Firm Size, Heterogeneous Strategic Complementarity, and Inflation Dynamics*

Takushi Kurozumi† Willem Van Zandweghe‡

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Abstract

Research based on micro data finds substantial differences in price-setting behavior between small and large firms, as only the latter exhibit strategic complementarity in price-setting. Consistent with this research, we present new evidence from firm survey data showing that cost-price pass-through declines with firm size. To examine the implications for inflation dynamics, we embed heterogeneity in strategic complementarity by firm size in a DSGE model. Such models commonly feature strategic complementarities to induce real rigidity in relative prices. Our model, calibrated to U.S. Census data on employment, revenues, and costs by firm size, generates little real rigidity. Taking heterogeneity in strategic complementarity into account weakens real rigidity because firms that exhibit strategic complementarity are expected to bring their product prices in line with those of firms who fully pass through cost changes.

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†Research and Statistics Department, Bank of Japan, 2-1-1 Nihonbashi-Hongokucho, Chuo-ku, Tokyo 103-8660, Japan (e-mail: takushi.kurozumi@boj.or.jp)

‡Corresponding author. Research Department, Federal Reserve Bank of Cleveland, P.O. Box 6387, Cleveland, OH 44101, USA (e-mail: willem.vanzandweghe@clev.frb.org)

1 Introduction

Firm size matters for price-setting. Amiti et al. (2019) present empirical evidence of substantial heterogeneity in strategic complementarity across firms. They find that "*small firms exhibit no strategic complementarities in price-setting, and fully pass through their marginal cost shocks into their domestic prices. In contrast, large firms exhibit strong strategic complementarities and incomplete pass-through of own marginal cost shocks.*" Complementing their study, we present new evidence based on firm survey data on price changes and cost changes. A panel regression analysis supports the conclusion that cost-price pass-through declines significantly with firm size. The evidence on price-setting indicates that firm size could matter for inflation dynamics.

Dynamic stochastic general equilibrium (DSGE) models commonly embed the assumption that monopolistically competitive firms exhibit strategic complementarity in price-setting. The strategic complementarity generates real rigidity in prices. Price-adjusting firms respond more cautiously to changes in their real marginal cost in order to keep their product prices close to those of their competitors. By generating real rigidity, strategic complementarity allows the models to reconcile micro evidence of moderate price stickiness with macro evidence of substantial monetary non-neutrality.[1]

We introduce heterogeneity in strategic complementarity by firm size in an otherwise standard DSGE model with monopolistic competition and staggered price-setting. Introducing these two features allows the model to be consistent with the micro evidence. First, heterogeneity in firm size arises because firms in the model differ in their level of total factor productivity. Higher productivity of a firm boosts its size in terms of steady-state output and labor input. Second, heterogeneity in strategic complementarity gives rise to differing price-setting behavior by firm size. In the model, small firms face a constant elasticity of demand while larger firms face a variable elasticity of demand arising from a Kimball (1995)-type non-CES aggregator of individual goods with a possibly different superelasticity (the elasticity of the elasticity) of demand for firms of different sizes.[2]

[1] This idea is due to Ball and Romer (1990). Gopinath and Itskhoki (2011) review empirical evidence of real rigidities. For micro evidence on the frequency of price changes, see, e.g., Klenow and Kryvtsov (2008), Nakamura and Steinsson (2008), and Nakamura et al. (2018). A large literature documents monetary non-neutrality; see, e.g., Christiano et al. (2005) and Bu et al. (2021).

[2] Kimball (1995) introduced the aggregator as a source of real rigidity in relative prices. Smets and

An advantage of accounting for firm size is that firm-size specific data can inform the values of the parameters governing the superelasticity of demand, whereas standard DSGE models with homogeneous firms are silent on the parameters. The model is calibrated to data from the Statistics of U.S. Businesses (SUSB) of the U.S. Census, which provides the number of firms, their employment, payrolls, and revenues for firm-size categories ranging from firms with less than five employees to those with 5,000 or more employees. Because many of the firm-size categories represent only a small share of aggregate revenues, we consolidate the number of categories into five groups using statistical (k-means) clustering. Thus, each firm in the model belongs to one of five groups based on its productivity level. After normalizing the productivity of small firms, which are assumed to face a constant elasticity of demand based on the micro evidence, we obtain for each of the four remaining firm-size groups values of their relative productivity levels and the parameters that govern the superelasticity of their demand, by targeting the empirical revenue shares and labor shares of each firm-size group. The resulting parameter values imply that strategic complementarity is stronger for larger firms, consistent with the micro evidence. For the category of largest firms (those with 5,000 or more employees), the superelasticity of demand is 6.61. A weighted average superelasticity implied by our calibration implies an overall measure of curvature of 3.80, a value that is in line with micro evidence (Dossche et al., 2010; Beck and Lein, 2020).

Our main quantitative result is that heterogeneity in strategic complementarity greatly reduces the real rigidity arising from that complementarity. We show the result by comparing impulse responses of inflation and output to a monetary policy shock, obtained in our calibrated model with heterogeneous strategic complementarity, to their counterparts obtained in the case where all firms face a constant elasticity of demand. Although curvature is sizable in our calibrated model (3.80) and is zero in the case of no price-setting complementarity, the corresponding impulse responses are very similar. Thus, strategic complementarity concentrated in large firms does not materially increase monetary non-neutrality in the model.

Strategic complementarity and firm size have offsetting effects on the cost-price pass-through of large firms in the calibrated model. While the price-setting complementarity

Wouters (2007) adopted it in their model, after which the aggregator has become mainstream in DSGE models. It is also employed in other macroeconomic models with firm-level heterogeneity (e.g., Edmond et al., 2023) and in international economics (e.g., Gopinath and Itskhoki, 2010).

lowers pass-through, firm size increases it as goods produced by larger, more productive firms have a lower steady-state relative price, which reduces the price elasticity of demand for the goods. However, the offsetting effect of firm size does not fully explain the lack of real rigidity in the presence of heterogeneous strategic complementarity. Stronger complementarity in price-setting by large firms or smaller differences in firm size reduce the cost-price pass-through of large firms in the model, yet still fail to materially increase monetary non-neutrality.

The model's equilibrium conditions provide a full explanation. The model features specific price-setting conditions by firm size. Each of the conditions relates inflation to expected future inflation, real marginal cost, and the expected change in the firm's future relative price. According to these conditions, firms with a smaller real marginal cost elasticity of their prices have larger expected changes in their future relative prices. Suppose an expansionary shock raises the real marginal cost. If small firms pass through the higher costs more readily than large firms, then the shock raises the relative prices of small firms and lowers the relative prices of large firms. Hence large firms are expected to raise their future relative prices to restore them in the presence of strategic complementarity. The latter effect on price-setting under strategic complementarity is absent in standard DSGE models in which all price-adjusting firms behave identically. The special case of two groups of firms, small and large, is illuminating, because the model can be represented with a single Phillips curve that is isomorphic to the New Keyesian Phillips curve where the slope (the real marginal cost elasticity of inflation) is a weighted average of the real marginal cost elasticities of small and large firms. A strengthening of strategic complementarity solely for large firms has almost no influence on the slope of the Phillips curve.

Our results indicate that the real rigidity induced by homogeneous strategic complementarity in standard DSGE models, which abstract from firm size, is an artefact of that homogeneity. Once we account for the observed heterogeneity in strategic complementarity across firms of different sizes, the real rigidity largely disappears as the firms that exhibit strategic complementarity are expected to bring their product prices in line with those of firms who fully pass through changes in real marginal costs. Levin et al. (2008) demonstrate that the source of real rigidity in DSGE models can have implications for optimal monetary policy, which suggests that adopting an empirically plausible source is policy relevant.

The paper relates to different strands of the macroeconomic literature. Previous macroeconomic research on firm size is concerned with business fluctuations. Gertler and Gilchrist (1994) and Crouzet and Mehrotra (2020) document that small firms are more cyclically sensitive than large firms. While the former authors associate the greater cyclicality of small firms with financial frictions, the latter authors attribute it to a larger industry scope of large firms.[3] Research on the implications of firm heterogeneity for inflation dynamics focuses on sectoral heterogeneity in nominal price rigidities. Carvalho (2006) finds that (homogeneous) strategic complementarity in price-setting leads firms with more flexible prices to behave similar to firms with stickier prices. Due to this strategic interaction effect, the firms with stickier prices have a disproportionate influence on the aggregate price level, so heterogeneity in nominal rigidities increases monetary non-neutrality.[4] Our model, in which all firms face the same nominal price rigidity, has a strategic interaction effect because firms that exhibit strategic complementarity in price-setting behave similar to firms that fully pass through cost changes, so heterogeneity in strategic complementarity reduces monetary non-neutrality. In our model, a variable elasticity of demand leads large firms to display both strategic complementarity and a large desired markup. A recent strand of research endogenizes the link between market power and strategic price-setting by departing from the assumption of monopolistic competition. Mongey (2021), Wang and Werning (2022), and Ueda (2023) study the implications of oligopolistic markets with nominal price rigidities for monetary non-neutrality. Our model retains monopolistic competition for tractability to highlight the interaction between large and small firms in a DSGE setting. The paper also contributes to research that challenges the use of strategic complementarity for generating monetary non-neutrality (e.g. Klenow and Willis, 2016; Bils et al., 2012).

The remainder of the paper proceeds as follows. Section 2 presents evidence supporting the notion that firm size matters for price-setting. Section 3 describes a New Keynesian model with heterogeneity in strategic complementarity by firm size. In the model, Section 4 discusses the calibration of model parameters and presents the quantitative results. Section 5 concludes.

[3] Gilchrist et al. (2017) show that liquidity constrained firms raised their product prices during the global financial crisis, while unconstrained firms lowered prices. Haque et al. (2024) examine the implications of multi-product firms for equilibrium stability.

[4] See also Nakamura and Steinsson (2010), Pasten et al. (2020) and Carvalho et al. (2021).

2 Empirical evidence

In this section, we present new evidence on the role of firm size in price-setting by using firm survey data to show that cost-price pass-through decreases with firm size.[5]

The data are taken from the Business Inflation Expectations (BIE) survey of the Federal Reserve Bank of Atlanta, a monthly survey of firms in the sixth Federal Reserve district.[6] In nine separate months during the period from February 2020 to February 2024, firms were asked about their prices and costs. We begin by discussing the three variables used in the panel estimation: Price growth, cost growth, and firm size.

First, the survey question on price growth was phrased in one of two slightly different ways across survey waves.[7] Given the minor differentiations between the two formulations we merged their answers into one variable, the 12-month percentage change in a firm's price, which provides a larger time series dimension of the panel.

