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# Sectoral heterogeneities in price rigidity and returns to scale

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# Sectoral Heterogeneities in Price Rigidity and Returns to Scale

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**Abstract**

Previous research on price-setting has shown that the degree of nominal price rigidity differs substantially across sectors. This paper proposes returns to scale as a key determinant of this sectoral heterogeneity in price rigidity. We develop a multi-sector menu cost model with heterogeneity in returns to scale and sectoral idiosyncratic shocks, and show analytically that a sector with higher returns to scale is associated with larger price rigidity. Numerical experiments using estimated returns to scale for US manufacturing sectors suggest that the effect of returns to scale is quantitatively large. We also provide empirical evidence consistent with the theoretical prediction.

**Keywords:** Menu costs, Sectoral heterogeneity, Price rigidity, Returns to scale
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# 1 Introduction

What explains the significant amount of heterogeneity in nominal price rigidity across sectors?[1] This paper considers this question using a multi-sector menu cost model where the degree of price rigidity is endogenized. Our main conclusion is that cross-sectoral differences in returns to scale are a key factor which shapes heterogeneity in price rigidity.

Our investigation on returns to scale as a possible determinant of sectoral heterogeneity in price rigidity is motivated by the following two observations. First, theory suggests that in the presence of menu costs (generic costs associated with nominal price adjustments), *returns to scale affect the degree of price rigidity*. To explain, Ball et al. (1988) highlight that when a firm's profit function is more concave and thus profits are more sensitive to the deviation of its price from the optimum, a firm has a larger incentive to pay menu costs and reset its price. Then, given that decreasing returns to scale make a profit function more concave than constant returns (Burstein and Hellwig (2007)), the degree of returns in general is expected to affect its incentive to adjust a price and thus the frequency of price changes.

Second, previous empirical evidence indicates that *returns to scale are different across sectors*. For example, Burnside (1996) shows that for the US manufacturing sector, the equality in returns to scale across its 20 sub-sectors is strongly rejected.[2] In line with this finding, Diewert et al. (2011) show that in Japan over 1964-88, the electrical machinery industry shows increasing returns to scale for most of the sample period, while the textiles industry tends to show decreasing returns to scale.[3] Thus, the above two observations, taken together, suggest that in the presence of menu costs, sectoral heterogeneity in returns to scale may contribute to the observed heterogeneity in price rigidity.

[1] Sectoral heterogeneity in price stickiness is an established fact, both for consumer and producer prices. See, for example, Carlton (1986), Bils and Klenow (2004), Klenow and Kryvtsov (2008), Nakamura and Steinsson (2008), Klenow and Malin (2011), and Vermeulen et al. (2012).

[2] Also, Basu and Fernald (1997), based on 34 US industries for the 1959-89 period, show that within manufacturing, durables show higher returns to scale than non-durables.

[3] In the Japanese context, Nakamura (1992) and Beason and Weinstein (1996) also find the heterogeneity in returns to scale across sectors.

To explore this possibility formally, we first develop a multi-sector menu cost model where sectors differ in returns to scale. Each sector consists of a large number of monopolistic firms. Firms in each sector are subject to an *ongoing* sector-specific productivity shock, and every period, after the shock is realized, a firm has an opportunity to adjust its price. When menu costs are absent, a firm *always* adjusts its price to the profit-maximizing price, which varies according to the realized value of the productivity shock. The price is fully flexible in this case. However, with menu costs present, a firm chooses *when* it pays menu costs and *what* new price to set, to maximize the present value of future profits net of menu costs. This means that not adjusting a price, i.e., inaction, can be an optimal decision. Our aim is to characterize how returns to scale, which differ across sectors, affect the optimal frequency of price changes.

To solve a monopolistic firm's problem with menu costs and ongoing shocks, we follow the approach of Alvarez and Lippi (2014), and map our optimisation problem onto an *impulse control* problem analyzed by Dixit (1991a). The solution of this problem consists of a *range* of the deviation of an actual price from the optimal price set in a flexible-price equilibrium (which follows a stochastic process): within this range a firm keeps its price, but when it deviates from the optimal price beyond the range, a firm pays menu costs and resets its price to the flexible-price optimum. Thus, the larger the range is, the less frequently the price adjustment occurs. The main analytical insight of our model is that the length of this range of inaction is *increasing* in returns to scale, implying that a firm in a sector with *higher* returns to scale changes its price *less* often. The intuition is that consistent with Burstein and Hellwig (2007), the profit function of a firm with higher returns to scale is less concave, making the firm less sensitive to mispricing. This way, theory predicts that there is a *positive* association between price rigidity and returns to scale across sectors.

Once we obtain the analytical result, we conduct numerical experiments to shed light on the quantitative importance of returns to scale as a determinant of sectoral heterogeneity in price rigidity. For this purpose, using the NBER-CES manufacturing industry database

(Bartelsman and Gray (1996)), and the multifactor productivity data from US Bureau of Labor Statistics (BLS), we first estimate returns to scale for each of the 447 6-digit US manufacturing sectors (according to North American Industry Classification System, NAICS) over the period of 1987-2011. Our reference estimate indicates that the average of returns to scale is 1.12 with the standard deviation of 0.25, suggesting that returns to scale are indeed heterogeneous across sectors. Then, using the calibrated theoretical model, we show that the contribution of cross-sectoral differences in returns to scale to sectoral heterogeneity in price rigidity is sizable. To illustrate, for the reference case considered, an increase in sectoral returns to scale from 0.87 (the estimated mean minus one standard deviation) to 1.12 (the mean) leads to a rise in the price rigidity measure (100 minus the monthly frequency of price changes, in percent) by 7 percentage points from 73% to 80%.

Last, we provide empirical evidence consistent with the theoretical prediction that there is a positive correlation between returns to scale and price rigidity across sectors. To do this, we first match the estimated returns to scale at the 6-digit manufacturing sector level with the frequency of changes in producer prices at the product category level estimated by Nakamura and Steinsson (2008). To highlight the association between returns to scale and price rigidity, we control for various factors which are known to contribute to the sectoral difference in price rigidity. Specifically, following the comprehensive study of Vermeulen et al. (2012) on the determinants of producer price rigidity at a sector level in the Euro area, we take account of sectoral differences in 1) labor and intermediate cost shares in production, 2) industry concentration ratio, and 3) sector-level average inflation rates. Using data on 200 6-digit manufacturing sectors matched with 275 product categories, we show that even after controlling for these factors, price rigidity and returns to scale are positively associated.

A number of papers have explored the question of what shapes the sectoral heterogeneity in nominal rigidities. For example, Peneva (2011) shows that labor cost share in production is positively related to price rigidity across sectors, possibly due to the predetermined nature of nominal wages. Also, earlier works of Carlton (1986) and Caucutt et al. (1999) show that the degree of industry concentration is positively associated with price rigidity, though Eckard (1982) finds that the association has the opposite sign. Vermeulen et al. (2012) show that in addition to factors such as the input cost structure and industry concentration, the level of sectoral inflation is also relevant.[4] This paper adds to this strand of the literature on nominal rigidities by proposing a new determinant of their sectoral heterogeneity in the shape of returns to scale.

This paper is also related to works which examine the macroeconomic outcomes of sectoral heterogeneity in nominal rigidities. For instance, Carvalho (2006), extending the time-dependent model of Calvo (1983), shows theoretically that the presence of sectoral heterogeneity in nominal price stickiness makes the size and persistence of the real effects of monetary shocks larger. Nakamura and Steinsson (2010) and Dixon and Kara (2011) also highlight the relevance of the sectoral heterogeneity in the investigation of monetary non-neutrality, by generalizing the state-dependent model of Golosov and Lucas (2007) and the time-dependent model of Taylor (1980), respectively.[5] The general message is thus that sectoral heterogeneity in nominal rigidities has an important implication on the non-neutrality of money. This paper complements these works by investigating the source of heterogeneity in price rigidity, rather than its outcome.

The rest of this paper is organized as follows. Section 2 presents the theoretical model, and Section 3 derives an analytical solution. Section 4 estimates returns to scale for US manufacturing sub-sectors, and conducts a calibration exercise. Section 5 offers an empirical evidence in support of theory. Section 6 gives concluding remarks.

[4]Regarding other possible determinants, Caucutt et al. (1999) show that goods durability is positively related to rigidity,. Further, Bils and Klenow (2004) and Klenow and Malin (2011) highlight that raw goods exhibit higher price flexibility since they are more prone to volatile cost shocks.

[5]Further, Bouakez et al. (2009) show that the interaction between sectoral heterogeneities in price stickiness and input-output structure plays an important role in the monetary transmission mechanism. They model nominal rigidity using the price adjustment costs of Rotemberg (1982).

