markup shocks from inflation rates:

$$-d \log \mu = (I - \Delta) \Delta^{-1} \pi$$

The indirect ("propagation") effect is captured by the Leontief inverse $(I - \Omega)^{-1}$: the price distortion induced in sector k by a change in i 's markup is given by $(I - \Omega)^{-1}_{ik} d \log \mu_i$.

Using Lemma 3 we can also derive the relative price distortion between each sector

pair (k, h) triggered by inflation in sector i . This is given by

$$d \log p_k - d \log p_h = \left((I - \Omega)_{ki}^{-1} - (I - \Omega)_{hi}^{-1} \right) \frac{1 - \delta_i}{\delta_i} \pi_i$$

This allows us to characterize the relative price distortions across t 's inputs associated with given sectoral inflation rates. The negative effect on t 's productivity is captured by the corresponding substitution operator Φ_t (see Definition 2). This productivity loss depends on the interaction between inflation in different sectors. More precisely, $\Phi_t(i, j)$ measures the productivity loss of sector t induced by a 1% increase in i 's inflation, given that j 's also increased by 1%. Intuitively, the distortions associated with π_i and π_j reinforce each other if they produce similar relative price changes across input pairs (k, h) , especially those with higher input shares or higher elasticity of substitution. Correspondingly, $\Phi_t(i, j)$ weights each pair (k, h) by the relevant input shares ω_{ti} and ω_{th} , and the substitution elasticity θ_{kh}^t :

$$\Phi_t(i, j) = \underbrace{\omega_{tk}\omega_{th}}_{\text{input shares}} \underbrace{\theta_{kh}^t}_{\text{substitution}} \underbrace{\left((I - \Omega)_{ki}^{-1} - (I - \Omega)_{hi}^{-1} \right) \frac{1 - \delta_i}{\delta_i} \pi_i}_{\text{distortion from } i} \underbrace{\left((I - \Omega)_{kj}^{-1} - (I - \Omega)_{hj}^{-1} \right) \frac{1 - \delta_j}{\delta_j} \pi_j}_{\text{distortion from } j}$$

When elasticities of substitution are uniform ($\theta_{kh}^t \equiv \theta^t$), the substitution operator is simply given by the covariance between the price distortions induced by i and j across sector pairs (k, h) , with probability weights given by t 's input shares $\{\omega_{tk}\}_{k=1..N}$:

$$\Phi_t(i, j) = \theta^t \text{Cov}_{\Omega_t} \left(\underbrace{(I - \Omega)_{(i)}^{-1} \frac{1 - \delta_i}{\delta_i} \pi_i}_{\text{distortion from } i}, \underbrace{(I - \Omega)_{(j)}^{-1} \frac{1 - \delta_j}{\delta_j} \pi_j}_{\text{distortion from } j} \right)$$

The total productivity loss in sector t is obtained by summing the contributions of all pairs (i, j) :

$$\text{Loss in } t = \sum_{i, j} \Phi_t(i, j)$$

and the aggregate productivity loss is given by Hulten's formula, as in Equation (36).

5.2 Optimal policy

Optimal monetary policy minimizes the welfare loss derived in Proposition 4, subject to the response of inflation to the output gap and productivity shocks.

In the one-sector model the central bank solves

$$\begin{aligned} \min_{\pi, \tilde{y}} \quad & \mathbb{W} = \frac{1}{2} \left[(\gamma + \varphi) \tilde{y}^2 + \epsilon \frac{1-\delta}{\delta} \pi^2 \right] \\ \text{s.t.} \quad & \pi = \kappa \tilde{y} \end{aligned} \quad (38)$$

Here the constraint is given by the aggregate Phillips curve. The “divine coincidence” implies that there is no tradeoff between stabilizing output and stabilizing prices, therefore the optimal policy achieves the first best by setting $\pi = \tilde{y} = 0$.

With multiple sectors the optimal policy problem extends this baseline in two dimensions. First, the inflation term is replaced by the more complex misallocation loss derived in Proposition 4, which captures both within- and cross-sector distortions. Second, the constraint is not just the aggregate Phillips curve, but it is given by the full vector of sectoral Phillips curves. Thus the problem becomes:

$$\begin{aligned} \min_{\tilde{y}, \pi} \quad & \frac{1}{2} \left[(\gamma + \varphi) \tilde{y}^2 + \pi^T \mathcal{D} \pi \right] \\ \text{s.t.} \quad & \pi = \mathcal{B} \tilde{y} + \mathcal{V} d \log A \end{aligned} \quad (39)$$

Proposition 5 characterizes the solution to the policy problem.

Proposition 5. *The value of the output gap that minimizes the welfare loss is*

$$\tilde{y}^* = - \frac{\mathcal{B}^T \mathcal{D} \mathcal{V} d \log A}{\gamma + \varphi + \mathcal{B}^T \mathcal{D} \mathcal{B}} \quad (40)$$

Proof. The result follows immediately from the first order conditions of the minimization problem (39). \square

The optimal policy trades off the marginal cost and benefit of deviating from the efficient aggregate output. The denominator in equation (40) reflects the marginal cost, and it is always positive. It comes from distortions in aggregate demand (whose welfare effect is proportional to the labor supply elasticities $(\gamma + \varphi)$), and from the relative price distortions caused by the output gap (captured by the term $\mathcal{B}^T \mathcal{D} \mathcal{B}$).