Second, firms in the survey indicate how their current unit costs compare with a year earlier, by selecting one of five categories ("down," "unchanged," "up somewhat," "up significantly," and "up very significantly"). We treat the cost growth indicator as an interval variable by assuming that each category covers a similar range of values for cost growth. The benefit of treating the ordinal variable as if it had linear effects is greater parsimony. Any disadvantages may be relatively minor, because our goal is to test whether the average association between price growth and cost growth——the sum of all the coefficients if we were to include one for each possible value of the ordinal variable in the panel regression——differs across firm-size groups. Hence, whether one interval is wider than the others should be less relevant to the extent it is wider for each firm size.

Third, a firm-size variable in the survey sorts firms into one of three groups: small (1-99 employees), medium (100-499 employees), or large (500 or more employees) firms. While a

[5]For evidence of strategic complementarity in cost-price pass-through, see Gopinath and Itskhoki (2010), Auer and Schoenle (2016), Dogra et al. (2023), and Gödl-Hanisch and Menkoff (2024).

[6]The sixth district includes Alabama, Florida, Georgia, and portions of Louisiana, Mississippi, and Tennessee.

[7]In six of the survey waves, the question was: "*In percentage terms, over the past 12 months, by how much did your firm increase [decrease] the price of the product or service responsible for the largest share of your revenue?*" In three of the survey waves, the question was instead: "*By roughly what percentage has your firm changed the price of the product/product line or service responsible for the largest share of your revenue of the last 12 months?*"

more precise employee count is available, we choose the three firm-size groups to ensure that each group contains a sufficient number of firms.

Using the three survey variables, we estimate the following panel regression:

$$\Delta Price_{f,t} = \mu + \beta_1 \Delta Cost_{f,t} \mathbb{I}_{f,t}(1) + \beta_2 \Delta Cost_{f,t} \mathbb{I}_{f,t}(2) + \beta_3 \Delta Cost_{f,t} \mathbb{I}_{f,t}(3) + \alpha_f + \gamma_t + \varepsilon_{f,t}, \quad (1)$$

where μ is a constant term, $\Delta Price_{f,t} \in \mathbb{R}$ denotes the price growth of firm f in month t, $\Delta Cost_{f,t} \in \{1, 2, 3, 4, 5\}$ indicates its cost growth, and $\mathbb{I}_{f,t}(i)$ is a dummy variable that indicates the size $i = 1, 2, 3$ of firm f by taking the value one if the firm is small, medium, or large, respectively, and zero otherwise. The regression model includes firm fixed effects α_f, which can absorb structural differences in price growth between firms, including differences in the responsiveness of own prices to competitors' prices, which could depend on firm size. Time fixed effects γ_t are also included to absorb aggregate drivers of price growth such as changes in the average markup during the sample period that saw a rise and fall in inflation. The coefficients β_i capture the cost-price pass-through of firms. Although the ordinal regressor renders the magnitude of the estimated coefficients not economically meaningful, the estimates allow testing whether cost-price pass-through differs statistically by firm size.

Before proceeding to the estimation we balance the dataset. The full dataset is an unbalanced panel; we select the largest possible balanced subset of the panel for the estimation. The balanced sample retains $T = 6$ survey months and contains at least 31 firms in each size group.[8] If T is larger than six, the sample size and the number of firms in each size group become smaller; if T is less than six, time variation is reduced without a gain in the sample size.

Table 1 presents the estimation results. The first column of numbers reports the estimated cost-price pass-through coefficients for small firms (β_1), medium firms (β_2), and large firms (β_3) in the balanced sample with $T = 6$. The estimators are decreasing in firm size and are significantly different from zero for small and medium firms but not for large firms, suggesting that large firms exhibit smaller pass-through from costs to prices. Some firms

[8]The six survey months are December 2020, April 2021, July 2021, November 2021, March 2022, and December 2022. Because there are multi-month time intervals between surveys, we did not attempt to balance the panel by imputing missing observations.

move between size groups in the sample, which could happen due to growth or downsizing. The second column shows the estimation results when the sample is limited to firms that remain in the same firm-size group. The decline in the point estimates across firm-size groups is slightly starker. The third column shows that larger time variation across firms in the sample, obtained by using the subsample with $T = 7$ survey months, somewhat increases the point estimates for each firm-size group, but leaves unchanged the result that large firms exhibit smaller cost-price pass-through.

Table 1: Estimation results of the panel regression model.

Variables	(1) Main sample	(2) Same firm size	(3) Larger T
$\Delta Cost_{f,t}\mathbb{I}_{f,t}(1)$	3.093***	3.192***	3.781***
	(1.069)	(1.104)	(0.842)
$\Delta Cost_{f,t}\mathbb{I}_{f,t}(2)$	2.965***	2.823***	3.214***
	(0.752)	(0.930)	(0.589)
$\Delta Cost_{f,t}\mathbb{I}_{f,t}(3)$	0.891	0.859	1.042
	(0.740)	(0.762)	(0.809)
Firm fixed effects	yes	yes	yes
Time fixed effects	yes	yes	yes
Sample size	724	641	669
Wald test	6.843**	6.016**	7.781**

Notes: ***, ** denotes significant at the 1 percent, 5 percent level, respectively. Column (1) presents the estimation results obtained with the main sample, a balanced panel in which firms are surveyed six times (i.e., $T = 6$). Column (2) shows the results obtained with only firms that remain in the same firm-size group during the sample period. Column (3) shows the results obtained with the sample of firms that are surveyed seven times (i.e., $T = 7$), during the same six months as in the main sample and in May 2023. The price growth variable is winsorized at the 5th and 95th percentiles. The within transformation of the panel regression model is estimated by OLS. Stock and Watson (2008) robust standard errors are reported in parentheses and critical values are based on the standard normal distribution.

We test whether cost-price pass-through depends on firm size using a Wald test. Defining the coefficient vector $\beta = (\beta_1, \beta_2, \beta_3)'$, the asymptotic distribution $\sqrt{nT}(\hat{\beta} - \beta) \xrightarrow{d} N(0, V)$, where V is the variance matrix of β. Under the null hypothesis that firm size is irrelevant to pass-through, $\beta_1 = \beta_2 = \beta_3$. Thus, the null is a two-dimensional vector $R\beta$, where

$$R = \begin{bmatrix} 1 & -1 & 0 \\ 1 & 0 & -1 \end{bmatrix}.$$

It follows that $\sqrt{nT}(R\hat{\beta} - R\beta) \xrightarrow{d} N(0, RVR')$. The Wald test statistic is

$$\xi_W = nT \left(R\hat{\beta}\right)' \left(R\hat{V}R\right)^{-1} \left(R\hat{\beta}\right),$$

where $\hat{V}$ is a consistent estimator for V that is obtained by following Stock and Watson (2008).[9] Under the null, the test statistic has a chi-square distribution with two degrees of freedom. The null hypothesis of no role for firm size in pass-through is rejected in the main sample and in the two alternative samples. Thus, the results in Table 1 indicate that large firms exhibit significantly less cost-price pass-through than smaller firms.

The evidence presented above complements existing evidence of heterogeneity in strategic complementarity by firm size. Amiti et al. (2019) study the extent of strategic complementarity in price-setting using micro data on the domestic prices, marginal costs, and competitors' prices of manufacturing firms in Belgium. The data features variation in firms' own marginal cost as the firms source intermediate inputs from different suppliers in different countries. The authors empirically decompose firms' price changes into the own cost pass-through and a response to competitors' price changes, which reveals strong evidence of strategic complementarity. The elasticity of firms' prices with respect to their competitors' prices is 0.4 while the elasticity with respect to own costs is 0.6 on average. Moreover, they find substantial evidence of *heterogeneity* in strategic complementarity, as noted in the Introduction. Small firms exhibit no strategic complementarity, whereas large firms are characterized by a competitor price elasticity of slightly more than 0.5 and an own cost elasticity of slightly less than 0.5. This evidence clearly establishes that firm size matters for price-setting and raises the question of whether it matters for inflation dynamics, which we turn to next.

3 Model with Heterogeneous Strategic Complementarity by Firm Size

We propose a model with heterogeneity in firm size and in strategic complementarity to assess whether firm size matters for inflation dynamics. The model consists of $k \geq 1$ groups of

[9] Specifically, $\hat{V} = \hat{Q}_{\tilde{X}\tilde{X}}^{-1} \hat{\Sigma} \hat{Q}_{\tilde{X}\tilde{X}}^{-1}$, where $\hat{Q}_{\tilde{X}\tilde{X}} = (nT)^{-1} \sum_{f=1}^{N} \sum_{t=1}^{T} \tilde{X}_{ft} \tilde{X}_{ft}'$, $\tilde{X}$ is the matrix of within-transformed regressors, and $\hat{\Sigma}$ is the bias-adjusted heteroskedasticity robust covariance matrix estimator described by Eq. (6) of Stock and Watson (2008).

individual-good producing firms distinguishable by the productivity levels of their production functions and the superelasticity of their demand curves, a representative composite-good producer, a representative household, and a monetary authority.

3.1 Households

There is a representative household that consumes a composite good C_t, makes a capital investment I_t, and supplies labor hours l_t so as to maximize the utility function

$$E_0 \sum_{t=0}^{\infty} \beta^t \left(\log\left(C_t\right) - \frac{l_t^{1+1/\chi}}{1+1/\chi} \right)$$

subject to the budget constraint

$$P_t\, C_t + P_t\, I_t + B_t = P_t\, W_t\, l_t + P_t\, r_{k,t}\, K_{t-1} + r_{t-1} B_{t-1} + P_t\, J_t$$

and the capital accumulation equation

$$K_t = (1-\delta)\, K_{t-1} + \left(1 - S\left(\frac{I_t}{gI_{t-1}}\right)\right) I_t, \tag{2}$$

where E_t denotes the expectation operator conditional on information available in period t, $\beta \in (0,1)$ is the subjective discount factor, $\chi > 0$ is the elasticity of labor supply, $\delta \in (0,1)$ is the depreciation rate of capital, P_t is the price of the composite good, W_t is the real wage rate, $r_{k,t}$ is the real rental rate of capital K_{t-1}, J_t is the real value of firm profits received, and $S(\cdot)$ is an adjustment cost function that is assumed to be quadratic:

$$S\left(\frac{I_t}{gI_{t-1}}\right) = \frac{\zeta}{2}\left(\frac{I_t}{gI_{t-1}} - 1\right)^2.$$

Combining the first-order conditions for utility maximization with respect to consumption, labor supply, capital, and investment yields

$$W_t = l_t^{1/\chi} C_t\,, \tag{3}$$

$$q_t = \beta E_t\left[\frac{C_t}{C_{t+1}}\left(r_{k,t+1} + (1-\delta)\, q_{t+1}\right)\right], \tag{4}$$

$$1 = q_t\left[1 - \frac{\zeta}{2}\left(\frac{I_t}{gI_{t-1}} - 1\right)^2 - \zeta\left(\frac{I_t}{gI_{t-1}} - 1\right)\frac{I_t}{gI_{t-1}}\right] + \zeta\beta E_t\left[\frac{C_t}{C_{t+1}} q_{t+1}\left(\frac{I_{t+1}}{gI_t} - 1\right)\frac{I_{t+1}^2}{gI_t^2}\right], \tag{5}$$

where q_t denotes the marginal cost of a unit of capital.