# 2 The model

## 2.1 Households

The preference of the representative household is given as

$$\int_0^\infty e^{-\rho t}\left[\log C_t + \kappa \log \frac{M_t}{P_t} - \alpha \int_0^1 f(k) \int_0^1 \frac{L_{kj,t}^\gamma}{\gamma} dj dk\right] dt. \tag{1}$$

The economy is divided into numerous sectors, and each sector is populated with a large number of firms. Sectors are indexed by $k \in [0;1]$, with a density function $f(k)$ summarizing the distribution of sectors, and within sector $k$, firms are indexed by $j \in [0;1]$. The representative household consumes the composite of differentiated goods produced by all the firms in the economy. Within the instantaneous utility function, $C_t$ is the composite consumption at time $t$. Money enters the model through the money-in-utility approach: utility increases in transaction services brought by real money balances, $M_t/P_t$. The household supplies labor to all the firms, reducing utility due to the loss of leisure time: $L_{kj,t}$ is labor supply to firm $j$ in sector $k$, and $\gamma$ equals $1 + \frac{1}{\nu}$, where $\nu$ is the Frisch elasticity of labor supply. $\rho$ is the discount rate. This utility function is similar to Carvalho (2006), who studies the role of sectoral heterogeneity in price rigidity in the output effects of money supply.[6]

Assuming a constant elasticity of substitution, $\varepsilon$, $C_t$ is given as

$$C_t = \left[\int_0^1 f(k)^{1/\varepsilon} A_{k,t}^{1/\varepsilon} C_{k,t}^{(\varepsilon-1)/\varepsilon} dk\right]^{\varepsilon/(\varepsilon-1)}, \tag{2}$$

where $C_{k,t} = f(k)\left[\int_0^1 C_{kj,t}^{(\varepsilon-1)/\varepsilon} dj\right]^{\varepsilon/(\varepsilon-1)}$. $C_{k,t}$ is the sector-level composite consumption, and $C_{kj,t}$ is the consumption of a differentiated good produced by firm $j$ in sector $k$ (firm $kj$ in short). $A_{k,t}$ is a sector-specific preference shock. At each (infinitesimally short) period $t$, households solve an intra-temporal problem where they maximize $C_t$ for a given level of

[6]The differences from Carvalho (2006) are that in our model, 1) the time is continuous (instead of discrete), 2) the consumption component takes a log (instead of constant-relative-risk-aversion) form, and 3) real money balances enter the utility function (instead of assuming a cashless economy).

income. The solution yields the downward-sloping demand curve for a good produced by firm $kj$:

$$C_{kj,t} = A_{k,t}\left(\frac{P_{kj,t}}{P_t}\right)^{-\varepsilon} C_t.^{7} \tag{3}$$

$P_{kj,t}$ is the price of good $j$ in sector $k$, and aggregate price index, $P_t$ is defined as

$$P_t = \left[\int_0^1 A_{k,t} f(k) P_{k,t}^{1-\varepsilon} dk\right]^{\frac{1}{1-\varepsilon}}, \tag{4}$$

where $P_{k,t} = \left[\int_0^1 P_{kj,t}^{1-\varepsilon} dj\right]^{\frac{1}{1-\varepsilon}}$. $P_t$ ($P_{k,t}$) is interpretable as the minimum expenditure necessary to obtain one unit of composite consumption, $C_t$ (sectoral composite consumption, $C_{k,t}$).

Turning to the inter-temporal problem, the household maximizes the utility subject to the following budget constraint:

$$P_t C_t + \dot{M}_t + \dot{B}_t = i_t B_t + \int_0^1 f(k) \int_0^1 W_{kj,t} L_{kj,t} dj dk + \Pi_t, \tag{5}$$

which says that the sum of nominal consumption, $P_t C_t$, a rise in money holding, $\dot{M}_t$, and a rise in nominal bond holdings, $\dot{B}_t$ is financed by the sum of nominal net earning from holding bond, $i_t B_t$ ($i_t$ is the nominal net interest rate), the integral of nominal wage, $W_{kj,t}$ paid by firm $kj$, and nominal profit, $\Pi_t$ from being a shareholder of monopolistic firms. The first order conditions yield the Euler equation of allocation of consumption over time (Eq.6), money demand function representing the equality between nominal interest rate and the marginal rate of substitution (MRS) between consumption and real money balances. (Eq.7), and the labor supply function (Eq.8) indicating the equality between the real wage and the MRS between consumption and leisure:

$$\frac{\dot{C}_t}{C_t} = i_t - \frac{\dot{P}_t}{P_t} - \rho \tag{6}$$

[7]This can be obtained by dividing the intra-temporal problem into the two stages: one is to maximize $C_{k,t}$ by allocating given income among $C_{kj,t}$, and another is to maximize $C_t$ by allocating given income among $C_{k,t}$. Solving the former yields $C_{kj,t} = f(k)^{-1}(P_{kj,t}/P_{k,t})^{-\varepsilon} C_{k,t}$, and solving the latter gives $C_{k,t} = f(k) A_{k,t}(P_{k,t}/P_t)^{-\varepsilon} C_t$. Combining these leads to Eq.3.

$$\frac{M_t}{P_t} = \kappa \frac{C_t}{i_t} \tag{7}$$

$$\frac{W_{kj,t}}{P_t} = \alpha C_t L_{kj,t}^{\gamma-1} \tag{8}$$

## 2.2 Firms

Each firm is a monopolistic competitor, facing the downward sloping demand curve (Eq. 3). To produce a differentiated good, firm $kj$ (firm $j$ in sector $k$) uses labor as a sole input. Returns to scale differ across sectors, with the distribution characterized by the density function $f(k)$. Firms in each sector $k$ are subject to sector-specific productivity shocks, $Z_{k,t}$ which follow the exponential of independent Brownian motions. This way of modeling idiosyncratic shocks is similar to Alvarez and Lippi (2014).[8] Formally, the production function of firm $kj$ is given as:

$$Y_{kj,t} = Z_{k,t} L_{kj,t}^{\psi_k}, \tag{9}$$

where $\psi_k$ is the degree of returns to scale in sector $k$, and $Z_{k,t}$ is modeled as:

$$Z_{k,t} = e^{\sigma x_{k,t}}, \tag{10}$$

where $x_{k,t}(k \in [0,1])$ follows standard Brownian motion, so that $\sigma$ reflects the size of volatility of the sector-specific shock.[9]

Every period, after sector-specific shocks are realized, a firm chooses whether or not to change its nominal price. However, changing the price requires the firm to pay menu costs,

[8] The difference is that they model idiosyncratic shocks across firms and products (they model a multi-product firm), whereas we model idiosyncratic shocks across sectors (firms within the same sector are subject to the same shocks).

[9] Standard Brownian motion is a stochastic process $W = (W_t, t \in [0, \infty))$ characterized by the following conditions (Mikosch (1998)): (1) It starts at zero: $W_0 = 0$; (2) It has stationary, independent increments. (Stationary increments means that $W_t - W_s$ and $W_{t+h} - W_{s+h}$ have the same distribution; Independent increments means that for every choice of $t_i$ with $t_1 < ... < t_n$ and $n \geq 1$, $W_{t_2} - W_{t_1}$, ..., $W_{t_n} - W_{t_{n-1}}$ are independent random variables.); (3) For every $t > 0$, $W_t$ has a normal N(0, t) distribution; (4) It has continuous sample paths: no jumps.

generic costs associated with nominal price adjustments.[10] In what follows, we consider two alternative ways of modeling menu costs paid by firm $kj$ in period $t$, $F_{kj,t}$. The first is to assume that $F_{kj,t}$ equals the fixed fraction, $\varphi$ of the firm's real revenue in the flexible-price equilibrium (i.e., equilibrium in the absence of menu costs), $r^*_{kj,t}$:

$$F_{kj,t} = \varphi\, r^*_{kj,t}. \tag{11}$$

The second is to assume that menu costs are a fixed fraction $\zeta$ of real profits in the flexible-price equilibrium: $F_{kj,t} = \zeta\, \pi^*_{kj,t}$. While both approaches are used in the literature, because a number of empirical studies on menu costs (e.g., Levy et al. (1997), Zbaracki et al. (2004) and Stella (2014)) estimate the magnitude of menu cost as a fraction of the revenue, we prefer the first approach in the light of subsequent calibration of the model.[11]

# 3 Analysis

## 3.1 Pricing decisions without menu costs

We first examine a firm's pricing behavior when menu costs are zero ($\varphi = 0$). In this case, every period, after sector-specific shocks are realized, firm $kj$ resets its price to maximize its real profits in period $t$, $\pi_{kj,t}$:

$$\pi_{kj,t} = \frac{P_{kj,t}}{P_t} Y_{kj,t} - \frac{W_{kj,t}}{P_t} L_{kj,t}. \tag{12}$$

[10] As often indicated, the term "menu costs" may be misleading, in that the material costs of printing menus and catalogs do not appear to be the most important barrier to price flexibility. What could be more important include, for example, wages to hire employees to change the price tags (Levy et al. (1997)) and the cost of computing the nominal price changes corresponding to desired, ideal real price changes (Ball et al. (1988)).

[11] For instance, Midrigan (2011) models menu costs as a fraction of (steady-state) revenue, while Alvarez and Lippi (2014) models as a fraction of profit.