The numerator in (40) is the marginal gain. For given current inflation π , the marginal benefit of inducing inflation $\tilde{\pi}$ is $-\tilde{\pi}^T \mathcal{D} \pi$. For $\tilde{y} = 0$ and a given productivity

shock $d \log A$, inflation is given by

$$\pi = \mathcal{V} d \log A$$

Increasing the output gap raises inflation by $\tilde{\pi} = \mathcal{B}$. Therefore the overall marginal gain is given by

$$-\tilde{\pi}^T \mathcal{D} \pi = -\mathcal{B}^T \mathcal{D} \mathcal{V} d \log A$$

The constraint tells us that monetary policy has limited effect on misallocation, because it can only implement relative price changes which are proportional to the vector \mathcal{B} of sectoral elasticities with respect to the output gap.

5.3 Inflation targeting

In the one sector model the optimal output gap is always zero, regardless of productivity. Moreover, thanks to the “divine coincidence” it is equivalent to target inflation or the output gap. This is a useful result from an implementation point of view, because the output gap and productivity are difficult to measure in real time.

Proposition 6 demonstrates that the multi-sector framework preserves the convenient implementation properties of the one sector model, and the optimal policy can still be implemented by stabilizing an appropriate inflation index.

Proposition 6. *Assume that no sector has fully rigid prices. Then there exists a unique vector of weights ϕ (up to a multiplicative constant) such that the aggregate inflation*

$$\pi_\phi = \phi^T \pi$$

is positive if and only if $\tilde{y} > \tilde{y}^$.*

This vector is given by

$$\phi^T = \lambda^T (I - \Delta) \Delta^{-1} + \mathcal{B}^T \mathcal{D} \quad (41)$$

Proof. See Appendix B2 in the Supplemental Material. □

To build intuition, note that the first order condition from the policy problem (39)

can be written as

$$(\gamma + \varphi) \tilde{y} + \mathcal{B}^T \mathcal{D} \pi = 0 \quad (42)$$

The policy target (41) can be immediately derived from Equation (42), just replacing the output gap with the divine coincidence inflation index (see Proposition 3).

Consistent with our discussion in Section 5.2, the optimal target weights the output gap against sectoral inflation rates according to the relative marginal benefit ($-\mathcal{B}^T \mathcal{D} \pi$) and marginal cost ($\gamma + \varphi$) of distorting aggregate output to reduce misallocation. This result extends with minimal modifications to the dynamic setup (see online Appendix D). Here the optimal policy can be implemented via a Taylor rule which targets the inflation statistic in Proposition (6), with an additional correction for inflation expectations.

6 Quantitative analysis

6.1 Data

Our economy is fully characterized by the variables and parameters introduced in Section 3.2. The parameters consist in labor, input and consumption shares (α , Ω and β), sectoral frequencies of price adjustment (Δ), and elasticities of substitution in production and consumption. To compute the expected welfare loss from business cycles (see Section 6.2) it is necessary to also calibrate the variance of sectoral productivity shocks.

I calibrate labor, input and consumption shares based on the input-output tables published by the BEA.¹⁹ I use tables for the year 2012, because this is the most recent year for which they are available at a disaggregated level (405 industries). Section 6.3.3 relies on less disaggregated historical input-output data (46 - 71 industries), always from the BEA input-output accounts, to study the slope of the Phillips curve and monetary non-neutrality over time.

¹⁹The BEA does not provide a direct counterpart to the input-output matrix Ω , however this can be constructed from the available data. The BEA publishes two direct requirement tables, the Make and Use table, which contain respectively the value of each commodity produced by each industry and the value of each commodity and labor used by each industry and by final consumers. In addition the BEA publishes an Import table that reports the value of commodity imports by industry. The Make and Use matrix (corrected for imports) can be combined, under proportionality assumptions, to compute the matrix Ω of direct input requirements and the labor and consumption shares α and β .

I calibrate industry-level frequencies of price adjustment based on estimates constructed by Pasten, Schoenle and Weber (2017). For sectors with missing data I set the adjustment probability equal to the mean. I set the quarterly probability of wage adjustment to 0.25, in line with Barattieri, Basu and Gottschalk (2014) and Beraja, Hurst and Ospina (2016).

I choose values for the elasticities of substitution across inputs and consumption goods based on estimates from the literature. I set the substitution elasticity between consumption goods to $\sigma = 0.9$,²⁰ the elasticity of substitution between labor and intermediate inputs to $\theta_L = 0.5$,²¹ the elasticity of substitution across intermediate inputs to $\theta = 0.001$,²² and the elasticity of substitution between varieties within each sector to $\epsilon = 8$.²³

I calibrate sectoral TFP shocks and their covariance matrix based on estimates of annual industry-level TFP changes for the period 1988-2016 from the BEA Integrated Industry-Level Production Account data.²⁴ I refer to the Multifactor Productivity (MFP) measure, and calibrate productivity shocks as the growth rate of this index at the sector level.²⁵

6.2 Welfare loss from business cycles

In the one-sector model productivity fluctuations do not generate a welfare loss with respect to an efficient economy with flexible prices. In turn, the well-known Lucas' estimate suggests that in frictionless economies business cycle fluctuations have a very small welfare cost, of about 0.05% of per-period GDP.²⁶

Section 5 argues that in a multi-sector economy monetary policy cannot replicate the flex-price efficient outcome. This makes the welfare loss from productivity fluctuations potentially large. In this section I calibrate the loss relative to the efficient economy under different policy rules. I assume that productivity shocks are nor-

²⁰Atalay (2017), Herrendorf et al. (2013), and Oberfield and Raval (2014)) estimate it to be slightly less than one.

²¹This is consistent with Atalay (2017), who estimates this parameter to be between 0.4 and 0.8.

²²See Atalay (2017).

²³This is consistent with estimates of the variety-level elasticity of substitution from the industrial organization and international trade literatures.