3.2 Firms

There is a continuum of firms f, each of which belongs to one subset $\Omega_i = \{f : z(f) = z_i\}$, where $z(f)$ is the firm-specific productivity of the firm's production technology. Thus, $i = 1, \ldots, k$ indicates each firm's productivity type. The measure of firms in each subset is n_i, so $\int_{\Omega_i} df = n_i$ and $\sum_{i=1}^{k} \int_{\Omega_i} df = 1$. Each firm f produces an individual differentiated good $Y_t(f)$ using the Cobb-Douglas production function

$$Y_t(f) = A_t z(f) K_t(f)^{\alpha} l_t(f)^{1-\alpha},$$

where $\alpha \in (0, 1)$ is the capital elasticity of output, A_t represents the level of economy-wide technology and grows at a constant rate $A_t/A_{t-1} = g^{1-\alpha}$, and $K_t(f)$ and $l_t(f)$ are firm f's inputs of capital and labor. The aggregate output of firms of type i (that is, firms $f \in \Omega_i$) is

$$Y_t \Delta_{i,t} n_i = A_t z_i K_{i,t}^{\alpha} l_{i,t}^{1-\alpha}, \tag{6}$$

where $K_{i,t} \equiv \int_{\Omega_i} K_t(f) df$, $l_{i,t} \equiv \int_{\Omega_i} l_t(f) df$, $\Delta_{i,t} \equiv (\tilde{\Delta}_{i,t} + \epsilon_i)/(1 + \epsilon_i)$, and

$$\tilde{\Delta}_{i,t} \equiv \frac{1}{n_i} \int_{\Omega_i} \left(\frac{P_t(f)}{P_t} \right)^{-\gamma_i} df. \tag{7}$$

The aggregate output of firms of type i consists of the n_i firms' average output per firm $Y_t \Delta_{i,t}$, where $\Delta_{i,t}$ is the average output of firms in group i relative to aggregate output Y_t. The relative output $\Delta_{i,t}$ can differ from one due the effects of the productivity level z_i on relative prices, strategic complementarity in price-setting on demand, and price dispersion across firms in Ω_i in the presence of staggered price-setting.

Firm f minimizes cost $TC_t(f) = P_t W_t l_t(f) + P_t r_{k,t} K_t(f)$ subject to the production technology (6), given the wage rate and the capital rental rate. In the presence of economy-wide, perfectly competitive factor markets, combining the first-order conditions for cost

minimization shows that all firms choose an identical capital–labor ratio[10]

$$\frac{K_t(f)}{l_t(f)} = \frac{\alpha}{1-\alpha}\frac{W_t}{r_{k,t}} = \frac{K_{t-1}}{l_t}. \tag{8}$$

However, a firm's real marginal cost of production varies inversely with its productivity level

$$mc_{i,t} = \frac{1}{A_t z_i}\left(\frac{W_t}{1-\alpha}\right)^{1-\alpha}\left(\frac{r_{k,t}}{\alpha}\right)^{\alpha}, \tag{9}$$

for each firm $f \in \Omega_i, i = 1, \ldots, k$. The ratios of the labor demand of each type of firm can be written as

$$\frac{Y_t \Delta_{i,t} n_i / l_{i,t}}{Y_t \Delta_{i-1,t} n_{i-1} / l_{i-1,t}} = \frac{mc_{i-1,t}}{mc_{i,t}} = \frac{z_i}{z_{i-1}},\ i = 2, \ldots, k, \tag{10}$$

where $Y_t \Delta_{i,t} n_i / l_{i,t}$ is the average output per hour of type-i firms. Thus, i indexes firms average labor productivity which is inversely proportional to their real marginal cost.

Price-setting is staggered as in Calvo (1983). In each period, a fraction $\xi \in (0,1)$ of firms indexes its prices to the trend inflation rate π, while the remaining fraction $1-\xi$ sets the price $P_t(f)$ so as to maximize relevant profit, taking into account the marginal cost (9) and the demand curve (12) for its good from composite-good producers, presented in the next subsection.

3.3 Composite-good producers

A representative composite-good producer combines the outputs of firms f. Generalizing the aggregator proposed by Kimball (1995), the composite good Y_t is produced by aggregating individual differentiated goods $\{Y_t(f)\}$ with

$$\sum_{i=1}^{k} \int_{\Omega_i} F_i\left(\frac{Y_t(f)}{Y_t}\right) df = 1. \tag{11}$$

The function $F_i(\cdot)$ is assumed to be of the form

$$F_i\left(\frac{Y_t(f)}{Y_t}\right) = \frac{\gamma_i}{(1+\epsilon_i)(\gamma_i - 1)}\left((1+\epsilon_i)\frac{Y_t(f)}{Y_t} - \epsilon_i\right)^{\frac{\gamma_i - 1}{\gamma_i}} + 1 - \frac{\gamma_i}{(1+\epsilon_i)(\gamma_i - 1)},$$

[10] The last equality in Eq. (8) can be obtained by using the capital and labor market clearing conditions $K_{t-1} = \sum_{i=1}^{k} \int_{\Omega_i} K_t(f) df$ and $l_t = \sum_{i=1}^{k} \int_{\Omega_i} l_t(f) df$.

where $\gamma_i \equiv \theta(1+\epsilon_i)$. The parameter ϵ_i governs the superelasticity of demand for each individual good. Values $\epsilon_i < 0$ generate a positive superelasticity and induce strategic complementarity in price-setting. This functional specification generalizes that of Dotsey and King (2005) and Levin et al. (2008) by allowing the parameter ϵ_i to vary by firms' productivity type.[11] In the special case of $\epsilon_i = 0$ for all i, the aggregator (11) is reduced to the CES one $Y_t = [\int_0^1 (Y_t(f))^{(\theta-1)/\theta} df]^{\theta/(\theta-1)}$, where $\theta > 1$ represents the elasticity of substitution between individual goods.

The composite-good producer maximizes profit $\Pi_t = P_t\, Y_t - \sum_{i=1}^k \int_{\Omega_i} P_t(f)\, Y_t(f)\, df$ subject to the aggregator (11), given individual goods' prices $\{P_t(f)\}$. Combining the first-order conditions for profit maximization and the aggregator (11) leads to

$$\frac{Y_t(f)}{Y_t} = \frac{1}{1+\epsilon_i}\left[\left(\frac{P_t(f)}{P_t\, d_t}\right)^{-\gamma_i} + \epsilon_i\right], \tag{12}$$

$$d_{i,t} = \left[\int_{\Omega_i} \left(\frac{P_t(f)}{P_t}\right)^{1-\gamma_i} df\right]^{\frac{1}{1-\gamma_i}}, \; i = 1, \ldots, k, \tag{13}$$

$$\sum_{i=1}^k \frac{\gamma_i}{(1+\epsilon_i)(\gamma_i - 1)} n_i = \sum_{i=1}^k \frac{\gamma_i}{(1+\epsilon_i)(\gamma_i - 1)} d_{i,t}^{1-\gamma_i} d_t^{\gamma_i - 1}, \tag{14}$$

$$1 = \sum_{i=1}^k \frac{1}{1+\epsilon_i}\, d_{i,t}^{1-\gamma_i} d_t^{\gamma_i} + \sum_{i=1}^k \frac{\epsilon_i}{1+\epsilon_i} \int_{\Omega_i} \frac{P_t(f)}{P_t}\, df\,, \tag{15}$$

where (12) is the demand curve for good f, (13) describes a relative price index $d_{i,t}$ of the goods produced by type-i firms, d_t is the Lagrange multiplier on the aggregator (11) and depends on the $d_{i,t}$ according to (14), and (15) is the zero-profit condition $\Pi_t = 0$ after making substitutions from (12) and (13).

The output of the composite good is equal to the household's consumption and investment,

$$Y_t = C_t + I_t. \tag{16}$$

[11] The composite-good producer aggregates individual differentiated goods according to the preferences of the household. A positive superelasticity of demand for the goods of large firms could arise, for example, if large firms invest in customer capital to make demand for their products less elastic as in the model of Crouzet and Mehrotra (2020). In the next section, we will let the data inform whether preferences for the goods of small and large firms differ.

3.4 Monetary authority and staggered price-setting

The monetary authority is assumed to follow a Taylor (1993)-type interest rate feedback rule

$$\log r_t = \log r + \phi_p \left(\log \pi_t - \log \pi\right) + \phi_y \log \left(\frac{Y_t}{A_t^{\frac{1}{1-\alpha}} y} \right) + \varepsilon_{r,t}, \tag{17}$$

where ϕ_p and ϕ_y are the policy responses to inflation and output, respectively, y is steady-state detrended aggregate output, and $\varepsilon_{r,t}$ is an i.i.d. policy shock.