Incorporating resource constraint, $Y_{kj,t} = C_{kj,t}$, demand function (Eq.3), labor supply function (Eq.8) and production function (Eq.9), we rewrite $\pi_{kj,t}$ as a function of $P_{kj,t}$:

$$\pi_{kj,t} = A_{k,t}\left(\frac{P_{kj,t}}{P_t}\right)^{1-\varepsilon} C_t - \alpha(A_{k,t}Z_{k,t}^{-1})^{\frac{\gamma}{\psi_k}}\left(\frac{P_{kj,t}}{P_t}\right)^{-\frac{\varepsilon\gamma}{\psi_k}} C_t^{1+\frac{\gamma}{\psi_k}}, \tag{13}$$

where $A_{k,t}$ and $Z_{k,t}$ are sectoral shocks, and a firm takes the aggregate variables, $P_t$ and $C_t$ as given. To ensure that this profit function remains concave, we introduce the following upper bound to the degree of return to scale (see Appendix A for derivation):

$$\psi^{max} = \frac{\varepsilon\gamma}{\varepsilon - 1}.\text{[12]} \tag{14}$$

Note also that setting this upper bound ensures that profit is positive: $\pi_{kj,t} > 0$.[13]

Following Alvarez and Lippi (2014), we assume that the sectoral preference shock, $A_{k,t}$ and productivity shock, $Z_{k,t}$ are negatively related: $A_{k,t}Z_{k,t}^{\varepsilon-1} = 1$. This assumption is necessary to solve the model analytically in the presence of menu costs.[14] Differentiating Eq.13 with respect to $P_{kj,t}$ then yields the following optimal relative price:

$$\frac{P^*_{kj,t}}{P_t} = \frac{1}{Z_{k,t}}\left[\frac{\alpha\gamma}{\psi_k}\frac{\varepsilon}{\varepsilon-1}C_t^{\frac{\gamma}{\psi_k}}\right]^{\frac{1}{1-\varepsilon+\frac{\varepsilon\gamma}{\psi_k}}}. \tag{15}$$

[12]This theoretical upper bound is not so restrictive in the light of an empirical estimate of returns to scale. For example, when $\varepsilon = 4$ and $\nu = 3$ (reasonable values for the elasticity of substitution and Frisch elasticity of labor supply), $\psi^{max} = 1.78$, which is above the value of returns to scale estimated below (Table 1).

[13]This is seen as follows. First, it can be shown that (average cost)/(marginal cost) = $\psi_k/\gamma$. Next, positive profit requires price being larger than average cost, which means that $(\varepsilon/(\varepsilon-1))$*(marginal cost)>(average cost). Combining the two observations, we know that profits are positive when $\psi_k < \psi^{max}$.

[14]As explained below, this assumption ensures that the stock variable of price gap, defined as the deviation of current price from the optimal price in the flexible price equilibrium, follows Brownian motion. Although this assumption is for simplification, it can still be justified as follows. Suppose that there is a *rise* in preference term, $A_{k,t}$. What this does is to shift the demand curve to the right (see Eq.3) for sector $k$, which, in turn, tends to push up the optimal price for a given level of production in this sector. Meanwhile, a *fall* in productivity term, $Z_{k,t}$ makes production in sector $k$ less efficient for a given input (Eq.9), which in turn tends to push up marginal costs and thus the optimal price for this sector. Thus, in essence, a rise in $A_{k,t}$ and a fall of $Z_{k,t}$ have a similar effect on firm's pricing behavior, justifying the negative association between these two sector-specific shocks.

Firm $kj$ sets its real price as the markup, $\varepsilon/(\varepsilon-1)$ over real marginal costs.[15] Notice that the optimal price depends not only on aggregate consumption, $C_t$, but also on the sector-specific shock, $Z_{k,t}$, which follows a stochastic process in the form of the exponential of Brownian motion (Eq.10).

In Eq.15, aggregate consumption, $C_t$ can be tied down by using the price index, $P_t$ (Eq.4):

$$\int_0^1 f(k)\left[\frac{\alpha\gamma}{\psi_k}\frac{\varepsilon}{\varepsilon-1}(C_t^*)^{\frac{\gamma}{\psi_k}}\right]^{\frac{1-\varepsilon}{1-\varepsilon+\frac{\varepsilon\gamma}{\psi_k}}} dk = 1, \tag{16}$$

where $C_t^*$ denotes aggregate consumption in the flexible-price equilibrium. Notice that this is time-invariant: $C_t^* = \bar{C}$, where $\bar{C}$ indicates the steady-state value.[16] In general, there is no closed-form solution for $\bar{C}$. However, to illustrate, when sectoral heterogeneity in returns to scale is absent (i.e., $\psi_k = \psi$), Eq.16 yields:

$$\bar{C} = \left[\frac{\psi}{\alpha\gamma}\frac{\varepsilon-1}{\varepsilon}\right]^{\frac{\psi}{\gamma}}.\text{[17]} \tag{17}$$

For later reference, we show that in the flexible-price equilibrium, firm $kj$'s real revenue, $r_{kj,t}^*(= P_{kj,t}^* Y_{kj,t}^*/P_t^*)$ is time-invariant: $r_{kj,t}^* = \bar{r}_{kj}$. This, in turn, means that when menu costs are modeled as a fraction of real revenue (Eq.11), menu costs paid by the firm, $F_{kj,t}$ are also time-invariant:

$$F_{kj,t} = \varphi\, \bar{r}_{kj}, \tag{18}$$

where

$$\bar{r}_{kj} = \left[\frac{\alpha\varepsilon\gamma}{\psi_k(\varepsilon-1)}\right]^{\frac{\psi_k(1-\varepsilon)}{\psi_k(1-\varepsilon)+\varepsilon\gamma}} \bar{C}^{\frac{(1-\varepsilon)\psi_k+\gamma}{\psi_k(1-\varepsilon)+\varepsilon\gamma}}.$$

[15] For example, in the case where production exhibits constant returns to scale in sector $k$ ($\psi_k = 1$), and labor supply affects utility linearly ($\gamma = 1$), Eq.15 reduces to $P_{kj,t}^*/P_t = (\varepsilon/(\varepsilon-1))(\alpha C_t/Z_{k,t})$, where $\alpha C_t/Z_{k,t}$ is real marginal cost, given as real wage divided by sectoral productivity.

[16] The resource constraint ($Y_t = C_t$) indicates that flexible-price equilibrium aggregate output is also constant: $Y_t^* = \bar{Y}$.

[17] This says that aggregate consumption (and output) increases in returns to scale, $\psi$, the elasticity of substitution, $\varepsilon$, and labor supply elasticity, $\nu$ ($\gamma = 1 + 1/\nu$), and decreases in the weight on leisure in the utility function, $\alpha$.

Likewise, real profits are time-invariant in the flexible-price equilibrium, so that even when menu costs are modeled as a fraction of real profits, they are constant: $F_{kj,t} = \zeta\, \bar{\pi}_{kj}$.

## 3.2 Introducing menu costs

When menu costs are present, inaction (not adjusting a price) can be optimal. Specifically, to maximize the present value of future profits net of menu costs, a firm chooses *when* it pays menu costs and *what* new price to set, rather than adjusting its price every period.

To formalize this optimization problem, we follow the approach of Alvarez and Lippi (2014), who develop a menu cost model to examine the pricing decision of a multi-product firm.[18] The approach constitutes the two main steps: 1) expressing firm's profits as a function of the deviation of actual price from the optimal price set under flexible-price equilibrium, called a price gap, and 2) applying a second-order Taylor approximation to a profit function to simplify it to a symmetric, quadratic function. The key advantage of taking this approach is that once acknowledging that a price gap follows Brownian motion, the problem maps onto a type of impulse control problem which is solved *analytically* by Dixit (1991a).[19] This analytical solution gives us a clear understanding of the role of returns to scale as a determinant of of price rigidity.

The first step is to obtain firm $kj$'s real profits, $\pi_{kj,t}$ as a function of a price gap, $\hat{p}_{kj,t}$, defined as the log deviation of its current price, $P_{kj,t}$ from the optimal price, $P^*_{kj,t}$:

$$\hat{p}_{kj,t} = log(P_{kj,t}) - log(P^*_{kj,t}).$$

[18]Unlike Alvarez and Lippi (2014), our focus is the pricing decision of a single-product firm, with the innovation of heterogeneity in returns to scale across sectors.

[19]As explained by Dixit (1991b), an impulse control problem is characterized by 1) the state variable following a Brownian motion, and 2) a lump-sum payment needed to move the state variable. In our context, the state variable is a price gap, and menu costs are the lump-sum payment. In general, solving this problem corresponds to finding the optimal range of $(s,\, r)$ and interior points of $S$ and $R$, whereby once the state variable hits the boundaries of $s$ and $r$, it is moved to $S$ and $R$ with costs, respectively. However, as seen below, once the above approach is taken, solving the problem for a firm in sector $k$ reduces to finding the optimal range of $(h_k,\, -h_k)$, with the interior point of zero: there is only one value, $h_k$ to tie down.