²⁴<https://www.bea.gov/data/special-topics/integrated-industry-level-production-account-klems>

²⁵The MFP is constructed taking into account labor, capital and intermediate inputs from manufacturing and services. Therefore this index captures changes in gross output TFP, which is the correct empirical counterpart of the sector-level TFP shocks in the model.

²⁶This welfare cost comes entirely from the uncertainty generated by fluctuations in consumption.

mally distributed with zero mean and covariance matrix Σ , which I calibrate from BEA-KLEMS data.

The results for the main calibration are plotted in Figure 4. Figure 5 reports results for an alternative calibration without input-output linkages. The bars correspond to the percentage of per-period GDP that consumers would be willing to forego in exchange of switching from a sticky-price economy to the efficient equilibrium, for a given monetary policy rule. Bars of different colors represent different rules. Each set of bars corresponds to a different assumption about the correlation of sectoral shocks, keeping the variance of aggregate productivity constant across calibrations. In the first set the covariance matrix is calibrated from the data, while in the second set there are only idiosyncratic shocks, and in the third there are only aggregate shocks.

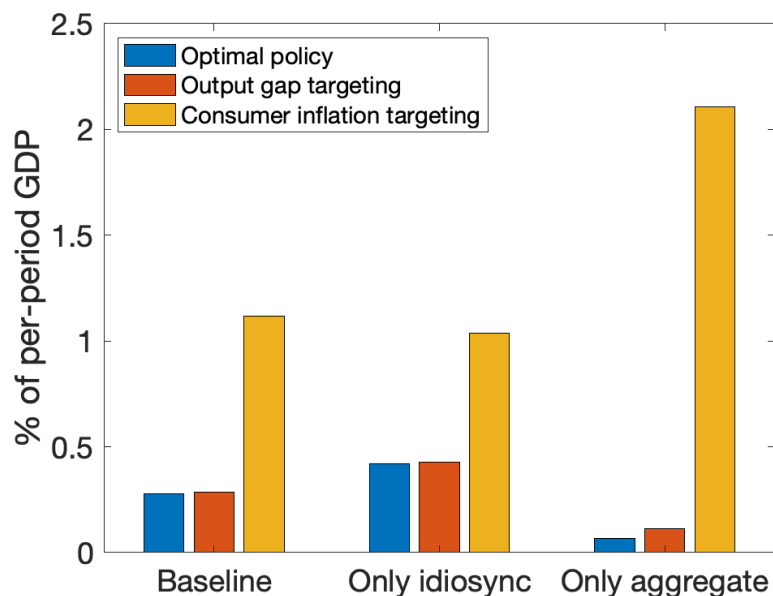


Figure 4: Actual input-output network; different calibrations keep the variance of aggregate output constant

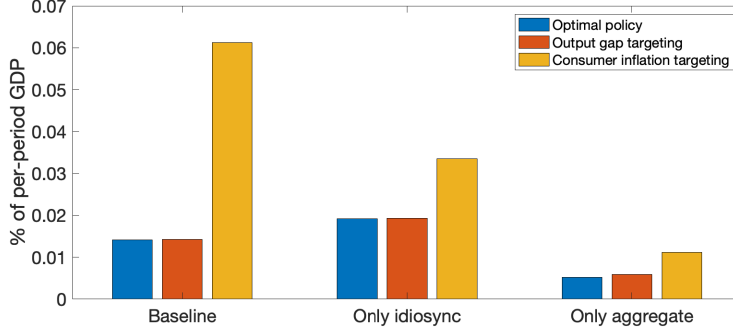


Figure 5: Model with no input-output linkages; different calibrations keep the variance of aggregate output constant

Quantitatively, the departures from the one sector benchmark are significant. There is a large loss from imperfect stabilization, equal to 0.28% of per-period GDP under the optimal policy. This means that the additional loss induced by price rigidities is one order of magnitude larger than the Lucas' estimate. From the second set of bars in Figure 5 we see that the idiosyncratic component of productivity is the main driver. Input-output linkages are key in determining these results. Figure 5 shows that the welfare loss is much smaller in an economy with the same wage rigidity, productivity shocks and price adjustment frequencies, but without input-output linkages.²⁷

The loss increases under suboptimal policy rules. Targeting consumer prices, which is first best in the one sector model, brings it to 1.12% of per-period GDP. Again, Figure 5 shows that the loss is much smaller in a calibration without input-output linkages, regardless of the distribution of the shocks.

The red bars in Figures 4 and 5 instead show that on average targeting zero output gap yields a small additional loss with respect to the optimal policy. Although monetary policy faces a tradeoff between stabilizing aggregate demand (the output gap) and relative demand across sectors, the fact that it has only one instrument makes it inefficient at correcting relative price distortions. Therefore in practice the optimal policy should focus on aggregate demand.

We reach a similar conclusion when comparing the behavior over time of the “divine coincidence” index DC -our inflation proxy for the output gap- and the optimal policy target, plotted in Figure 6. The two series move closely together, which means that

²⁷Here consumption shares are calibrated to replicate relative sales shares.

the optimal target almost coincides with the output gap. The target however is often a few basis points lower than DC , suggesting that the optimal policy should be slightly more expansionary than output gap targeting.