Monetary policy shocks generate short-run responses in real activity due to nominal price rigidity in the model. As mentioned in Subsection 3.2, a fraction $1-\xi$ of firms set their price to maximize relevant profits

$$E_t \sum_{j=0}^{\infty} \xi^j \, \Lambda_{t,t+j} \left(P_t(f) \pi^j - P_{t+j} \, mc_{t+j} \right) Y_t(f),$$

where $\Lambda_{t,t+j}$ is the (nominal) stochastic discount factor between period t and period $t+j$. Using the equilibrium condition $\Lambda_{t,t+j} = \beta^j (C_t/C_{t+j})/(P_t/P_{t+j})$, the first-order conditions for profit maximization can be written as

$$0 = E_t \sum_{j=0}^{\infty} (\beta\xi)^j \frac{Y_{t+j}}{C_{t+j}} \left[\left(\frac{p_{i,t}^*}{d_{t+j}} \right)^{-\gamma_i} \prod_{\tau=1}^{j} \left(\frac{\pi_{t+\tau}}{\pi} \right)^{\gamma_i} \left(p_{i,t}^* \prod_{\tau=1}^{j} \left(\frac{\pi_{t+\tau}}{\pi} \right)^{-1} - \frac{\gamma_i}{\gamma_i - 1} mc_{i,t+j} \right) \right.$$
$$\left. - \frac{\epsilon_i}{\gamma_i - 1} p_{i,t}^* \prod_{\tau=1}^{j} \left(\frac{\pi_{t+\tau}}{\pi} \right)^{-1} \right], \tag{18}$$

for $i = 1, \ldots, k$, where $p_{i,t}^* \equiv P_{i,t}^*/P_t$, $P_{i,t}^*$ is the price set by firms of type i that can change prices in period t, and $\pi_t \equiv P_t/P_{t-1}$ is the gross inflation rate of the composite good's price. Moreover, under staggered price-setting, eqs. (7), and (13) can be reduced to, respectively,

$$d_t^{-\gamma_i} \tilde{\Delta}_{i,t} = \xi \left(\frac{\pi_t}{\pi} \right)^{\gamma_i} d_{t-1}^{-\gamma_i} \tilde{\Delta}_{i,t-1} + (1-\xi) \left(p_{i,t}^* \right)^{-\gamma_i}, \tag{19}$$

$$d_{i,t}^{1-\gamma_i} = \xi \left(\frac{\pi_t}{\pi} \right)^{\gamma_i - 1} d_{i,t-1}^{1-\gamma_i} + (1-\xi) \, n_i \left(p_{i,t}^* \right)^{1-\gamma_i}, \tag{20}$$

for $i = 1, \ldots, k$.

3.5 Log-linearized equilibrium conditions

The equilibrium conditions of the model consist of equations (2)−(6), (8), (9), (12), and (14)−(20). After removing the stochastic trend $\Upsilon_t \equiv A_t^{1/(1-\alpha)}$ we can log-linearize the equilibrium conditions expressed in terms of stationary variables including $y_t = Y_t/\Upsilon_t$, $c_t = C_t/\Upsilon_t$, $w_t = W_t/\Upsilon_t$, $\iota_t = I_t/\Upsilon_t$, and $k_t = K_t/\Upsilon_t$. The log-linearized model captures firm heterogeneity in $2k+1$ conditions,

$$\hat{\pi}_t = \beta E_t \hat{\pi}_{t+1} + \kappa_i \hat{mc}_t + \beta E_t \hat{p}_{i,t+1} - \frac{1}{\xi}\hat{p}_{i,t},\ i = 1, \ldots, k \tag{21}$$

$$\hat{d}_{i,t} = \xi\, \hat{d}_{i,t-1} + \hat{p}_{i,t},\ i = 1, \ldots, k \tag{22}$$

$$0 = \sum_{i=1}^{k} n_i p_i^* \Delta_i\, \hat{d}_{i,t}. \tag{23}$$

Equations (21) are the price-setting equations of firms of type i. The subscript i for the deviations of real marginal costs from their steady-state values has been dropped, because the deviations do not depend on firm size. The real marginal cost elasticity of a firm's price is

$$\kappa_i = \frac{(1-\xi)(1-\beta\xi)}{\xi\left[1 - \frac{\epsilon_i \gamma_i \left(p_i^*/d\right)^{\gamma_i}}{\gamma_i - 1 - \epsilon_i \left(p_i^*/d\right)^{\gamma_i}}\right]},\ i = 1, \ldots, k, \tag{24}$$

which depends on ϵ_i and z_i through the steady-state values of p_i^* and d. A smaller, negative value of ϵ_i results in a smaller value of κ_i, as stronger strategic complementarity in price-setting leads to less pass-through of costs. In the presence of strategic complementarity, firm size influences the pass-through via its effects on steady-state relative prices.

The additional terms in (21) show that relative prices also influence inflation, which is another implication of strategic complementarity. The relative price $\hat{p}_{i,t} \equiv (1-\xi)\hat{p}_{i,t}^* + \xi(-\hat{\pi}_t)$ of firms of type i is the average of the optimal relative prices of the $1-\xi$ price-adjusting firms and the relative prices of the ξ non-adjusting firms that erode when inflation exceeds its steady-state (or trend) rate. The additional terms indicate that inflation increases with approximately the expected change in the future relative price. The relative price terms are absent from the canonical Phillips curve based on homogeneous firms, because all adjusting firms choose the same price.

The conditions (22) describe the evolution of $\hat{d}_{i,t}$, which is a moving average of the

relative prices of firms of type i. Equation (23) is the log-linearized zero-profit condition of the composite-good producer (15) that requires that nominal GDP equals the sum of all firm revenues. For this condition to be met, the variables $\hat{d}_{i,t}$ cannot all move in the same direction.

The complete log-linearized model also includes the conditions

$$\begin{aligned}
\hat{mc}_t &= (1-\alpha)\hat{w}_t + \alpha\hat{r}_{k,t}, && (25)\\
\hat{w}_t + l_t &= \hat{r}_{k,t} + \hat{k}_{t-1}, && (26)\\
\hat{y}_t &= (1-\alpha)\hat{l}_t + \alpha\hat{k}_{t-1}, && (27)\\
\hat{w}_t &= \chi\hat{l}_t + \hat{c}_t, && (28)\\
\hat{c}_t &= E_t\hat{c}_{t+1} - \hat{r}_t + E_t\hat{\pi}_{t+1}, && (29)\\
\hat{k}_t &= \frac{1-\delta}{g}\hat{k}_{t-1} + \left(1 - \frac{1-\delta}{g}\right)\hat{\iota}_t, && (30)\\
\hat{q}_t &= \zeta\left(\hat{\iota}_t - \hat{\iota}_{t-1}\right) - \zeta\beta\left(E_t\hat{\iota}_{t+1} - \hat{\iota}_t\right), && (31)\\
\hat{q}_t &= \hat{c}_t - E_t\hat{c}_{t+1} + \left[1 - \beta\left(\frac{1-\delta}{g}\right)\right]E_t\hat{r}_{k,t+1} + \beta\left(\frac{1-\delta}{g}\right)E_t\hat{q}_{t+1}, && (32)\\
\hat{y}_t &= \frac{c}{y}\hat{c}_t + \frac{\iota}{y}\hat{\iota}_t, && (33)\\
\hat{r}_t &= \phi_p\hat{\pi}_t + \phi_y\hat{y}_t + \varepsilon_{r,t}, && (34)
\end{aligned}$$

which are the same as in the standard DSGE counterpart model with homogeneous firm size and homogeneous strategic complementarity.

3.6 Firm size and curvature

Thus far firms differ by their productivity, as indexed by $i = 1, \ldots, k$. Empirically there is a well documented relationship between labor productivity and firm size (Leung et al., 2008). We now explore the relationship in the model's steady state.

In the special case of a constant elasticity of demand (i.e., $\epsilon_i = 0$ for all i), we have that $p_i^* = \theta/(\theta-1)mc_i$, such that the real marginal cost ratios (10) imply $p_i^* = p_1^*/z_i$. It follows that output per firm $y\Delta_i = (z_i/p_1^*)^\theta$ is increasing in z_i, where Δ_i is the steady-state relative output of type-i firms. Likewise, given that all firms face the same real wage rate, more productive firms demand more labor. As a result, the average labor input per firm is increasing in z_i, that is, $l_i/n_i > l_{i-1}/n_{i-1}$ for $i = 2, \ldots, k$.

In the case of empirical interest, firms with higher productivity display greater strategic complementarity. The price elasticity of demand $\eta(Y_t(f)/Y_t) = \theta(1 + \epsilon_i - \epsilon_i(Y_t(f)/Y_t)^{-1})$ for more productive firms is then smaller, which leads their desired markups to be larger. The larger markups mitigate the differential in relative prices caused by the productivity differential between firms. In the next section we will confirm numerically that firm size tends to increase with productivity in the calibrated model. Thus, in the remainder of the paper we will refer to groups $i = 1, \ldots, k$ as indexing firm size. The feature that larger firms have larger markups is consistent with micro evidence of De Loecker et al. (2020) and Autor et al. (2020). The latter authors refer to the largest firms, which have the largest markups and the smallest labor shares, as superstar firms.

The extent of strategic complementarity in the model economy can be summarized by the curvature, which is defined as the mean superelasticity evaluated at a relative demand of one. The superelasticity of demand for good $f \in \Omega_i$ (i.e., the price elasticity of $\eta(Y_t(f)/Y_t)$) is derived as $\sigma(Y_t(f)/Y_t) = -\theta\epsilon_i/(Y_t(f)/Y_t)$. Hence stronger strategic complementarity (i.e., a smaller value $\epsilon_i \leq 0$) or a larger firm size in terms of the output share $Y_t(f)/Y_t$ lead to a larger superelasticity. Evaluating a firm's superelasticity at the relative demand $Y_t(f)/Y_t = 1$ prevents firm size from directly affecting the curvature and is consistent with previous research (e.g. Dossche et al., 2010; Klenow and Willis, 2016; Beck and Lein, 2020). Weighting the superelasticity at the relative demand of one by the steady-state revenue share of each firm and aggregating across firms yields the curvature

$$\sigma = \sum_{i=1}^{k} n_i p_i^* \Delta_i \left(-\theta\epsilon_i\right). \tag{35}$$

In the next section, we will compare cases of heterogeneous versus homogeneous strategic complementarity that have the same curvature.

4 Quantitative Analysis

In this section, we explain the method used for calibrating the parameters of the model and demonstrate the main result that accounting for firm size weakens the link between strategic complementarity and real rigidity.

4.1 Calibration

For the parameters that are not related to firm size we adopt values that are commonly used in the macroeconomic literature. Table 2 presents the calibration values of these parameters. We set the subjective discount factor at $\beta = 0.995$, that is, 2 percent annually, and the labor supply elasticity at $\chi = 1$. We assume a quarterly depreciation rate of capital of $\delta = 0.025$ and a capital elasticity of output of $\alpha = 0.33$. The rate of balanced growth is chosen at $g = 1.005$, that is, 2 percent annually. The parameter governing investment adjustment costs is set to ζ=2.5, the estimate of Christiano et al. (2005). The probability of a firm not updating its price is set at $\xi = 0.6$, which implies that prices change every 2.5 quarters on average in line with the micro evidence. The parameter governing the elasticity of substitution between individual goods is chosen at $\theta = 10$ to target a desired markup of about 11 percent for firms that face a constant elasticity of demand; firms that exhibit strategic complementarity will have a larger desired markup. The policy responses to inflation and output are set at the values in Taylor (1993) of ϕ_π=1.5 and ϕ_y=0.125, respectively.