Substituting Eq.15 into Eq.13 (and using $P_{kj,t}/P_t = (P_{kj,t}/P^*_{kj,t})(P^*_{kj,t}/P_t))$ yields $\pi_{kj,t} = \pi(\hat{p}_{kj,t}, C_t)$.[20] Then, the time 0 problem of firm $kj$ that starts with a price gap, $\hat{p}_{kj,0} = \hat{p}_{kj}$ is to choose $\{\boldsymbol{\tau}, \triangle\hat{\boldsymbol{p}}_{\boldsymbol{kj}}\} \equiv \{\tau_i, \triangle\hat{p}_{kj}(\tau_i)\}_{i=1}^{\infty}$, where $(\tau_i)_{i\in 1,2,\ldots}$ is a set of periods when the firm incurs menu costs, and $\triangle\hat{p}_{kj}(\tau_i)$ is a change made to the price gap at time $\tau_i$. Formally, the firm's problem is written as:

$$V(\hat{p}_{kj}) = \max_{\boldsymbol{\tau}, \triangle\hat{\boldsymbol{p}}_{\boldsymbol{kj}}} \boldsymbol{E}\bigg[\int_0^{\infty} e^{-\rho t}\pi(\hat{p}_{kj,t}, C_t)dt - \sum_{i=1}^{\infty} e^{-\rho\tau_i} F_{kj,\tau_i} \ \mid\ \hat{p}_{kj,0} = \hat{p}_{kj}\bigg], \tag{19}$$

where the first term in the objective function is the present value of real profits, and the second term is the present value of menu costs in real terms. Notice that considering the case where menu costs are a fraction of flexible-price equilibrium revenue, and realizing that menu costs are time-invariant (Eq.18), $\bar{r}_{kj}$ can be factored out from the objective function of Eq.19, yielding:

$$V(\hat{p}_{kj}) = \bar{r}_{kj} \max_{\boldsymbol{\tau}, \triangle\hat{\boldsymbol{p}}_{\boldsymbol{kj}}} \boldsymbol{E}\bigg[\int_0^{\infty} e^{-\rho t} g(\hat{p}_{kj,t}, C_t)dt - \sum_{i=1}^{\infty} \varphi\, e^{-\rho\tau_i} \ \mid\ \hat{p}_{kj,0} = \hat{p}_{kj}\bigg], \tag{20}$$

where $g(\hat{p}_{kj,t}, C_t)(= \pi(\hat{p}_{kj,t}, C_t)/\bar{r}_{kj})$ is firm $kj$'s profits scaled by the flexible-price equilibrium revenue.

The second step is to apply a second-order Taylor approximation to the scaled profit function, $g(\hat{p}_{kj,t}, C_t)$. Approximating it around the flexible-price equilibrium of $g(0, \bar{C})$ gives the following *minimization* problem (Appendix B for derivation):

$$V(\hat{p}_{kj}) = \min_{\boldsymbol{\tau}, \triangle\hat{\boldsymbol{p}}_{\boldsymbol{kj}}} \mathbf{E}\bigg[\int_0^{\infty} S_k\, \hat{p}^2_{kj,t}\, e^{-\rho t}dt + \sum_{i=1}^{\infty} \varphi\, e^{-\rho\tau_i} \ \mid\ \hat{p}_{kj,0} = \hat{p}_{kj}\bigg], \tag{21}$$

where

$$S_k = \frac{1}{2}(\varepsilon - 1)(1 - \varepsilon + \frac{\varepsilon\gamma}{\psi_k}) > 0. \tag{22}$$

[20] The exact expression of $\pi(\hat{p}_{kj,t}, C_t)$ is shown in Appendix B.

The coefficient on the price gap squared, $S_k$ is always positive (due to the existence of the upper-bound threshold $\psi^{max}$, Eq.14), and captures how firm $kj$'s profit loss is sensitive to the deviation of an actual price from the optimal price. The key insight here is that $S_k$ is decreasing in return to scale, $\psi_k$:

$$\frac{\partial S_k}{\partial \psi_k} < 0. \tag{23}$$

This indicates that in a sector with *higher* returns to scale, firm's profits are *less sensitive* to a price misalignment, measured by the gap between its current and optimal prices. In other words, a profit function is less concave at the top when returns to scale are higher. To report, even when menu costs are modeled as a fraction of flexible-price equilibrium profits (instead of revenue), the insight remains the same.[21]

To solve Eq.21, observe that under the assumption that money supply is constant ($M_t = \bar{M}$), a price gap follows Brownian motion: $d\hat{p}_{kj,t} = \sigma\, dx_{k,t}$, where $x_{k,t}$ is standard Brownian motion (Appendix C for the proof).[22] Intuitively, a price gap inherits Brownian motion from the idiosyncratic productivity shock, $Z_{k,t}$, through its effect on the optimal price, $P^*_{kj,t}$ (Eq.15). It is thus the case that Eq.21 is an impulse control problem, characterized by 1) a price gap (state variable) following Brownian motion, 2) a time-invariant cost needed to move a price gap, and 3) the quadratic loss function being symmetric. This problem directly maps onto a type of impulse control problem solved *analytically* by Dixit (1991a) in the context of a menu costs model.[23] The key difference, however, is that since our model is micro-founded (unlike his model), the curvature of the profit function is affected by a composite of micro parameters, including returns to scale.[24]

[21]When $F_{kj,t} = \zeta\, \bar{\pi}_{kj}$, the only difference made to Eq.21 is that $S_k$ equals $(1/2)(\varepsilon - 1)(\varepsilon\gamma/\psi_k)$, and $\zeta$ replaces $\varphi$.

[22]This is where the negative association between the preference shock and productivity shock, $A_{k,t}Z^{\varepsilon-1}_{k,t} = 1$ plays a key role. Without this assumption, a price gap does *not* follow Brownian motion, which in turn indicates that a firm's optimization problem is not solvable analytically.

[23]Compare Eq.21 with Eq.3 on page 142 of his paper.

[24]Dixit (1991a) directly postulates a loss function without modeling a firm's problem explicitly.

### 3.3 Analytical results

As explained by Dixit (1991a), solving this problem corresponds to determining the range of a price gap in which no action, i.e., keeping the current price, is optimal. In particular, because in Eq.21 the loss function is symmetric with the central value of zero (corresponding to the price gap of zero), the solution to the problem consists of a range of price gap $(h_k, -h_k)$ within which a firm in sector $k$ does not to change its price: only when the stochastic process of a price gap hits the boundaries of either $h_k$ and $-h_k$, a firm $kj$ pays menu costs and reset its price gap to zero. Acknowledging this, the value of this threshold value, $h_k$ can be tied town analytically, by taking account of the following two conditions: the Value Matching Condition ($V(h_k) - V(0) = \varphi$) and the Smooth Pasting Condition ($V^{'}(h_k) = 0$).[25] These conditions lead to the following proposition regarding the determinants of the threshold value $h_k$.

**Proposition 1.** *A firm in sector $k$ chooses to adjust its price to the optimal, frictionless price $P^*_{kj,t}$ whenever the absolute value of the price gap, $|\hat{p}_{kj,t}|$ reaches $h_k$:*

$$h_k = \left(\frac{6\sigma^2\varphi}{S_k}\right)^{1/4}. \tag{24}$$[26]

With menu costs present ($\varphi > 0$), the range of inaction exists (i.e., $h_k > 0$). This implies that a firm may not reset its price every period, because a price gap (which follows Brownian motion) may not hit the boundaries of $h_k$ or $-h_k$ for some periods. Importantly, the range of inaction is an *increasing* function of the returns to scale, i.e., $\partial h_k/\partial \psi_k > 0$ (due to Eq.23: $\partial S_k/\partial \psi_k < 0$). This means that a firm belonging to a sector characterized by higher returns

[25]Details of the solution of this impulse control problem is found in Dixit (1991a).

[26]To be exact, the analytical expression of $h_k$ is based on an approximation. Following Eq.9 and Eq.12 in Dixit (1991a), this approximation is valid if $\delta_k = (2\rho/\sigma^2)^{1/2}h_k$ is sufficiently small so that $\delta_k^5/120$ ($\delta_k^6/720$) is negligible compared to $\delta_k^3/6$ ($\delta_k^4/24$). Using the estimated and calibrated values considered in the subsequent numerical experiments, we report that these conditions are satisfied. Specifically, the highest value of $\delta_k$ is 0.44, corresponding to the highest estimated value of returns to scale below, $\psi_k = 1.76$, combined with the following set of parameters: $\sigma = 0.03$, $\varepsilon = 4$, $\gamma = 4/3$, and $\rho = 0.0025$. In this case, $\delta_k^5/120 = 0.00014$ ($\delta_k^6/720 = 0.00001$) being negligible compared to $\delta^3/6 = 0.0143$ ($\delta_k^4/24 = 0.00157$).

to scale chooses to reset its current price *only when* it deviates from the optimal price by a *larger* margin.

The next proposition highlights the role of returns to scale in the expected duration of inaction, i.e., the duration for which a firm chooses to keep the current price (see Appendix D for proof).

**Proposition 2.** *The expected duration of inaction of a firm in sector $k$, $D_k$ is given as:*

$$D_k = \frac{h_k^2}{\sigma^2} = \left(\frac{6\varphi}{\sigma^2 S_k}\right)^{1/2}, \tag{25}$$

*so that $D_k$ is an increasing function of sectoral returns to scale $\psi_k$: $\partial D_k/\partial \psi_k > 0$.*

This result is explained by the observation that higher returns to scale make a profit function less concave. Intuitively, when firms characterized by higher returns to scale are less sensitive to price misalignments, they reset prices less frequently. Also, it is worth noting that as the menu cost parameter, $\varphi$ rises or the volatility of sector-specific shocks, $\sigma$ falls, the expected duration of inaction becomes longer.

For completeness, the next corollary gives the conversion of the expected duration of inaction, $D_k$ into the per-period probability of a firm in sector $k$ keeping the same price, i.e., a direct measure of price stickiness.