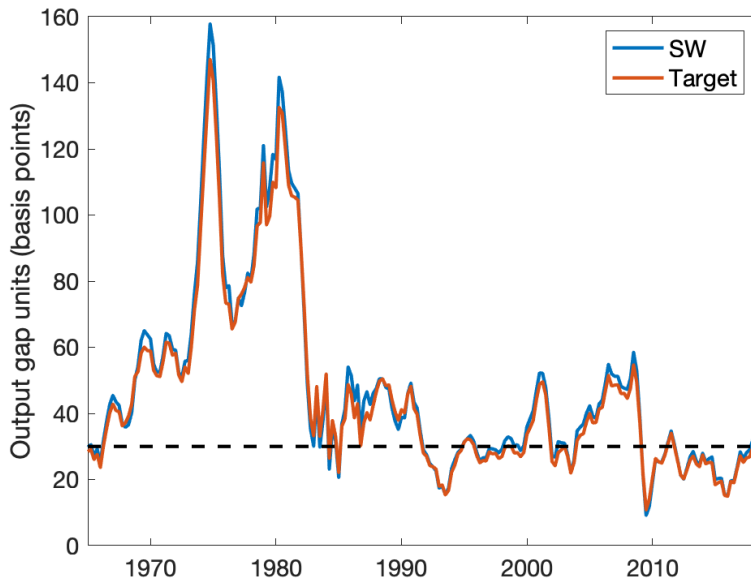


Figure 6: Time series of the DC inflation index and the optimal policy target

Appendix E1 in the Supplemental Material provides analytical expressions for the welfare loss under different policy rules, and a decomposition of the welfare loss between within- and cross-sector misallocation.

6.3 Slope of the Phillips curve and monetary non-neutrality

Corollary 2 in Section 4 establishes that the presence of intermediate inputs reduces the slope of the Phillips curve. To evaluate the quantitative importance of this result I carry out two exercises. Section 6.3.1 computes the slope of the Phillips curve based on the input-output tables for 2012, under different assumptions about input-output linkages, wage rigidities and pricing frictions. Section 6.3.3 instead studies how the slope implied by the model for the US economy has changed over time, based on the observed evolution of the input-output structure from 1947 to 2017.

The slope of the Phillips curve is also related with monetary non-neutrality,²⁸

²⁸See section 6.3.2 below for a discussion.

which is a measure of the effectiveness of monetary policy. Section 6.3.2 shows that both input-output linkages and heterogeneous pricing frictions increase monetary non-neutrality.

6.3.1 Slope of the Phillips curve

Table 1 shows that input-output linkages and wage rigidity flatten the Phillips curve, while heterogeneous adjustment frequencies play no role. In the baseline calibration (first column) the slope is 0.09, which is in the same ballpark as empirical estimates (see Section 7). The second column reports the slope implied by an alternative calibration which directly maps the one-sector model to the data, ignoring input-output linkages and wage rigidities. Here the slope is more than one order of magnitude larger than in the baseline. The third column reports the slope in a calibration with sticky wages, but without input-output linkages. We find that the implied slope more than doubles with respect to the baseline calibration.

	full model	no IO, flex w	no IO	$\delta = \text{mean}$
slope	0.09	1.16	0.22	0.08
slope relative to full calibration	1.00	0.07	0.38	1.05

Table 1: Phillips curve slope in the main and alternative calibrations

Finally, the last column shows that eliminating heterogeneity in adjustment frequencies does not affect the calibrated slope. This is not a general result, but it depends on the specific joint distribution of labor shares and adjustment frequencies that we observe in the data. Heterogeneity in price stickiness instead matters in the dynamic version of the model, where it increases monetary non-neutrality (see Section 6.3.2).

6.3.2 Monetary non-neutrality

I use the dynamic version of the model (derived in online Appendix D) to study the effect of input-output linkages and heterogeneous pricing frictions on monetary non-neutrality. Monetary policy is less neutral (i.e. more effective) if it can achieve the same change in real output with a smaller inflation response. Figure 7 plots the

impulse response of consumer inflation to a 1% real rate shock, with persistence 0.5, under a Taylor rule with $\varphi_\pi = 1.24$ and $\varphi_y = .33/12$.

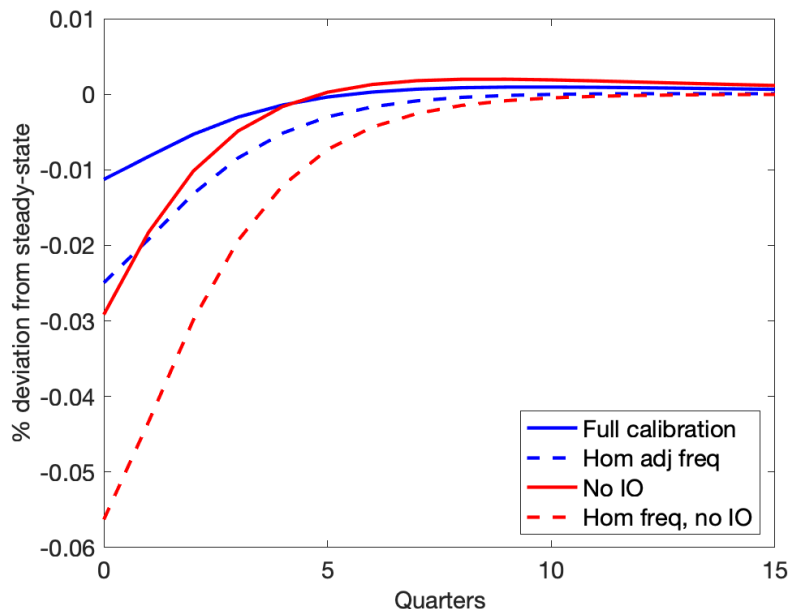


Figure 7: Impulse response to a 1% interest rate shock

While eliminating heterogeneity in adjustment frequencies does not affect the slope of the Phillips curve in the static setup, in the dynamic model both input-output linkages and heterogeneous adjustment frequencies increase monetary non-neutrality.²⁹ This happens because, in contrast with the one-sector model, the response of consumer inflation to real rate shocks is not fully characterized by the slope κ of the Phillips curve. First, the response of current inflation π_t^C to discounted future output gaps $\rho^s \tilde{y}_{t+s}$ is not proportional to κ as the time horizon s varies.³⁰ Second, inflation not only responds to the aggregate output gap, but also to anticipated changes in relative markups.