Table 2: Quarterly calibration of model parameters.

Parameter	Description	Value
β	Subjective discount factor	0.995
g	Gross steady-state rate of technological change	1.005
χ	Elasticity of labor supply	1
δ	capital depreciation rate	0.025
α	capital elasticity of production	0.33
ζ	investment adjustment cost parameter	2.5
ξ	Probability of not updating price	0.6
θ	Elasticity of substitution between goods	10
ϕ_p	Policy response to inflation	1.5
ϕ_y	Policy response to output gap	0.5/4

Heterogeneity in strategic complementarity by firm size introduces $3k$ new parameters: n_i, z_i, and ϵ_i for $i = 1, \ldots, k$. The measure of firms of each firm size n_i for $i = 1, \ldots, k$ is provided by the SUSB. While the SUSB provides summary statistics for 23 firm size categories, many of them represent only a small share of aggregate revenues.[12] This indicates that the model

[12]We use firms as the business unit under the assumption that price-setting decisions are more often made at the firm level than at the establishment level. A firm in the survey is a business consisting of one or more domestic establishments in the same geographic area and industry. Using establishments as the business unit

can capture the role of firm size by choosing a smaller number of groups k than the 23 available categories. Thus we select $k = 5$ and use k-means clustering to combine the 23 categories into five clusters or groups. The first group consists of all firms with fewer than 500 employees, which can be characterized as small and medium-sized enterprises. The second, third, fourth, and fifth groups consist of the firms with 500 to 1,499, 1,500 to 2,499, 2,500 to 4,999, and 5,000 or more employees, respectively.

Values for z_i and ϵ_i for all i are obtained as follows. The value $z_1 = 1$ is set as a normalization and the value $\epsilon_1 = 0$ is chosen based on the micro evidence that small firms exhibit no strategic complementarity (Amiti et al., 2019). To calibrate the remaining $2k-2$ parameters z_i and ϵ_i for $i = 2, \ldots, k$, we target data of the SUSB. For each firm size category the survey provides not only the number of firms and employment, but also the payroll and revenue.[13] Specifically, we target the empirical labor share $\hat{S}_i$ and revenue share $\hat{R}_i$ by firm size i. First, the steady-state labor demand conditions imply the steady-state labor share $S_i = l_i w/(n_i y \Delta_i p_i^\star) = (1-\alpha) mc_i/p_i^\star$. The $k-1$ marginal cost equalities (10) can then be written as

$$S_i p_i^* z_i - S_{i-1} p_{i-1}^* z_{i-1} = 0, \; i = 2, \ldots, k. \tag{36}$$

Second, revenue by firm size as a percentage of aggregate revenues is $R_i = n_i p_i^* \Delta_i$ for $i = 1, \ldots, k$. We can only target revenues of $k-1$ firm-size groups because of the constraint that the revenue shares across firm categories sum to one, so we match the revenue shares $R_2, \ldots, R_k$ with their empirical counterparts using the $k-1$ conditions

$$n_i p_i^* \Delta_i - R_i = 0, \; i = 2, \ldots, k. \tag{37}$$

We simultaneously solve the following $k+1$ steady-state conditions for the k variables p_i^*

would substantially reduce the dispersion in firm size, because the largest establishments are much smaller than the largest firms. The SUSB distinguishes firms with less than 5, 5-9, 10-14, 15-19, 20-24, 25-29, 30-34, 35-39, 40-49, 50-74, 75-99, 100-149, 150-199, 200-299, 300-399, 400-499, 500-749, 750-999, 1,000-1,499, 1,500-1,999, 2,000-2,499, 2,500-4,999, and 5,000 or more employees.

[13] The data on revenues is provided every five years. We use the latest expanded survey which covers 2017.

and d:

$$0 = \sum_{i=1}^{k} n_i p_i^* \Delta_i - 1, \tag{38}$$

$$0 = \sum_{i=1}^{k} \frac{n_i}{\gamma_i - 1} \left[\left(\frac{p_i^*}{d} \right)^{1-\gamma_i} - 1 \right], \tag{39}$$

$$0 = \frac{\gamma_i - 1}{\gamma_i} \left[1 - \frac{\epsilon_i}{\gamma_i - 1} \left(\frac{p_i^*}{d} \right)^{\gamma_i} \right] p_i^* z_i - \frac{\gamma_1 - 1}{\gamma_1} \left[1 - \frac{\epsilon_1}{\gamma_1 - 1} \left(\frac{p_1^*}{d} \right)^{\gamma_1} \right] p_1^* z_1, \; i = 2, \ldots, k \tag{40}$$

Table 3 presents the values of the firm-size specific parameters and the steady-state values of the price variables.[14] Recall that these variables can affect economic dynamics through the real marginal cost elasticity κ_i in equations (21) and the revenue shares in equation (23). The data reported in the top panel of the table is taken directly from the SUSB. The first row shows that small and medium-sized firms make up the vast majority of all firms (n_1=0.9966), whereas the measure of larger firms in each of the groups $i > 1$ is very small. However, revenue shares are more evenly distributed across firm sizes, as shown in the second row. The group of largest firms actually has the largest revenue share.

Table 3: Values of firm-size specific model parameters and steady-state prices.

		Value for firm-size group i				
	Description	1	2	3	4	5
n_i	Share of firms (percent)	99.66	0.22	0.04	0.03	0.04
$n_i p_i^* \Delta_i$	Revenue share (percent)	35.64	8.30	4.12	6.75	45.19
z_i	Relative productivity level	1	2.24	2.11	5.51	17.29
$-\theta\epsilon_i$	Superelasticity of demand	0	4.03	1.95	5.95	6.61
p_i^*	Steady-state optimal goods price	1.30	0.63	0.63	0.28	0.10

Source: U.S. Census.

Notes: The table presents the values of firm-size specific model parameters n_i, z_i, and ϵ_i (multiplied by $-\theta$) and steady-state prices p_i^*. The values of n_i are taken from the SUSB. The values of z_i, ϵ_i, and p_i^* are obtained as a solution to equations (36)−(40), by setting $z_1 = 1$, $\epsilon_1 = 0$, and using the data for n_i, the revenue shares $\hat{R}_i$, and the labor shares $\hat{S}_{i,t}$, and the calibration of model parameters reported in Table 2.

The numbers shown in the bottom panel are obtained by combining the SUSB data, the parameter values reported in Table 2, and the assumptions $z_1 = 1$ and $\epsilon_1 = 0$ with

[14] Heterogeneity in firm size in the model is needed to determine values of the parameters ϵ_i that govern strategic complementarity. If firm size is homogeneous, that is, $z_i = 1$ for all i, then for arbitrary values of ϵ_i a solution to equations (38)−(40) is $p_i^* = d = 1$ for all i. The solution implies that $\Delta_i = 1$ for all i and that equations (36) and (37) are inconsistent with the empirical evidence on the number of firms, the labor share, and the revenue share by firm-size group.

equations (36)−(40). The third row of the table shows the relative productivity levels of firms in each group. Productivity of the largest firms is an order of magnitude larger than that of small and medium-sized firms, as indicated by the value of z_5.[15] Productivity is positively associated with firm size, except for the middle group of firms.

The fourth row of the table shows the superelasticity of demand $-\theta\epsilon_i$ by firm size. Two points are worth noting. First, the superelasticity increases with productivity, and thus it increases with firm size except for the middle group of firms. The stronger superelasticity for large firms agrees with the micro evidence that price-setting of large firms exhibits strategic complementarity while that of small firms is consistent with a constant elasticity of demand, as discussed in Section 2. Second, given the firm-size specific values reported in the table, curvature as defined by Eq. (35) is $\sigma = 3.80$, a value in line with the micro evidence of Dossche et al. (2010) and Beck and Lein (2020), who indicate that values in the range of $2-4$ are plausible.

The steady-state reset prices p_i^* are shown in the last row of Table 3. Given the firm-size specific parameter values, the reset prices are lower for more productive firms. Hence the prices fall with larger firm size except for the middle group of firms.[16] The steady-state real marginal cost of aggregating differentiated goods is $d = 1.14$.

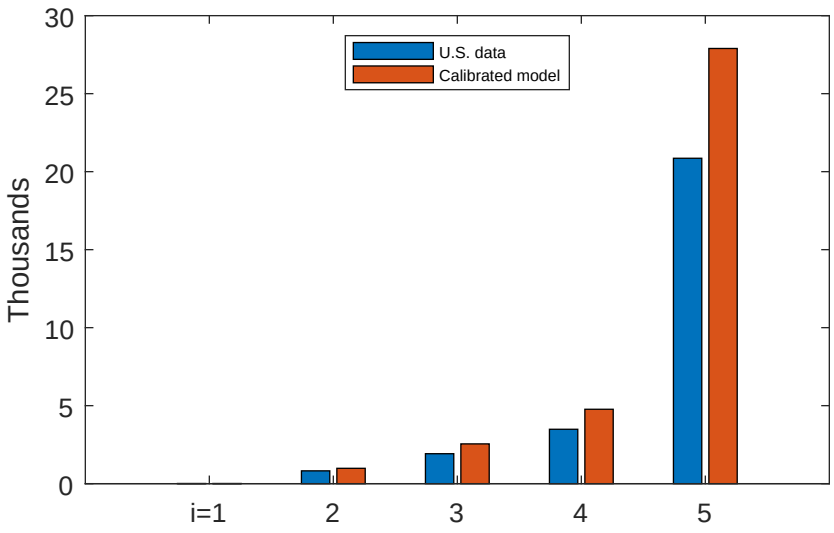
As for the relationship between firm productivity and firm size in the calibrated model, Figure 1 plots average employment in each of the five groups of firms in the SUSB (left bars) and their counterparts in the steady state of the calibrated model (right bars). Firm size increases in the model as it does in the data, although the dispersion in firm size is somewhat larger in the model.[17] Because the data on average employment per firm is not targeted in the calibration, the firm-size distribution provides an additional check on the model. The correlation of firm size and productivity in the calibrated model is imperfect due to the middle group of firms, yet it is strong. Thus, the figure confirms that firm size is

[15] Cunningham et al. (2023) present micro evidence of establishment-level productivity dispersion. Across detailed manufacturing industries, total factor productivity of establishments at the 99th percentile is 2.38 times that of establishments at the 90th percentile. This differential is close to the productivity differential z_2/z_1=2.24 in Table 3. We are not aware of micro evidence on productivity dispersion within the top one percentile of firms.