**Corollary 1.** *The per-period probability of a firm in sector $k$ keeping the same price, the measure of price rigidity, $\chi_k$ is given as:*

$$\chi_k = e^{-\frac{1}{D_k}}, \tag{26}$$

*so that $\chi_k$ is an increasing function of $\psi_k$: $\partial \chi_k/\partial \psi_k > 0$.*

Thus, the key prediction of the model is that returns to scale and price rigidity are positively correlated across sectors. As pointed out, this is primarily because higher returns to scale make firms less sensitive to price misalignments. Incidentally, larger price stickiness is associated with higher menu costs and lower volatility of sectoral shocks.

# 4 Numerical Experiments

## 4.1 Estimation of returns to scale

Having formalized how sectoral heterogeneity in returns to scale may contribute to the heterogeneity in nominal price rigidity, we now aim to shed light on its quantitative relevance. For this purpose, this section first estimates returns to scale across US manufacturing sectors. However, at the outset, we admit that it is not our intention to claim that our estimates are without issues. This is because as noted by Diewert et al. (2011), there are in general different possible sources of erroneous estimates of returns to scale, and it is difficult to address them. For example, Basu and Fernald (1997) show that the estimates of returns to scale are likely to be upward biased when data is aggregated over firms[27]. Although we use data on highly disaggregated (6-digit) sectors, this issue is likely to remain. Further, as previous papers indicate (e.g., Basu and Fernald (1997) and Diewert and Fox (2008)), instruments commonly used in the estimation of returns to scale, such as government defense spending and world oil prices, tend to be weak, which we confirm in the context of our estimations.[28]

With the above caveats, our estimation methodology follows the one initiated by Hall (1990) and extended by Basu and Fernald (1997), who propose to estimate returns to scale following a cost minimization problem in the presence of non-constant returns to scale and imperfect competition. The methodology involves regressing sector by sector the output growth on the cost share-weighted average of inputs growth. Formally, the regression equation

[27]This is what they called the aggregation bias, namely the fact that the higher is the aggregation level, the more upward biased the estimates are likely to be. A natural way to dampen this bias is therefore to use the lowest aggregation level possible (in our case the 6-digit manufacturing level).

[28]Ideally, to solve the endogeneity issue, we would want to have instrument sets with sector-specific components, but when considering highly disaggregated sectors, finding such instruments appears to be particularly difficult.

is given as:

$$\Delta Y_{k,t} = \alpha_k + \psi_k \Delta X_{k,t} + \varepsilon_{k,t}, \tag{27}$$

where $k$ and $t$ denote sector and time. The dependent variable, $\Delta Y_{k,t}$ is the growth rate of real gross output, and the independent variable, $\Delta X_{k,t}$ is the average of growth rates of different inputs, weighted by the shares of those input costs in the total cost, and $\varepsilon_{k,t}$ is the error term. The coefficient, $\psi_k$ represents the returns to scale of sector $k$.

As for data, we use the NBER-CES manufacturing industry database (Bartelsman and Gray (1996)), which gathers information on output and various inputs for 473 manufacturing sectors defined at the 6-digit level of North American Industry Classification System (NAICS) codes, at annual frequency over the 1958-2011 period.[29,30] The database covers capital, labor and intermediate inputs in real terms for each of the 473 sectors.[31] Because it does not provide data on the cost share of each input in the total cost, we merge it with the data on multifactor productivity provided by US Bureau of Labor Statistics (BLS).[32] Subsequently, the weighted average of input growth, $\Delta X_{k,t}$ in Eq.27 becomes:

$$\Delta X_{k,t} = c^K_{k,t} \Delta K_{k,t} + c^L_{k,t} \Delta L_{i,t} + c^M_{k,t} \Delta M_{i,t} \quad \text{with} \quad c^K_{k,t} + c^L_{k,t} + c^M_{k,t} = 1, \tag{28}$$

where $\Delta K_{k,t}$ ($\Delta L_{k,t}$, $\Delta M_{k,t}$) and $c^K_{k,t}$ ($c^L_{k,t}$, $c^M_{k,t}$) are the growth rates and cost share of capital (labor and intermediate inputs) in sector $k$ in year $t$. After the two databases are merged, the sample period becomes 1987-2011, still covering 473 sectors.

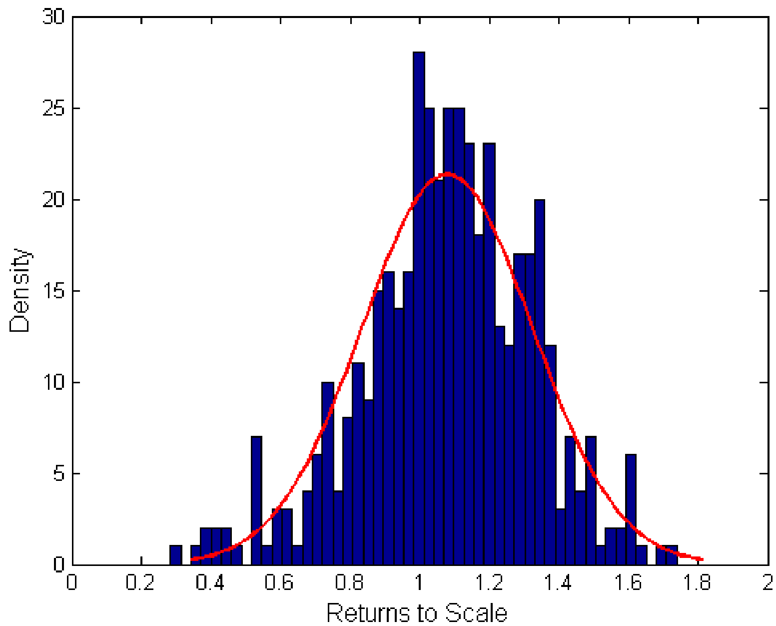
[29]The dataset is available at http://www.nber.org/nberces/. Most of the variables covered by this dataset are taken from the ASM (Annual Survey of Manufacturing), which in turn gathers more than 50,000 firms selected from the 350,000 firms from the CMF (Census of Manufacturing). This database follows the 1997 NAICS. (The classification system has been updated every five years since the introduction in NAICS in 1997. For more details, visit https://www.census.gov/eos/www/naics/.)

[30]Many of the previous empirical works on returns to scale (including Basu and Fernald (1997) and Diewert and Fox (2008)) use less disaggregated, two-digit level of Standard Industrial Classification (SIC) codes. (NAICS was established in 1997 to replace the SIC system which has not been updated since 1987.)

[31]Intermediate input is a composite of materials, energy and purchases services.

[32]Specifically, the data on the multifactor productivity (which contains data on the cost structure) are assembled by the Division of Industry Productivity Studies (DIPS) in the office of Productivity and Technology at BLS. The data is available at https://www.bls.gov/mfp/#data. When data on the cost structure for 6-digit sectors are not available, we use data at the corresponding 5-, or 4-digit level (with the preference given to the former).

Figure 1: Distribution of Returns to scale across 6-digits sectors




Note: Histogram of returns to scale across 6-digit US manufacturing sub-sectors (2 outliers are excluded). A normal distribution is fitted to the histogram. Source: Authors' calculation using NBER-CES Manufacturing Industry and BLS Multifactor Productivity databases

We estimate Eq.27 sector by sector, using Ordinary Least Squares (OLS). Figure 1 presents the distribution of returns to scale across 447 out of the 473 sectors, for which $\psi_k$ is positive and significant at the 5 percent level.[33] The average is 1.12 and the standard deviation is 0.25, with the maximum (minimum) of 1.76 (0.27).[34] The distribution is approximately bell-shaped, as indicated by the a normal distribution fitted to the histogram. Out of the 447 sectors, 112 (20) sectors exhibit increasing (decreasing) returns to scale, with $\psi_k$ significantly larger (smaller) than 1 at the 5 percent level: the remaining 315 sectors show constant returns to scale.

[33] The figure excludes 2 clear outliers, which are $\psi_k = 2.83$ and $\psi_k = 5.26$.

[34] The maximum point estimate of 1.76 is observed for "electronic coil, transformer, and other inductor manufacturing (NAICS code, 334416)", while the minimum estimate of 0.27 is observed for "flour milling (311211)".

To report, in the view of possible endogeneity issues, we also estimated using instrumental variables (IV) estimator. In particular, following works such as Hall (1990) and Basu and Fernald (1997), we used military spending (relative to GDP), world oil prices, and the political party of the president as possible instruments. However, we found that for the majority of the sectors, these instruments are weak, not having a strong correlation with the regressor. Therefore, because the use of a weak instrumental variable can lead to substantial bias, the following analysis uses the OLS estimates. Basu and Fernald (1997) and Diewert and Fox (2008) also prefer OLS estimates of returns to scale to IV estimates, on the basis of weak instruments.