To gain intuition consider two economies, both with the same average probability of price adjustment across sectors. In the first economy all sectors have the same adjustment probability, while in the second some sectors are more flexible and some

²⁹My results are consistent previous work, such as Carvalho (2006) and Nakamura and Steinsson (2010).

³⁰Producers preemptively update their prices in response to anticipated shocks, and in doing so they take into account how these shocks propagate through the network. Since the propagation is different for different time horizons s , the impact price response is also different.

are stickier. As long as the discount factor is large enough, producers reset their prices to be an “average” of the optimal prices over the period before their next opportunity to adjust. If all sectors have the same adjustment probability, the producers who can adjust know that many others will also have changed their price by the time they get to adjust again. Therefore they preemptively adjust more. If instead some sectors adjust very infrequently, producers in the flexible sectors know that they will likely have another opportunity to reset their price before the stickier sectors also get to change theirs. Therefore it is optimal for them to wait. The expectations channel gets muted as the discount factor goes to zero. This is why heterogeneous adjustment frequencies play a different role in the dynamic versus the static setting.

6.3.3 Phillips curve and monetary non-neutrality over time

The analysis in this Section is based on historical input-output data, which the BEA provides for each year between 1947 and 2017. I study how the slope of the Phillips curve and the impulse responses implied by the calibrated model have evolved over this time period. Due to lack of data, I need to keep the frequencies of price adjustment constant.

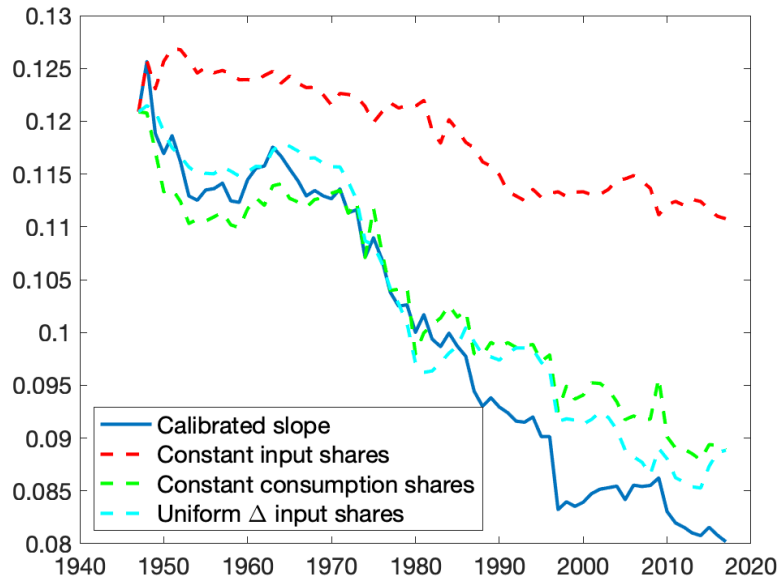


Figure 8: Slope of the Phillips curve over time

Figure 8 plots the slope of the Phillips curve computed for each year between 1947 and 2017. The blue solid line depicts the calibrated slope, which has decreased by about 30% over this time period. This result is consistent with the conventional wisdom that the Phillips curve has flattened (see for example Blanchard (2012)).³¹

The effect represented by the blue line in Figure 8 comes from two channels. The first is a change in the input-output structure, while the second is a shift in consumption shares, away from manufacturing and towards services. To isolate these two components we can use Corollary 1 in Section 6.3.1, which shows that the slope is determined by the pass-through of nominal wages into consumer prices, $\bar{\delta}_w$. This pass-through in turn can be decomposed into a term related with consumption shares, and a term related with the input-output structure:

$$\bar{\delta}_w = \underbrace{\beta^T}_{\text{consumption}} \underbrace{\Delta (I - \Omega \Delta)^{-1} \alpha}_{\text{input-output}}$$

The evolution of these two components is represented by the dashed red and green lines in Figure 8. The red line represents the slope implied by a calibration where the input-output matrix is fixed at its 1947 value, and consumption shares evolve as observed in the data. The green line plots the slope of the Phillips curve implied by an alternative calibration where consumption shares remain constant at their 1947 value, while the input-output matrix changes over time as observed in the data. The shift of consumption from manufacturing towards services contributed to the decline after 1980. Service sectors have more rigid prices, therefore a shift towards these sectors increases average price stickiness and flattens the Phillips curve. Pre-1980, however, all of the decline can be attributed to the evolution of the production structure.

This last effect is driven by a uniform increase in intermediate input purchases, and not by a raise in the input share of rigid sectors. The light blue line depicts the slope implied by a calibration where consumption shares remain constant, and input shares increase uniformly in all sectors. The change in input shares is calibrated to replicate the change in the aggregate value added to output ratio observed in the

³¹It is difficult to evaluate which fraction of the observed flattening is explained by changes in the input-output structure relative to other factors, given that we do not have consensus estimates of the slope of the Phillips curve at any point in time (see Mavroeidis, Plagborg-Møller and Stock (2013)). The calibration suggests that the input-output structure played an important role. Nonetheless, the fact that the calibrated slope at the beginning of the period is low compared to conventional estimates suggests that other channels, such as the anchoring of inflation expectations, might be relevant as well.

data. We see that the light blue line tracks the green one closely. A more detailed breakdown of the components highlighted in Figure 8 is provided in Appendix *E2* in the Supplemental Materials.