[16] Lower prices for more productive firms implies that revenue productivity is less dispersed than physical productivity, consistent with establishment-level evidence of Foster et al. (2008).

[17] Firm size in the model measured as steady-state relative output Δ_i also increases with i.

Figure 1: Average number of employees by firm-size group.



Source: U.S. Census.

Notes: The figure presents the average employment per firm in each of the five groups of firms based on the SUSB data (left bars) and the corresponding steady-state average employment per firm in the model (i.e., l_i/n_i; right bars) for the calibration of model parameters reported in tables 2 and 3. Steady-state output y is normalized so that l_1/n_1 is equal to its empirical counterpart.

positively associated with firm productivity in the calibrated model.

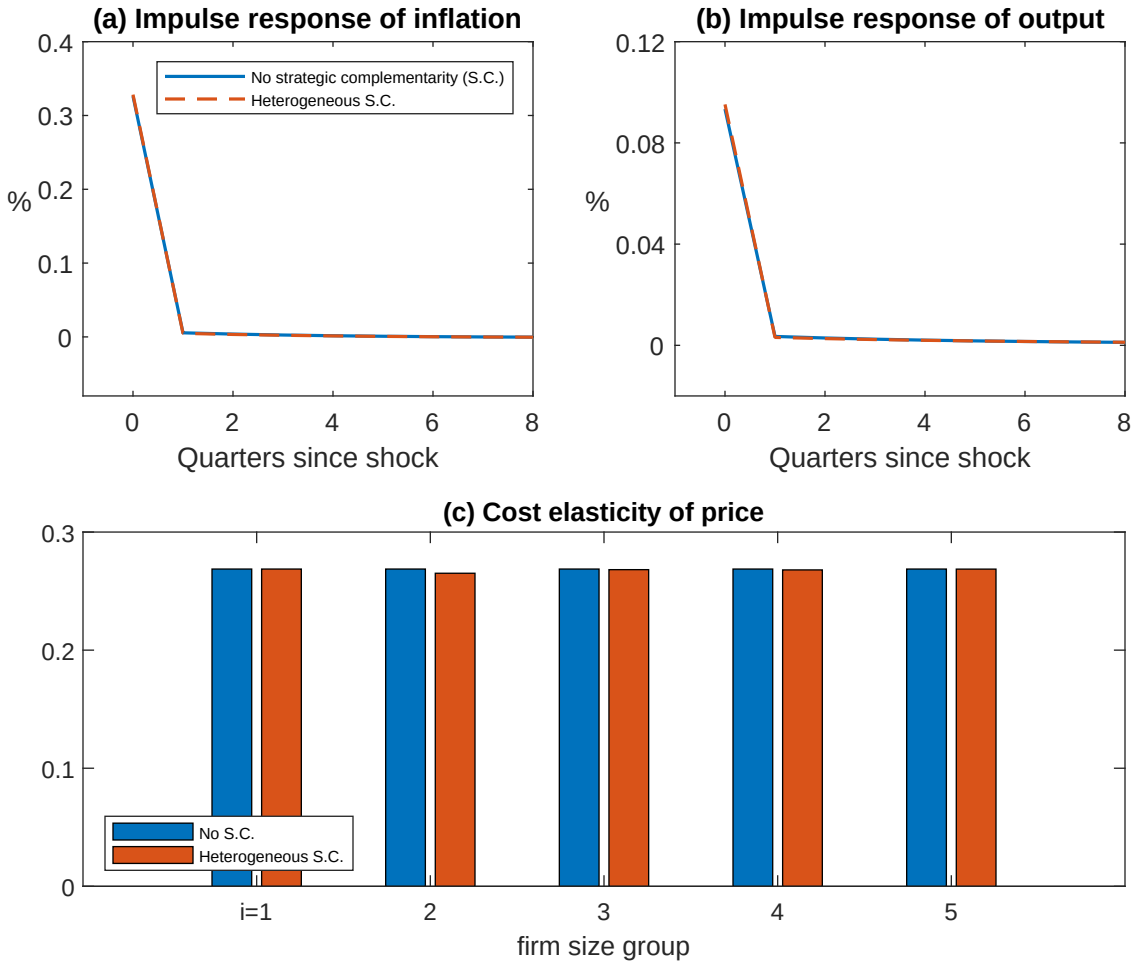
4.2 Main result

In this subsection, we use the calibrated model to show that heterogeneity in strategic complementarity by firm size does not materially increase monetary non-neutrality compared to the case of a constant elasticity of demand for all goods, indicating that such complementarity generates little real rigidity.

Monetary non-neutrality in the calibrated model can be gauged by its impulse responses to a monetary policy shock. Panels (a) and (b) of Figure 2 plot the responses of inflation and output, respectively, to a one percent expansionary shock using the values of model parameters summarized in tables 2 and 3 (dashed lines), and compares them to the responses arising in the absence of strategic complementarity obtained by setting $\epsilon_i = 0$ for all i (solid lines). The impulse responses in each panel are practically identical. Output and inflation jump on impact as the shock raises consumption demand and the real marginal cost, before returning to their steady-state levels. For a more quantitative assessment of the price-

setting complementarity, we can compare the cumulative impulse responses. The ratio of the cumulative response of inflation obtained under the baseline calibration and that obtained in the absence of strategic complementarity is 0.996, while the ratio of the cumulative responses of output is 1.017. Seeing both ratios near one indicates that the heterogeneous strategic complementarity dampens the response of inflation and amplifies the response of output only slightly. Thus, heterogeneous strategic complementarity concentrated in large firms generates little increase in monetary non-neutrality.

Figure 2: Strategic complementarity and monetary non-neutrality.



Notes: Panels (a)−(b) present impulse response functions and panel (c) displays the real marginal cost elasticity of firms' prices κ_i for all i. The results labeled 'Heterogeneous S.C.' are obtained with the values of ϵ_i reported in tables 2 and 3 while the results labeled 'No strategic complementarity (S.C.) represent the special case of $\epsilon_i = 0$ for $i = 1, \ldots, k$.

To better understand the result, panel (c) of the figure plots the real marginal cost elas-

ticity of the price-setting equations (21) for each firm-size group i. As a reference, the left bars display the elasticity $\kappa_i = (1-\xi)(1-\beta\xi)/\xi$ in the absence of strategic complementarity (i.e., $\epsilon_i = 0$). The right bars show the cost elasticity for the model with strategic complementarity in price-setting of larger firms. Evidently, such heterogeneous price-setting complementarity has almost no effect on cost-price pass-through. Stronger strategic complementarity for larger firms reduces the elasticity κ_i through a more negative value of ϵ_i, but the larger firm size increases the elasticity through a lower steady-state relative price p_i^*. Intuitively, the lower relative price leads to a smaller steady-state price elasticity of demand for the goods of larger firms. On net pass-through varies little with firm size in the calibrated model, indicating little variation in the relative prices of different sized firms.[18]

4.3 Roles of complementarity and firm size

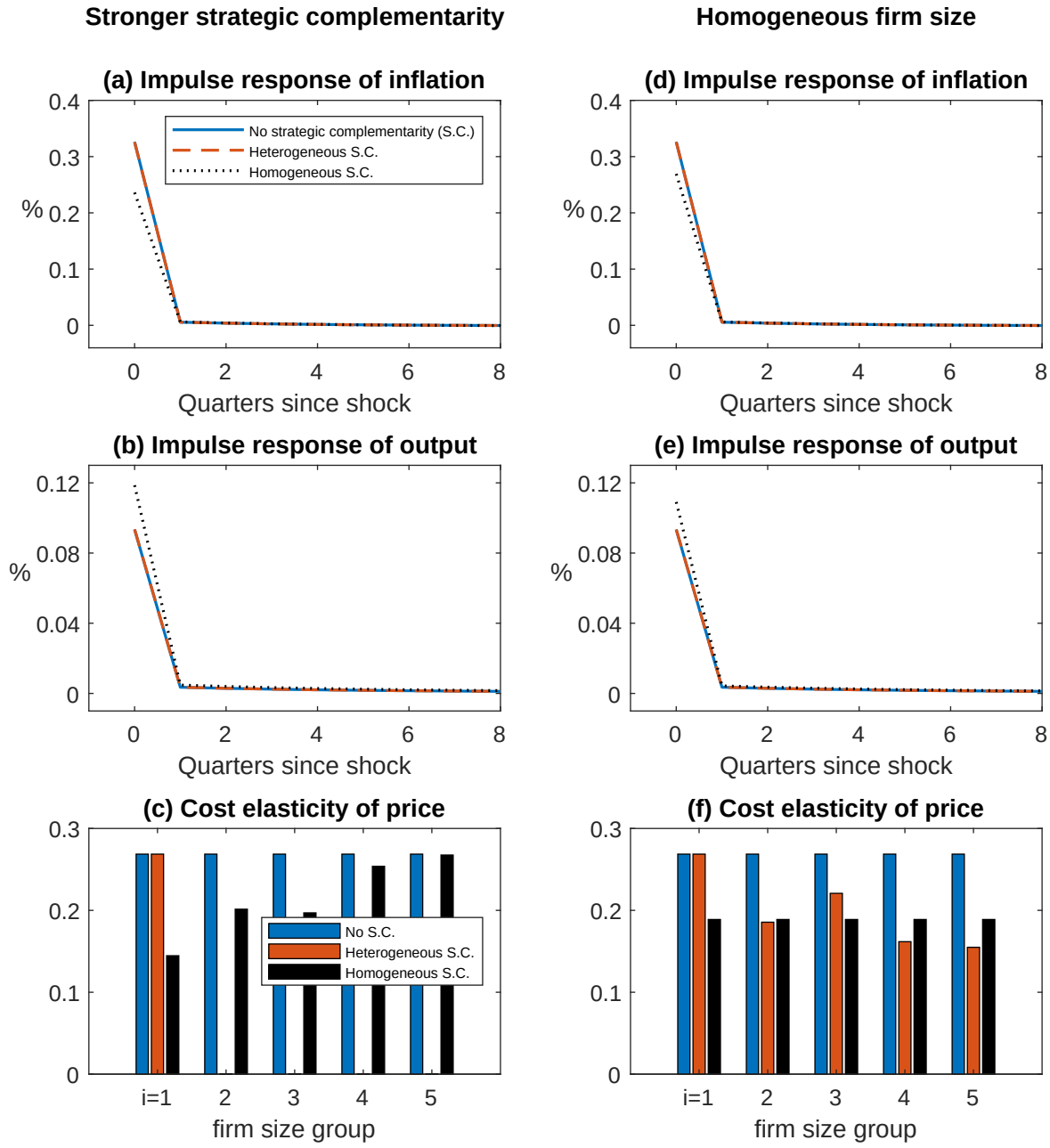
Strategic complementarity and firm size have largely offsetting effects on the cost-price pass-through of large firms under the baseline calibration of parameter values. The invariance of the pass-through to firm size does not sit well with the empirical evidence presented in Table 1. Strengthening the effect of strategic complementarity on price-setting relative to that of firm size can reduce the cost-price pass-through of large firms and reconcile the model with the micro evidence. We examine changes in parameter values that increase strategic complementarity of large firms or reduce the size of large firms in turn and show that they preserve the result on monetary non-neutrality obtained in the previous subsection.[19]