## 4.2 Numerical results

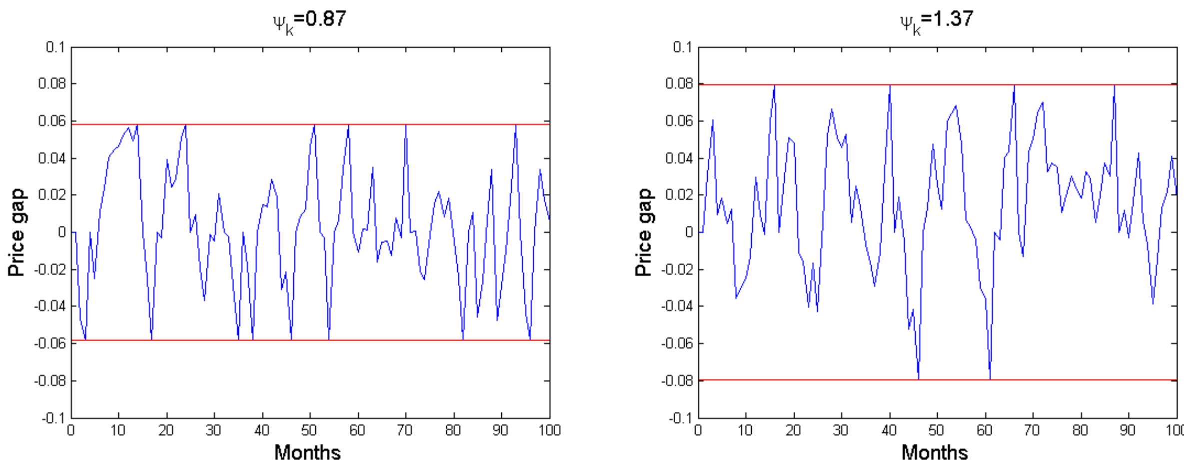
Having estimated returns to scale at the sectoral level, we present numerical results using the theoretical model. As for the proportion of menu costs in firm's revenue (Eq.11), we use $\varphi = 0.01$ as a reference parameter value. This choice is based on the estimates of menu costs in previous empirical studies, which range from 0.22% to 1.22% of firm's revenue (cf. Levy et al. (1997), Zbaracki et al. (2004) and Stella (2014)).[35] Regarding the volatility parameter of firm's productivity shock, $\sigma$ (Eq.10), we follow Dixit (1991b) and Alvarez and Lippi (2014), whose models also entail stock variables which follow Brownian motion. They use the volatility parameter of $\sigma = 0.1$ assuming that the unit of time is a year. Reassuringly, we estimate this parameter (Appendix E), and obtain a very similar value of $\sigma = 0.105$. Since in what follows we assume that the time unit is a month (to be in line with the subsequent empirical analysis where we use the monthly frequency of price change estimated by Nakamura and Steinsson (2008)), we use the monthly equivalent of $\sigma = 0.03$ (instead of $\sigma = 0.1$).[36] The remaining parameters of the model follow values commonly used in the

[35] In this numerical experiment, we focus on the case where menu costs are modeled as a proportion of firm's revenue (rather than profits).

[36] To explain, in case time is measured in months, the variance of the exponential of Brownian motion (with no drift term as in the theory model) after one year (12 months) is equal to $e^{\sigma_m^2 * 12}(e^{\sigma_m^2 * 12} - 1)$, where

literature: elasticity of demand, $\varepsilon = 4$ (e.g., Nakamura and Steinsson (2010)); Frisch elasticity of labor supply, $\nu = 3$ (e.g., Peterman (2016)), corresponding to $\gamma = 1.33$.

Figure 2: Price gap and the range of inaction for different returns to scale



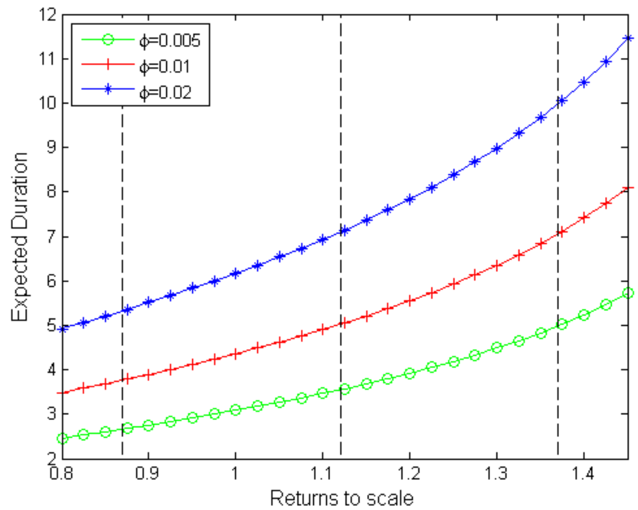

Note: Sample paths of price gap following a Brownian motion with $\sigma = 0.03$ for $\psi_k = 0.87$ and $\psi_k = 1.37$. The former (latter) value of $\psi_k$ is the mean minus (plus) one standard deviation. Horizontal lines are the boundaries of $h_k$ and $-h_k$ (see Eq.24). Parameter values are as explained in the text. Source: Authors' calculation

**Evolution of price gaps** Figure 2 shows a sample path of firm's price gap for two different values of returns to scale, $\psi_k = 0.87$ and $\psi_k = 1.37$, which correspond to the mean of returns to scale estimated above (1.12) plus and minus one standard deviation (0.25). The other parameter values are as explained above. With these values, sectoral price gap threshold $h_k$ is 0.058 for $\psi_k = 0.87$, while 0.080 for $\psi_k = 1.37$ (see Eq.24). That is, whenever its current price deviates from the optimal flexible equilibrium price by 5.8% (8.0%) in the absolute value, a profit-optimizing firm in a sector with the returns to scale of 0.87 (1.37) pays menu costs and adjusts its price to the optimal price, corresponding to the price gap of zero. Under the low returns to scale (the left sub-figure), price gap hits boundaries 14 times over the course of 100 months, while under the high returns to scale (right sub-figure), it hits

$\sigma_m$ is the variance parameter relevant for a month after the start of the shock. This variance should be equal to $e^{\sigma_y^2 * 1}(e^{\sigma_y^2 * 1} - 1)$, where $\sigma_y$ is a yearly counterpart. Thus, when $\sigma_y = 0.1$, we have $\sigma_m = 0.03$.

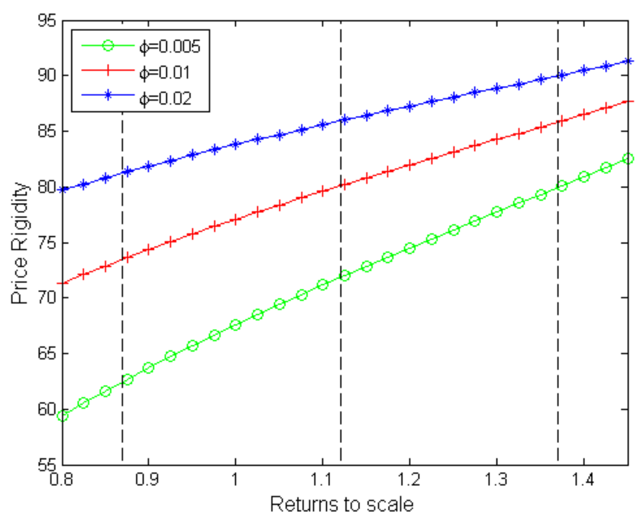
the boundaries only 6 times, implying that higher returns to scale match a longer expected duration of inaction.

Figure 3: Expected duration and Returns to scale for different menu costs




Note: Expected durations are defined in months. The left (middle, right) vertical dashed lines correspond to the sample mean of returns to scale (1.12) minus one standard deviation (0.25) (the mean, the mean plus one standard deviation). Source: Authors' calculation

Figure 4: Price rigidity and Returns to scale for different menu costs




Note: Price rigidity is defined as the probability (in percent) of keeping the current price fixed in a given month, calculated as "100−100*(1/expected duration of inaction in months)", where the expected duration is as calculated in Figure 3. The three dashed lines are as defined in Figure 3. Source: Authors' calculation

**Expected duration of inaction and price rigidity** Next, Figure 3 shows the expected duration of inaction, $D_k$ as a function of returns to scale $\psi_k$ (Eq.25). The duration of inaction is defined in months. The left (middle; right) vertical dashed lines correspond to the sample mean of returns to scale (1.12) minus one standard deviation (0.25), 0.87 (the mean; the mean plus one standard deviation, 1.37). The relation between $D_k$ and $\psi_k$ are plotted for different values of menu costs around the reference value of $\varphi = 0.01$: 0.005 and 0.02. Figure 4 presents corresponding figures, showing instead the measure of price rigidity defined as "100−100*(1/expected duration of inaction in months)".[37] For the reference case of $\varphi = 0.01$, for example, returns to scale of 0.87, 1.12, and 1.37 are associated with the price rigidity of 73%, 80%, and 85%. Judging from the fact that empirical estimates of price rigidity used below (Table 1) yield the standard deviation of 22% with the mean of 85%, the effect of returns to scale on price rigidity appears quantitatively sizable. Incidentally, for a given value of returns to scale (1.12), a rise in the menu cost parameter from 0.01 to 0.02, for example, correspond to a rise in price rigidity from 80% to 86%, which also appears non-trivial.

# 5 Empirical evidence

## 5.1 Matching with data on price rigidity

To see if the theoretical prediction is supported empirically, this section examines the correlation between returns to scale and price rigidity across US manufacturing sectors. For this purpose, we first match returns to scale estimated above for 6-digit manufacturing sectors with the monthly frequency of change in producer prices at the product level estimated by Nakamura and Steinsson (2008).[38,39] Using the survey of firms conducted by BLS, they

[37] This way of converting from expected duration to price rigidity is different from Eq.26. This is because we are now conducting numerical experiments in a discrete time framework.

[38] The estimates are available in Table 23 of their online appendix.