I find similar results in the dynamic setting. Figure 9 plots the calibrated impact response of inflation to a 1% shock to the real rate between 1947 and 2017. Consistent with the results in the static setting, the impact response has declined over time. Again, most of the effect can be attributed to changes in the production structure.

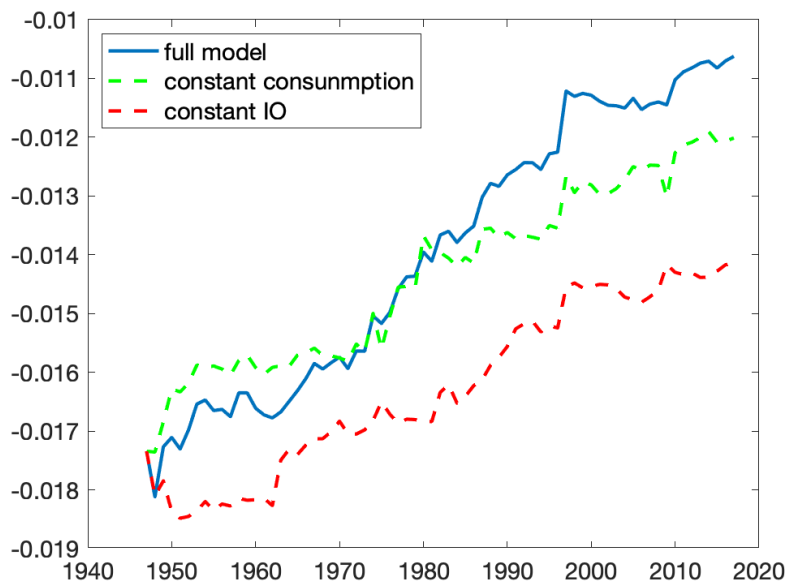


Figure 9: Impact response of consumer inflation to a 1% real rate shock

6.3.4 Wage Phillips curve vs consumer price Phillips curve

Empirical studies (see for example Hooper, Mishkin, Sufi (2019)) found that the wage Phillips curve is steeper than the price Phillips curve, and it has not flattened over time (or at least not as much as the price Phillips curve). This evidence is consistent with the predictions of the multi-sector model. The calibrated slope of the wage Phillips curve is 0.78 for 1947 and 0.77 for 2017, much larger than for the price Phillips curve and constant over time.

6.4 Endogenous cost-push shocks

As explained in Section 4, in the multi-sector model productivity shocks can generate an “endogenous” tradeoff between stabilizing prices and output. Section 6.4.1 below demonstrates that this phenomenon is quantitatively important in the case of oil shocks. It also shows that the optimal policy response to a negative oil shock is to implement a positive output gap, even if this raises inflation. Section 6.4.2 instead uses measured sectoral productivity shocks to construct a time series of the Phillips curve residual derived in Corollary 3, which captures the endogenous inflation-output tradeoff generated by these shocks. I find that adding this variable to otherwise standard Phillips curve regressions significantly increases the R-squared (see Section 7.2 below).

6.4.1 Oil shocks

Example 3 in Section 4.2 presents a stylized model to discuss the channels through which negative oil shocks raise consumer inflation. Even if the actual US network is much more complex, the example captures well the mechanisms at play. Our simple model highlights three elements: the presence of wage rigidities, the presence of a positive correlation between oil shares and adjustment frequencies, and the fact that oil prices are very flexible. Table 2 compares the inflation response to oil shocks in the full calibration versus alternative calibrations that shut down each of these channels, showing that all of them are important. Overall the inflation response is sizable in the baseline calibration, equal to 0.22 for a 10% negative oil shock.

	$\delta = \text{actual}$	$\delta \equiv \delta_{mean}, \delta_{oil} = 1$	$\delta \equiv \delta_{mean}$
sticky wages	0.22	0.07	-0.00
flexible wages	0.18	0.01	-0.06

Table 2: Consumer inflation after a 10% negative shock to the oil sector (full model)

To complement the discussion in Example ?? (see online Appendix C), Table 3 presents the optimal monetary policy response to a 10% negative oil shock. Here policy is expressed in terms of the optimal output gap (in percentage points). The implied percentage change in output is obtained by adding the log change in natural

output, $y_{nat} = -0.69$. The calibration suggests that the central bank should implement a positive output gap in response to negative oil shocks, even though this raises inflation.

	full model	$\delta = \delta_{mean}, \delta_{oil} = 1$	$\delta = \delta_{mean}$
sticky wages	0.11	0.16	0.18
flex wages	-0.03	0.06	0.09

Table 3: Optimal output gap (in percentage points) after a 10% negative oil shock

6.4.2 Time series

In this Section I construct a time series for the residual u^C in the consumer-price Phillips curve determined by productivity shocks, as derived in Corollary 3. I proxy for productivity shocks using sector-level measures of yearly TFP growth from the BEA KLEMS data. Figure 10 plots the results.