First, we consider stronger strategic complementarity in the price-setting of large firms. Panels (a) and (b) of Figure 3 display the impulse responses of inflation and output, respectively, obtained by doubling the curvature (dashed lines). The value $\sigma = 7.60$ is attained by scaling up the parameter values of ϵ_i reported in Table 3. Despite the stronger price-setting

[18] A possible concern could be that small firms, being numerous, shape the aggregate price index, thus requiring large price changes by larger firms, that is, large fluctuations in $\hat{d}_i$ for $i > 1$. However, condition (23) indicates that the weights on $\hat{d}_{i,t}$ are the revenue shares of each firm size group i. Since larger firms account for the majority of revenues, the condition does not necessitate particularly large fluctuations in the relative prices of large firms.

[19] Changing the firm-size specific parameter values leads the revenue shares and labor shares in the calibrated model to deviate from their empirical counterparts in the SUSB. Thus, the quantitative model faces a tension between replicating the micro evidence on price-setting presented in Table 1 and matching the aggregate data by firm size. The paper shows that heterogeneity in strategic complementarity by firm size has little effect on monetary non-neutrality, regardless of which evidence is prioritized by the model calibration. Future research can consider model enhancements that allow it to reconcile the micro and macro evidence.

Figure 3: Strategic complementarity and monetary non-neutrality with alternative parameter values.



Notes: Panels (a)−(c) present results obtained by scaling up the parameters ϵ_i for all i to reach $\sigma = 7.60$ (dashed lines and middle bars), results for the case of homogeneous strategic complementarity in which the value of $\epsilon_i = \bar{\epsilon}$ for all i is chosen to achieve the same curvature (dotted lines and right bars), and results for the case of a constant elasticity of demand obtained by setting $\epsilon_i = 0$ for all i (solid lines and left bars). Panels (d)−(f) present analogous results for the case of homogeneous firm size, obtained by setting $z_i = 1$ for all $i = 1$. The values of model parameters other than those indicated are given in tables 2 and 3.

complementarity, the impulse responses remain almost the same as those obtained in the case of a constant elasticity of demand (solid lines). The ratios of cumulative impulse responses of inflation and output are 0.998 and 1.002, respectively. The panels include impulse responses for the case of homogeneous strategic complementarity (dotted lines), obtained by choosing a constant value of the parameter $\epsilon_i = \bar{\epsilon}$ for all i (including $i = 1$) that generates the same curvature $\sigma = -\theta\bar{\epsilon} = 7.60$ as that under heterogeneous strategic complementarity. If all firms exhibit strategic complementarity, the response of inflation to a policy shock is dampened while that of output is amplified. The ratios of cumulative impulse responses for inflation and output are 0.697 and 1.284, respectively. Thus, homogeneous strategic complementarity generates a substantial increase in monetary non-neutrality.

Panel (c) of the figure shows the real marginal cost elasticity of prices for each firm size group in the case of stronger complementarity in price-setting for large firms. The left bars represent the case of a constant elasticity of demand. The middle bars show that the cost-price pass-through of large firms is almost zero, indicating that these firms influence inflation dynamics largely through expected changes in their future relative prices, which are induced by the cost-price pass-through of small firms. The right bars show that if all firms exhibit strategic complementarity equally, pass-through *increases* with firm size, as the lower relative price of large firms leads to a smaller price elasticity of demand for their goods.

Another change in the calibration consists of reducing differences in firm size to mitigate the effect of size on the cost-price pass-through of large firms. Arguably, the model accounts primarily for heterogeneity in firm size to pin down the values of the parameters ϵ_i using the SUSB data. As the curvature (35) omits the effect of firm size, so too can the dynamics of the model abstract from firm size by considering values for the productivity parameters of $z_i = 1$ for each i while holding the parameters ϵ_i at the values reported in Table 3.

For the case of homogeneous firm size, panels (d) and (e) of Figure 3 display impulse responses of inflation and output, respectively. The impulse responses obtained in the presence of heterogeneous strategic complementarity (dashed lines) are similar to those obtained in the absence of price-setting complementarity (solid lines). The ratios of the cumulative impulse responses are 0.999 and 1.000 respectively for inflation and output, indicating that heterogeneous strategic complementarity generates almost no increase in monetary non-neutrality. The results with homogeneous strategic complementarity (dotted lines) are obtained by

choosing a constant value of the parameter $\epsilon_i = \bar{\epsilon}$ for all i such that the curvature is equal to $\sigma = 3.80$. If all firms exhibit complementarity in price-setting, the ratios of cumulative impulse responses are 0.810 and 1.176 respectively for inflation and output, indicating a substantial increase in monetary non-neutrality in line with standard DSGE models that abstract from heterogeneity in firm size and in strategic complementarity.

Panel (f) of the figure shows the real marginal cost elasticity of prices when firm size is homogeneous because $z_i = 1$ for all i. If strategic complementarity is also homogeneous, the parameter value $\bar{\epsilon} < 0$ reduces the cost elasticity of prices of each group of firms equally (right bars) compared to the case of no strategic complementarity (left bars). In contrast, heterogeneity in strategic complementarity using the parameter values ϵ_i reported in Table 3 reduces the cost elasticity for firms with a positive superelasticity, that is, firms in groups $i > 1$ (middle bars).

Stronger strategic complementarity or homogeneous firm size generate cost-price pass-through by firm size consistent with the empirical evidence presented in Table 1. Nevertheless, if strategic complementarity is concentrated in large firms, the model fails to materially increase monetary non-neutrality, indicating that the price-setting complementarity generates little real rigidity. An explanation is as follows. If small firms adjust their prices according to a constant elasticity demand curve they fully pass through changes in real marginal costs to their prices. Large firms, however, display strategic complementarity and hence incomplete pass-through. An aggregate shock that increases real marginal costs then raises the relative prices of small firms and lowers the relative prices of large firms. Thus the shock leads to an expected future increase in the relative prices of large firms, as strategic complementarity leads those firms to bring their product prices back in line with those of their competitors. The larger is the differential in cost-price pass-through between small and large firms, the larger will be the expected future realignment of the relative prices of large firms.[20] In this way, both small and large firms adjust their prices substantially after a policy shock, when they can adjust them, resulting in weak real rigidity.

[20]Stronger strategic complementarity or smaller differences in firm size both reduce the dispersion in steady-state relative prices p_i^* across firm sizes i. As steady-state relative prices are closer to one, so are steady-state relative outputs Δ_i. Consequently, the revenue share of each firm size group approaches the number of firms n_i in the group. As the vast majority of firms are small, the zero profit condition (23) implies relatively small fluctuations in the moving average of relative prices of small firms $d_{1,t}$ and relatively large fluctuations in those of large firms $d_{i,t}$ for $i > 1$.

4.4 Other robustness analysis

We have found that heterogeneous strategic complementarity by firm size weakens monetary non-neutrality due to such complementarity. In this subsection, we verify the robustness of the finding to alternative values of model parameters.

Table 4: Cumulative impulse responses and their ratios.

Case	CIR Inflation	Ratio	CIR Output	Ratio
(a) *Baseline calibration*				
No strategic complementarity (S.C.)	0.317	1	0.127	1
Heterogeneous S.C.	0.315	0.996	0.129	1.017
(b) *Stickier prices* (ξ=*0.75*)				
No S.C.	0.135	1	0.195	1
Heterogeneous S.C.	0.132	0.977	0.198	1.016
(c) *Inelastic labor supply* (χ=*1/2*)				
No S.C.	0.268	1	0.144	1
Heterogeneous S.C.	0.265	0.992	0.147	1.019
(d) *Frictionless investment* (ζ=*0*)				
No S.C.	0.338	1	0.394	1
Heterogeneous S.C.	0.312	0.921	0.412	1.047
(e) *More firm-size groups* (k=*8*)				
No S.C.	0.317	1	0.127	1
Heterogeneous S.C.	0.315	0.996	0.129	1.016

Notes: The table presents the cumulative impulse response (CIR) of inflation and output to a one percent negative shock to the annualized monetary policy rate obtained with the values of ϵ_i reported in Table 3 and their ratio with the corresponding CIR in case of no strategic complementarity (i.e., $\epsilon_i = 0$ for each i). Other parameter values are reported in tables 2 and 3, except for the alternative parameter values used in panels (b)−(d).

Table 4 reports the cumulative impulse responses obtained under heterogeneous strategic complementarity, the corresponding ones in the case of a constant elasticity of demand, and their ratios. Panel (a) summarizes the numbers obtained under the baseline calibration reported in Table 2 and the firm-size specific parameter values in Table 3. As observed previously, the heterogeneous strategic complementarity does little to dampen the response of inflation or amplify the response of output to a policy shock. Panels (b), (c), and (d) of Table 4 consider a lower frequency of updating prices (ξ=0.75), a less elastic labor supply (χ=1/2), and no investment adjustment costs (ζ=0), respectively. While alternative parameter values can influence the cumulative impulse responses substantially, their influence is

similar in the case of heterogeneous strategic complementarity and a constant elasticity of demand, so that the ratios of the corresponding cumulative impulse responses remain close to one in each panel. Finally, panel (e) assumes a larger number of firm-size groups ($k = 8$) and finds almost no change from the results reported in panel (a).

4.5 Large and small firms

In this subsection, we analyze the implications of heterogeneous strategic complementarity for inflation dynamics using the smallest possible number of firm-size groups: $k = 2$. The Phillips curve arising in this version of the model provides additional insight into the lack of real rigidity induced by heterogeneous strategic complementarity.