[39] The reason why we choose producer prices rather than consumer prices is twofold. First, in our view, using producer prices is more relevant to test our theoretical prediction, which is about producer's pricing behavior. Second, from a practical perspective, it has turned out that a large proportion of sectors for which we estimated returns to scale cannot be matched with the frequency of consumer prices at a product level

estimate the monthly frequency of producer price change of identical products (as well as the frequency of price change including changes associated with product substitutions) for 348 categories of product over the 1998-2005 period. To illustrate how matching is done, product categories such as "butter" and "natural and processed cheese" are matched with 6-digit sub-sectors of "creamery butter manufacturing (NAICS code: 311512)" and "cheese manufacturing (311513)", and product categories such as "cigarettes" and "cigars" with "cigarette manufacturing (312221)" and "other tobacco product manufacturing (312229)".[40] Overall, we managed to match 277 (out of 348) categories of products with 202 NAICS 6-digit manufacturing sectors, for which returns to scale are estimated.[41] Appendix F lists product categories together with corresponding 6-digit NAICS manufacturing sectors.

Figure 5 plots returns to scale against the measure of price rigidity, calculated as 100 minus the monthly frequency of price changes of identical products in percent. Since the frequency at which price is kept unchanged is bounded in the 0 to 100 range by definition, the fitted line in Figure 5 is based on the regression line for the association between the logit transformation of price rigidity and returns to scale, which is positive and significant at the 1 percent level.[42] The indication is thus that products made in sectors characterized by higher returns to scale exhibit larger price stickiness. This association holds even when we use the frequency including price changes associated with product substitutions. In what follows, we conduct a regression analysis, to examine if the positive correlation between returns to scale and price rigidity still holds even when other determinants of price rigidity highlighted in the previous empirical literature are controlled for.

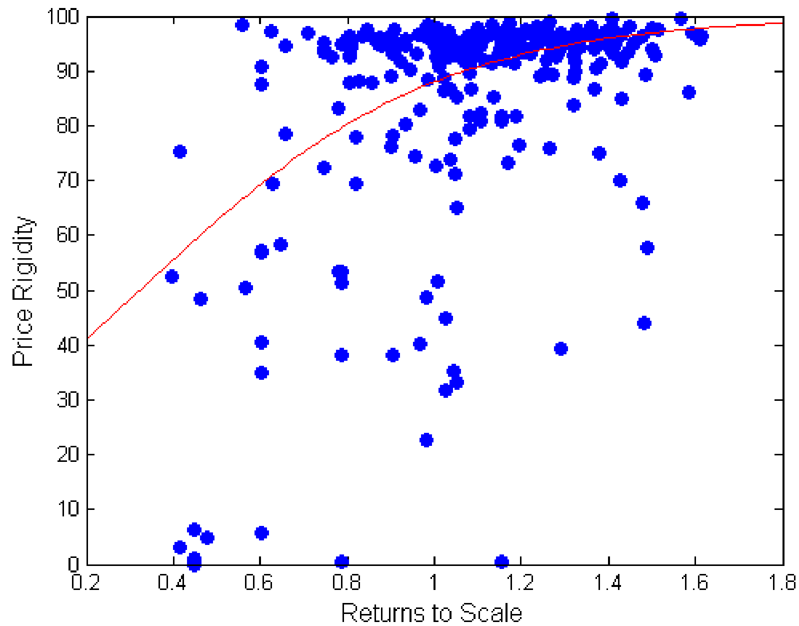
estimated by Nakamura and Steinsson (2008), reducing the sample size dramatically. The same happened even when we used the frequency of consumer prices estimated by Klenow and Kryvtsov (2008) instead.

[40]Regarding "creamery butter manufacturing (NAICS 311512)", for example, the NAICS manual says that "this U.S. industry comprises establishments primarily engaged in manufacturing creamery butter from milk and/or processed milk products".

[41]Some products are not possible to match. For example, products for which Nakamura and Steinsson (2008) estimate the frequency of price changes include agricultural products such as fresh foods, and these products are produced outside manufacturing sectors.

[42]See Baum (2008) for the use of logit transformation to model proportions.

Figure 5: Returns to scale and price rigidity




Note: 277 product categories matched with 202 6-digit manufacturing sectors (according to NAICS) are considered. Price rigidity is calculated as "100 − the monthly frequency of producer price change of identical products (in percent, from Nakamura and Steinsson (2008))". Returns to scale are as estimated above (cf. Eq.27). The fitted line is based on the regression line for the relation between the logit transformation of price rigidity and returns to scale. Source: Authors' calculation.

## 5.2 Regression results

Based on Vermeulen et al. (2012)'s comprehensive study of sectoral heterogeneity in producer price setting in the Euro area, the following regression analysis takes account of 1) the cost structure of production, highlighting labor and intermediate cost shares, 2) the degree of market concentration, and 3) the inflation rate at the sector level, as possible determinants of the heterogeneity in producer price rigidity. We run a cross-sectional regression to examine the relation between returns to scale and producer price rigidity, controlling for an average of these determinants over the sample period of 1987-2011 at the sector level.

Table 1 describes the data used for the analysis. Focusing on the case where all the control variables are available, the statistics are based on 275 observations from 200 US 6-digit

Table 1: Summary statistics

| Variable | Mean | Std. dev. | Min. | Max. |
|---|---|---|---|---|
| Price rigidity | 84.82 | 21.93 | 0 | 99.60 |
| Returns to scale | 1.08 | 0.26 | 0.4 | 1.61 |
| Labor cost share | 22.93 | 7.93 | 3.56 | 42.47 |
| Intermediate cost share | 57.43 | 9.42 | 37.08 | 82.16 |
| Concentration ratio | 697.38 | 594.11 | 2.67 | 2707.2 |
| Average inflation | 2.14 | 3.28 | -13.38 | 15.77 |

Note: Based on 275 product categories matched with 200 6-digit manufacturing sectors according to NAICS. Source: Authors' calculation using data from NBER-CES Manufacturing Industry database, US Census Bureau, BLS databases, and Nakamura and Steinsson (2008).

manufacturing sectors. Regarding the determinants controlled for, labor cost and intermediate cost shares in production (from BLS) are calculated as the average over the 1987-2011 period.[43] On average, labor and intermediate cost shares account for 22.9 % and 57.4 %, respectively. Labor share is expected to show a positively association with price rigidity, while intermediate share shows a negative association (Peneva (2011), Vermeulen et al. (2012)). Next, concentration ratio (from US Census Bureau) is the Herfindahl-Hirschman index (HHI) for 50 largest companies at each of the 6-digit NAICS sector, averaged over 1997, 2002, and 2007.[44] In the most (least) concentrated sector, the index takes 2707.2 (2.67), with the average of 697.4.[45] Since previous works reach different conclusions (e.g., Carlton (1986) and Eckard (1982)), there is no clear conjecture about the sign of the association with price rigidity. Last, inflation rates at the 6-digit sector level are obtained from BLS as an average of as much data as available over the 1987-2011 period. In line with Vermeulen et al. (2012), we expect that this variable is negatively related to price rigidity.

[43] As explained above, data on the cost structure for 6-digit sectors are not always available. When not available, corresponding data at the 5- or 4-digit level are used.

[44] The data are available only at those three data points.

[45] HHI takes a maximum of 10,000 when one firm has a 100% market share, and it takes close to zero at a minimum when each of many firms has nearly 0% share.

Formally, regression equation is described as:

$$rigid_i = \alpha + \beta\, rts_i + \sum_{j=1}^{n} \delta_j\, \mathbf{z}_{i,j} + \epsilon_i, \tag{29}$$

where $i$ denotes a product category. The dependent variable, $rigid_i$ is the logit transformation of the price rigidity measure, "100 minus the monthly frequency of price changes of identical products in percent". Our main independent variable, $rts_i$ is the returns to scale estimate for product category $i$, matched with the 6-digit sector $k$ (cf. Eq.27). Next, $\mathbf{z}_{i,j}$ is a vector of additional controls as explained above (i.e., labor cost share, the intermediate cost share, concentration ratio, and sectoral inflation rate) relevant for product category $i$. We estimate Eq.29 using OLS. Because different product categories sometimes belong to the same 6-digit sector, clustered standard errors are used to adjust for correlation of error terms within a sector.

Table 2: Returns to scale and price rigidity

**Dependent variable: price rigidity (transformed using logit function)**

| **Regressors** | (1) | (2) | (3) | (4) | (5) |
|---|---|---|---|---|---|
| Returns to scale | 2.936*** | 1.252*** | 2.954*** | 2.288*** | 0.976** |
| | (3.853) | (2.721) | (3.875) | (3.848) | (2.332) |
| Labor cost share | | 0.0748*** | | | 0.0567*** |
| | | (4.085) | | | (3.492) |
| Intermediate cost share | | -0.0321** | | | -0.0345*** |
| | | (-2.212) | | | (-2.733) |
| Concentration ratio | | | -0.000419** | | -0.000349** |
| | | | (-2.136) | | (-2.038) |
| Inflation rate | | | | -0.143*** | -0.117*** |
| | | | | (-3.000) | (-3.465) |
| Constant | -0.937 | 1.011 | -0.651 | 0.0688 | 2.366*** |
| | (-1.027) | (0.955) | (-0.708) | (0.0980) | (2.626) |
| Observations | 277 | 277 | 275 | 277 | 275 |
| Adj R-squared | 0.209 | 0.373 | 0.237 | 0.273 | 0.425 |

Note: OLS estimations. In Column (5), for example, 275 product categories are matched with 200 6-digit manufacturing sectors according to NAICS. t-statistics using robust standard errors that adjust for correlation within 6-digit NAICS are in parentheses.*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Table 2 summarizes the results. Column (1) is without any additional controls, corresponding to the positive regression line in Figure 5. The positive and significant coefficient 2.936 can be interpreted using odds ratio[46]. For example, an increase in returns to scale by 0.1 is associated with a rise in the odds ratio by 34% ($e^{0.1*2.936} - 1 = 0.34$). Thus, if the initial price rigidity is 84.82% (sample mean, see Table 1), a rise in returns to scale by 0.1 corresponds to the increase in price rigidity by 3.4 percentage points, which appears substantial.[47] While Columns (2) to (4) control for cost shares, concentration ratio, and inflation rate, respectively, the association between returns to scale and price rigidity remains positive and significant at the 1 percent level. As expected, the coefficients on labor and intermediate cost shares are significantly positive and negative. In line with Eckard (1982), concentration ratio is negatively associated with price rigidity. The negative and significant coefficient on inflation rate means that under high inflation, producer price changes more frequently.