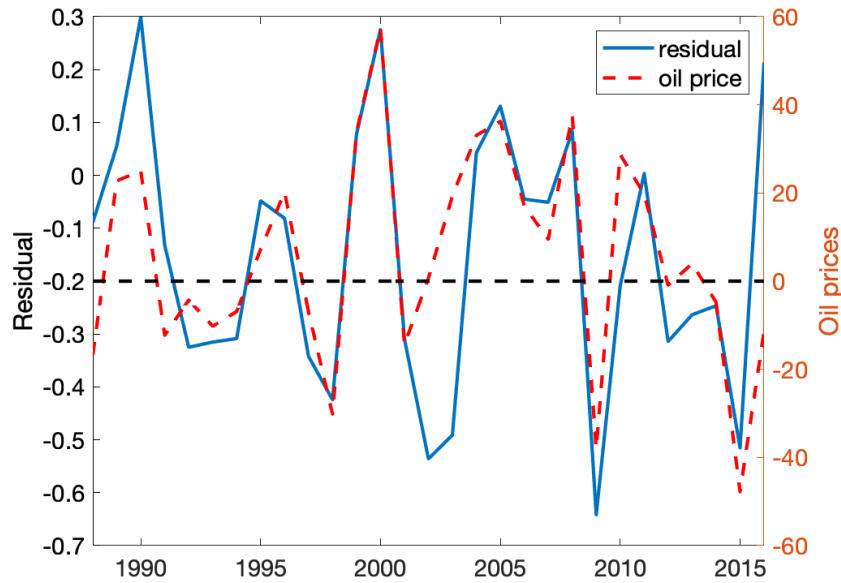


Figure 10: Time series of the endogenous residual

The estimated residual tracks oil prices quite closely, as shown in the figure. It has a mean of -0.16 and a standard deviation of 0.25 . Both mean and standard deviation

are large relative to the calibrated slope of the consumer-price Phillips curve, which is 0.09. This suggests that endogenous “cost-push” shocks coming from TFP fluctuations explain a significant fraction of the variation in consumer price inflation. I test this more directly in Section 7.2, by adding the endogenous residual u^C in Figure 10 to an otherwise standard Phillips curve regression. I find that the R-squared increases significantly, getting close to the “divine coincidence” specification.

7 Phillips curve regressions

In this section I run Phillips curve regressions using different inflation measures as left-hand-side variables (various measures of consumer price inflation and the “divine coincidence” inflation index). I compare the estimated coefficients and R-squareds.

The estimation results validate my theoretical framework. First, the R-squared is 2 to 4 times higher when using the “divine coincidence” index on the left-hand-side. This is consistent with Proposition 3: the explanatory power of the output gap should be maximal for the “divine coincidence” index, because the corresponding Phillips curve is the only one without an endogenous residual. Second, the calibrated model predicts the estimated slopes correctly for both consumer prices and the “divine coincidence” index. Third, controlling for the endogenous cost-push shocks constructed in Section 6.4.2 increases the R-squared of the consumer-price Phillips curve, bringing it in the same ballpark as the “divine coincidence” specification.

Rolling regressions confirm that these results are robust to the choice of a sample period: the estimated coefficient is stable and always significant when using the “divine coincidence” index as left-hand-side variable, in contrast with traditional consumer price specifications.

7.1 Data

I construct a time series of the “divine coincidence” index DC for the US economy based on sector-level PPI data from the BLS. I measure inflation as the percentage price change from the same quarter of the previous year. I aggregate sectoral inflation rates based on sales shares implied by the BEA input-output tables, and on sector-level price adjustment frequencies constructed by Pasten, Schoenle and Weber (2018).

A key difference between DC and PCE is that PCE places no weight on wage

inflation, which instead has a weight of 18% in *DC*. Other important sectors in *DC* are professional services, financial intermediation and durable goods, whereas the PCE places high weight on health care, real estate and nondurable goods. A more detailed comparison between the weighting of sectoral inflation rates in the PCE and in *DC* is reported in Appendix F1 in the Supplemental Materials, which also includes plots of *DC* against consumer price inflation (CPI and PCE) and aggregate producer price inflation (PPI), and scatterplots of the output gap against *DC* and consumer inflation.

In the main text I focus on a regression specification with no lags and a proxy for inflation expectations, which is consistent with the dynamic model. I also present results for a specification without inflation expectations. I construct the proxy for inflation expectations based on the statistical properties of the inflation process, whose changes are well approximated by an IMA(1,1) (see Stock and Watson (2007)). I estimate the IMA(1,1) parameters and use them to construct a forecast series for each of the inflation measures that I use in the regressions. For consumer inflation it has been shown that survey measures of forecasted inflation (such as the SPF) are well approximated by this IMA(1,1) forecast. The forecast series are plotted in Appendix F2 in the Supplemental Material. Results for other specifications, which include lagged inflation and other variables, are reported in Appendix F in the Supplemental Material.

7.2 Regressions over the full sample period

The results presented here use the CBO unemployment gap as a measure of the output gap on the right-hand-side. Appendix F3 shows that the results are robust when using two other measures of the output gap: the CBO output gap and the unemployment rate.

Table 4 reports results for a regression specification with just inflation and the output gap:

$$\pi_t = c + \kappa \tilde{y}_t + u_t \quad (43)$$

	SW	CPI	core CPI	PCE	core PCE
gap	-3.8814** (0.6329)	-0.2832** (0.0729)	-0.1839** (0.0642)	-0.1667** (0.0628)	-0.1007* (0.0565)
intercept	1.9842** (0.0475)	2.9052** (0.1196)	2.9021** (0.1052)	2.3978** (0.103)	2.372** (0.0926)
R-squared	0.2154	0.0991	0.0566	0.0489	0.0227

Table 4: Regression results for the CBO unemployment gap

Table 5 reports results for the preferred specification with inflation expectations:

$$\pi_t = c + \rho \mathbb{E}_t \pi_{t+1} + \kappa \tilde{y}_t + u_t \quad (44)$$