The log-linearized zero-profit condition of the composite-good producer (23) becomes

$$\hat{d}_{1,t} = -\rho\, \hat{d}_{2,t}, \tag{41}$$

where $\rho \equiv n_2 p_2^* \Delta_2 / (n_1 p_1^* \Delta_1)$ is the ratio of the steady-state revenue shares of large and small firms. The equation can be combined with the two price-setting conditions (21) into a single-equation Phillips curve,

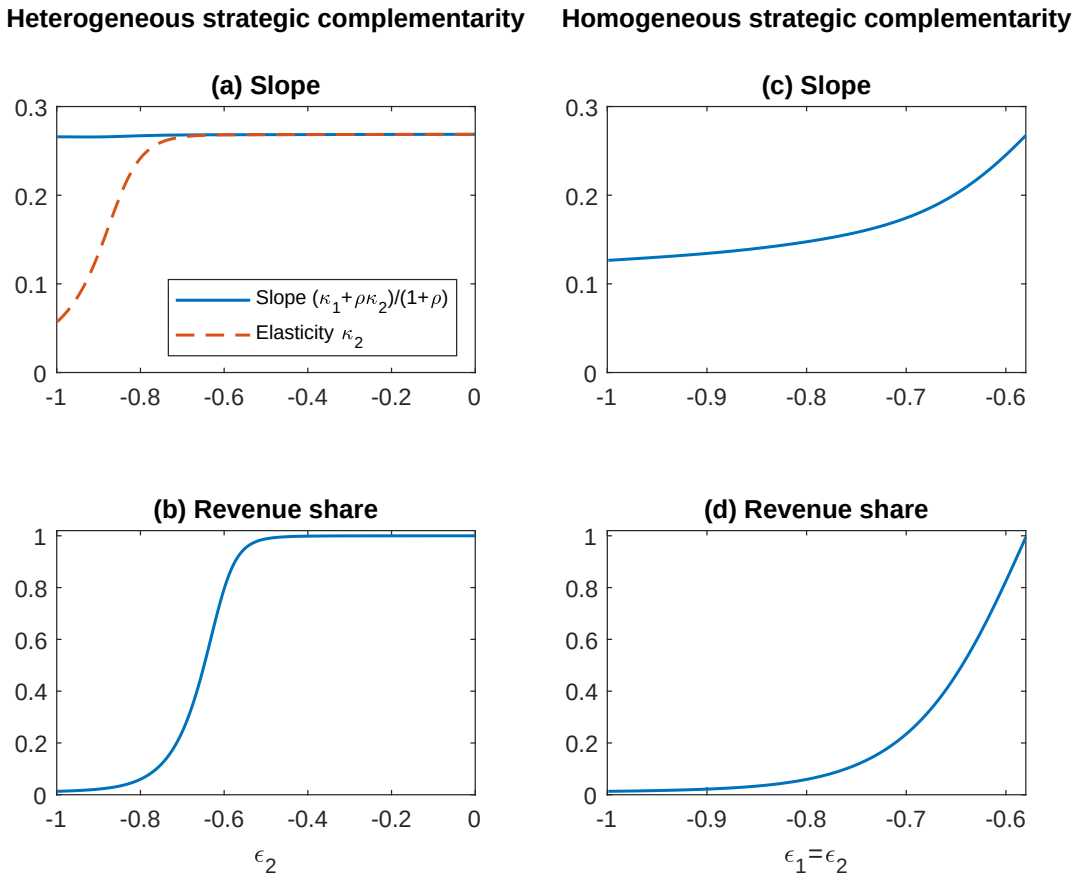
$$\hat{\pi}_t = \beta E_t \hat{\pi}_{t+1} + \frac{\kappa_1 + \rho\kappa_2}{1+\rho}\, \hat{mc}_t, \tag{42}$$

where the coefficients κ_1 and κ_2 are described by (24). The slope of the Phillips curve (42) is a linear combination of the real marginal cost elasticities of the price-setting equations (21) of both types of firms. If $\rho \to 0$, implying a large revenue share of small firms, $(\kappa_1 + \rho\kappa_2)/(1+\rho) \to \kappa_1$. The slope of the Phillips curve approaches the relatively large marginal cost elasticity that characterizes the price-setting equation of small firms. And the moving average of relative prices of large firms $\hat{d}_{2,t}$ exceeds that of small firms $\hat{d}_{1,t}$ in absolute value according to Eq. (41). If $\rho \to +\infty$, implying a large revenue share for large firms, $(\kappa_1 + \rho\kappa_2)/(1+\rho) \to \kappa_2$. Now the slope approaches the relatively small marginal cost elasticity in the price-setting equation of large firms, who exhibit strategic complementarity, and the moving average of relative prices of large firms is smaller than that of small firms in absolute value.

To pin down the values of the firm-size specific parameters, firms with fewer than 500 employees are labeled as small, which implies they make up $n_1 = 0.9966$ of all firms. Using

the baseline calibration of parameters reported in Table 2, the calibration method explained in subsection 4.1 implies that large firms have a relative productivity z_2=6.32, a value of the parameter governing their superelasticity $\epsilon_2 = -0.62$, and a revenue share of 0.64. These values imply that the curvature is $\sigma = 3.99$.

Figure 4: Slope of the Phillips curve and revenue share of large firms.



Notes: The figure presents the slope coefficient of the Phillips curve (42) and the revenue share of large firms under the calibration of model parameters reported in Table 2 and the parameter values $(n_1, n_2) = (0.9966, 0.0034)$, $(z_1, z_2) = (1.00, 6.32)$. Panels (a) and (b) set $\epsilon_1 = 0$ to vary the value of ϵ_2 while panels (c) and (d) vary ϵ_1 and ϵ_2 equally.

We illustrate the implications of heterogeneity in strategic complementarity between small and large firms by considering the slope $(\kappa_1 + \rho\kappa_2)/(1 + \rho)$ at various alternative values of the curvature parameters ϵ_2 while holding ϵ_1 at zero. The solid line in panel (a) of Figure 4 traces the magnitude of the slope and shows that it remains nearly constant at its level associated with no strategic complementarity (i.e., $\epsilon_2 = \epsilon_1 = 0$). This occurs even as the real marginal cost elasticity of large firms' goods prices κ_2 declines with ϵ_2, as the dashed line

shows.[21] The slope remains flat because smaller values of ϵ_2 reduce the steady-state revenue share of large firms as indicated in panel (b), thus reducing the ratio of steady-state revenue shares ρ and offsetting the downward pull of a smaller elasticity κ_2 by pushing the slope $(\kappa_1 + \rho\kappa_2)/(1+\rho)$ toward the elasticity κ_1. The ratio ρ declines because smaller values of ϵ_2 raise the steady-state relative price of large firms p_2^* closer to that of small firms. The larger relative price is associated with a larger price elasticity of demand for large firms' products and thus has an increasingly negative effect on the steady-state relative output of large firms Δ_2. Unpacking the Phillips curve into the two price-setting equations (21), a smaller revenue share for large firms implies larger fluctuations in the moving average of the relative price of large firms $\hat{d}_{2,t}$. Thus, as smaller values of ϵ_2 lower the real marginal cost elasticity of the prices of large firms, expected changes in their future relative prices become larger and contribute more to inflation dynamics from the perspective of large firms.

Panel (c) of Figure 4 shows the slope of the Phillips curve in the case of homogeneous strategic complementarity. The slope takes into account the productivity differential between small and large firms who all face the same value of the parameter governing the superelasticity of their demand $\epsilon_1 = \epsilon_2 = \bar{\epsilon}$, such that curvature is $\sigma = -\theta\bar{\epsilon}$. Smaller values $\bar{\epsilon}$ result in a smaller real marginal cost elasticity of prices for small and large firms alike. Hence the slope of the Phillips curve declines, regardless of which firm-size group has the largest revenue share. Panel (d) shows that smaller values $\bar{\epsilon}$ result in a lower revenue share of large firms, as the relative prices p_1^* and p_2^* shift in the presence of the productivity differential. A notable feature is that the lines in panels (c) and (d) are missing for values of $\bar{\epsilon}$ in the interval $(-0.58, 0)$, because no solution is found for the steady-state conditions (38)–(40). A larger difference in firm size increases the wedge between the steady-state relative prices p_1^* and p_2^*, as larger, more productive firms choose a lower price. With a productivity differential z_2 well above one, sufficient strategic complementarity is required to mitigate the price wedge and ensure that small and large firms can each have non-negative revenue shares.[22]

[21] The dashed line has a flat segment, which arises because the direct effect of ϵ_2 on the elasticity κ_2 is largely offset by its indirect effect through the steady-state relative reset price p_2^*. This observation is consistent with the result shown in panel (c) of Figure 2 that the cost elasticities are largely unaffected by the heterogeneity in strategic complementarity under the calibration of model parameters reported in tables 2 and 3.

[22] What matters is the interaction between firm size and strategic complementarity in price-setting. In the absence of the complementarity (i.e., $\epsilon_i = 0$ for all i) or heterogeneity in firm size (i.e., $z_i = 1$ for all i) the

In sum, Figure 4 reinforces the earlier finding that strategic complementarity is no longer a substantial source of real rigidity once heterogeneity by firm size is taken into account.

5 Concluding Remarks

This paper has presented new evidence based on survey data showing that large firms exhibit significantly less cost-price pass-through than small firms. The evidence complements other micro evidence showing that only large firms exhibit strategic complementarity in price-setting. To examine the implications of firm size for inflation dynamics, the paper has proposed a DSGE model with heterogeneity in firm size due to differences in productivity between firms and heterogeneity in strategic complementarity induced by a Kimball-type non-CES aggregator of differentiated goods. The model is calibrated to firm data from the U.S. Census and the calibration implies that larger firms exhibit stronger strategic complementarity. Heterogeneous strategic complementarity generates almost no increase in monetary non-neutrality in the calibrated model. The price-setting complementarity induces little real rigidity in relative prices because firms that exhibit strategic complementarity are expected to bring their product prices in line with those of firms who fully pass through cost changes.

Policy analysis at central banks relies on DSGE models that commonly embed strategic complementarity to induce real rigidity and generate plausible monetary non-neutrality. The paper has shown that the link between strategic complementarity and real rigidity is a fragile one that depends on the unrealistic simplifying assumption that firm size is irrelevant for price-setting. Hence we recommend that future research in DSGE models consider other sources of real rigidity. A shift in emphasis from so-called micro real rigidities such as strategic complementarity toward macro real rigidities such as real wage rigidities and the input-output structure of the economy may put DSGE models on a more robust footing.[23]

steady-state conditions (38)–(40) can be solved analytically.

[23] Rubbo (2023) examines implications of input-output linkages for the Phillips curve.

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