	SW	CPI	core CPI	PCE	core PCE
gap	-1.1054** (0.3275)	-0.1613** (0.0809)	-0.0344 (0.052)	-0.062 (0.0487)	0.0047 (0.0368)
inflation expecations	0.8287** (0.0383)	0.4846** (0.1557)	0.5446** (0.0559)	0.6364** (0.0621)	0.6406** (0.045)
intercept	0.3484** (0.0789)	1.3851** (0.5021)	1.3193** (0.1818)	0.5522** (0.196)	0.8388** (0.1228)
R-squared	0.8234	0.159	0.4425	0.4635	0.6072

Table 5: Regression results for the CBO unemployment gap , with expectations

Two results are worth noting. First, the R-squared is much higher when using the “divine coincidence” inflation index on the left-hand-side. This is consistent with the fact that the “divine coincidence” index Phillips curve is the only one without an endogenous residual (see Proposition 3). Second, the calibrated model predicts well the estimated slope, for both consumer prices and the “divine coincidence” index DC . The slope implied by the calibrated model for the consumer-price and the “divine coincidence” Phillips curve is reported in Table 6.³²

³²The model predicts a higher slope when using the “divine coincidence” index, consistent with the fact that the weights in this index have a larger sum than for consumer prices (where they always sum to 1). The mapping between sectoral weights and the slope of the corresponding Phillips curve however is non-trivial, and relies on the propagation mechanism described in Section 4.1.2. Therefore our result can be viewed as a validation of this mechanism.

	DC	consumer prices
κ	-3.00	-0.09

Table 6: Calibrated slope of the Phillips curve ($\gamma = 1$, $\varphi = 2$)

As a further validation of my theoretical framework, I run a specification that augments (43) to include the time series of the endogenous residual constructed in Section 6.4.2. The new regression equation is:

$$\pi_t = c + \kappa \tilde{y}_t + u_t^C + v_t$$

	SW	CPI	core CPI	PCE	core PCE
cost-push	0.5627** (0.2345)	2.5545** (0.565)	0.4886 (0.4768)	2.3948** (0.4745)	1.1224** (0.4102)
gap	-3.7586** (0.6872)	-0.1906** (0.0758)	-0.2175** (0.064)	-0.0783 (0.0637)	-0.0886 (0.0551)
intercept	2.0842** (0.058)	3.2239** (0.1398)	2.8559** (0.118)	2.6509** (0.1174)	2.397** (0.1015)
R-squared	0.3317	0.2782	0.142	0.2558	0.1275

Table 7: Regression results for the CBO unemployment gap , with CP shock

where u_t^C is the endogenous component of the residual constructed in Section 6.4.2, and v_t is the exogenous component. The results are reported in Table 7.

Note that including our proxy for the endogenous residual brings the R-squared for consumer price regressions close to the “divine coincidence” specification. The result holds for both CPI and PCE, but not for their core versions. This is consistent with the model, as core inflation excludes flexible sectors (such as food and energy) which are among the main drivers of the residual.

Appendix F3 in the Supplemental Material reports additional specifications which include lags and inflation changes, together with residual plots.

7.3 Rolling regressions

I run rolling Phillips curve regressions with a 20 year window, over the period January 1984 - July 2018. I report results for the preferred specification (44) with inflation expectations, using the CBO unemployment gap as right-hand-side variable. Appendix F5 in the Supplemental Material reports results for different measures of the output gap and other specifications.

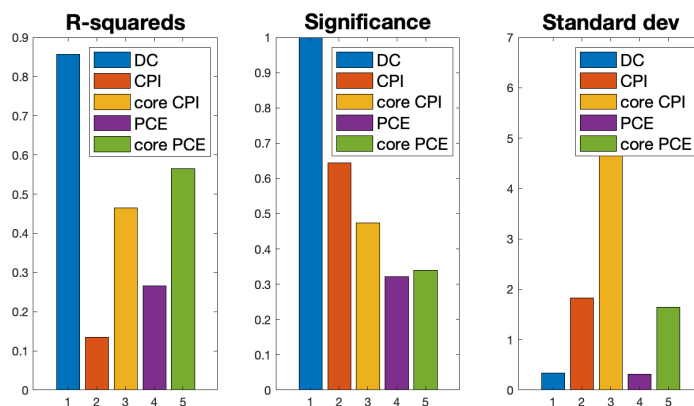


Figure 11: Summary statistics for rolling Phillips curve regressions

Figure 11 compares the strength and stability of the estimated relation for different left-hand-side variables. The left panel reports the average R-squared over the sample period, the middle panel reports the fraction of windows in which the estimated coefficient is significant, and the right panel plots the standard deviation relative to the mean of the estimated coefficient, as a measure of its stability over time. The figure shows that *DC* dominates consumer prices along all three dimensions. Plots of the rolling coefficients and confidence intervals are reported in Appendix F6 in the Supplemental Material.

8 Conclusion

This paper develops a New Keynesian framework with a realistic representation of production, consisting of multiple sectors arranged in a general input-output network. I provide an exact multi-sector counterpart to the traditional results. I derive analytical expressions for the Phillips curve and welfare as a function of the underlying

production primitives, and construct two novel indicators (the “divine coincidence” index and the optimal policy target) which inherit the positive and normative properties of inflation in the one-sector model. I calibrate the model to the US economy, finding quantitatively important departures from the one-sector benchmark.

With respect to the baseline model the consumer-price Phillips curve is flatter, and productivity shocks generate an endogenous inflation-output tradeoff. These predictions are new, and consistent with empirical evidence. I further validate my framework by showing that the “divine coincidence” index implied by the model provides a better fit for Phillips curve regressions than traditional specifications with consumer prices.

I also evaluate the performance of the two standard targets in the Taylor rule, the output gap and consumer inflation, against the optimal policy. I find that targeting the output gap is close to optimal, while stabilizing consumer prices generates an expected loss of 0.8% of per-period GDP relative to the optimal policy.

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