Last, Column (5) shows that even when all the variables are controlled for simultaneously, the positive correlation between returns to scale and price rigidity still holds, albeit the coefficient on returns to scale is smaller (0.976). To interpret as above, a rise in returns to scale by 0.1 at the mean price rigidity of 84.82% is associated with a rise in the price rigidity by 1.22 percentage points. Given that one standard deviation change (= 0.26) corresponds to 3.17 percentage points change, the effect does appear to matter quantitatively. To report, the results are robust to the use of the frequency of price changes including changes associated with product substitutions. Interestingly, the quantitative effect is somewhat close to the result from the calibration exercise above: there, a one standard deviation increase in returns to scale at the reference point (where the price rigidity measure takes 80 percent) causes a rise in price rigidity by 5 percentage points.

[46]The Odds ratio is the ratio between the probability that an event occurs and the probability that it does not. In our case, the event is defined as an inaction, i.e., *not* changing the current price.

[47]With the price rigidity of 84.82%, the adds ratio is $84.82/(100 - 84.82)(=5.588)$. When the odds ratio rises by 34%, the new ratio is 7.487. Then, the price rigidity corresponding to the new ratio is tied down as 88.22%, an increase by 3.4 percentage points from the initial rigidity.

### 5.3 Robustness

The above regressions are based on the point estimates of returns to scale. However, as mentioned, estimating returns to scale is inherently difficult due to different sources of erroneous estimates. Acknowledging this, instead of exploiting the variations of the point estimates of returns to scale as in Table 2, we here use the variations among the three categories: increasing, constant, and decreasing returns to scale.

Specifically, we consider the following model:

$$rigid_i = \alpha + \beta IRS_i + \gamma DRS_i + \sum_{j=1}^{n} \delta_j \mathbf{z}_{i,j} + \epsilon_i, \tag{30}$$

where the only difference from Eq.29 is that instead of using $rts_i$, a point estimate of returns to scale of product category $i$, we use $IRS_i$, a dummy variable which takes the value of 1 if product category $i$ is matched with a sector characterized by IRS technology, 0 otherwise (i.e., if it is matched with a sector with CRS or DRS technology). Likewise, $DRS_i$ is a dummy which takes the value of 1 if product category $i$ is associate with a sector characterized by DRS technology, 0 otherwise. When returns to scale are larger (smaller) than the value of 1 at the 5 percent level, a sector is considered to exhibit increasing (decreasing) returns to scale. A CRS dummy is omitted, to avoid perfect multicollinearity. Our interests in Eq.30 are the signs of coefficients, $\beta$ and $\gamma$, which, to the extent that the above results in Table 2 prevails, should be positive and negative, respectively.

Table 3 summarizes the results. The structure is the same as Table 2, except that the dummy variables of returns to scale are used instead of the point estimates. Among 277 observations for Column (1), for example, 67 (195, 15) product categories are matched with industries which exhibit increasing (constant, decreasing) returns to scale. As expected, coefficients on IRS is always positive, and ones on DRS is always negative. While those coefficients are mostly significant, in Column (5) the coefficient on IRS is not significant. However, it can be confirmed that it is significantly different from the coefficient on DRS.

Table 3: Returns to scale and price rigidity: dummy variable approach

**Dependent variable: price rigidity (transformed using logit function)**

| **Regressors** | (1) | (2) | (3) | (4) | (5) |
|---|---|---|---|---|---|
| IRS | 0.592*** | 0.303** | 0.572*** | 0.392** | 0.199 |
| | (3.231) | (2.005) | (3.232) | (2.345) | (1.292) |
| DRS | -3.155*** | -1.571* | -3.173*** | -2.691*** | -1.494* |
| | (-2.809) | (-1.660) | (-2.813) | (-2.939) | (-1.784) |
| Labor cost share | | 0.0761*** | | | 0.0561*** |
| | | (4.097) | | | (3.734) |
| Intermediate cost share | | -0.0280** | | | -0.0285** |
| | | (-2.257) | | | (-2.461) |
| Concentration ratio | | | -0.000487* | | -0.000378** |
| | | | (-1.931) | | (-1.973) |
| Inflation rate | | | | -0.156*** | -0.122*** |
| | | | | (-4.065) | (-3.943) |
| Constant | 2.287*** | 2.120** | 2.640*** | 2.640*** | 3.164*** |
| | (15.69) | (2.193) | (14.75) | (18.25) | (3.646) |
| Wald IRS_DRS, p-value | 0.000971 | 0.0457 | 0.00103 | 0.000733 | 0.0407 |
| Observations | 277 | 277 | 275 | 277 | 275 |
| Adj R-squared | 0.220 | 0.385 | 0.249 | 0.303 | 0.442 |

Note: OLS estimations. In Column (5), for example, 275 product categories are matched with 200 6-digit manufacturing sectors according to NAICS. IRS (DRS) is a dummy variable, taking the value of one if product category $i$ belongs to a sector characterized by increasing (decreasing) returns to scale, and the value of zero otherwise. Wald IRS_DRS tests the equality of coefficients on IRS and DRS. t-statistics using robust standard errors that adjust for correlation within 6-digit NAICS are in parentheses.*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

This is based on the observation that the Wald test rejects the equality of coefficients on IRS and DRS for all the columns, including Column (5). It is thus the case that even when we do not exploit the variations of point estimates, the price of a product category from a sector characterized by IRS changes less frequently than the price of a product from a DRS sector. Coefficients on all the additional controls are in line with the ones in Table 2, both in terms of the sign and significance.

# 6 Concluding remarks

This paper proposes returns to scale as a possible explanatory factor behind sectoral heterogeneity in nominal price stickiness. We first built a dynamic multi-sector menu-cost model to show analytically that there is a positive association between returns to scale and price rigidity across sectors. This happens because higher returns to scale make firms less sensitive to price misalignment, prompting them to adjust prices less often in the presence of menu costs. We then estimated returns to scale using data on 6-digit US manufacturing sectors. A calibration exercise using the returns to scale estimates suggests that returns to scale are a quantitatively important factor behind sectoral heterogeneity in price stickiness. Last, we provided evidence in support of our main theoretical prediction. The positive correlation between returns to scale and producer price rigidity still stands even when controlling for some of the key determinants of price rigidity highlighted in the literature.

Regarding possible future research, one idea is to examine monetary non-neutrality using a theoretical framework with heterogeneities in both nominal price rigidity *and* returns to scale across sectors. Although the previous research emphasizes the relevance of heterogeneity in price rigidity by showing that it makes the real effects of money shocks stronger and more persistent, this result is not taking account of the positive correlation between price rigidity and returns to scale across sectors. Therefore, there is a scope of examining how the introduction of the two dimensions of sectoral heterogeneity may enrich the transmission mechanism of monetary shocks.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# Appendix

# A Upper-bound of returns to scale, $\psi^{max}$

Firm $kj$'s real profit in time $t$ is given as (Eq.13):

$$\pi_{kj,t} = A_{k,t} p_{kj,t}^{1-\varepsilon} C_t - \alpha (A_{k,t} Z_{k,t}^{-1})^{\frac{\gamma}{\psi_k}} p_{kj,t}^{-\frac{\varepsilon\gamma}{\psi_k}} C_t^{1+\frac{\gamma}{\psi_k}},$$

where $p_{kj,t} = \frac{P_{kj,t}}{P_t}$. Firm $kj$ maximizes its profits by choosing an optimal relative price $p^*_{kj,t} = \frac{P^*_{kj,t}}{P_t}$. We first obtain the stationary point, $p^s_{kj,t}$ that satisfy $\frac{\partial \pi_{kj,t}}{\partial p_{kj,t}}(p^s_{kj,t}) = 0$, and then check if $\frac{\partial^2 \pi_{kj,t}}{\partial p^2_{kj,t}}(p^s_{kj,t}) < 0$ to ensure that the stationary point corresponds to a maximum.

The stationary point $p^s_{kj,t}$ is obtained as:

$$(p^s_{kj,t})^{1-\varepsilon+\frac{\varepsilon\gamma}{\psi_k}} = \frac{\alpha\gamma}{\psi_k} \frac{\varepsilon}{\varepsilon - 1} A_{k,t}^{\frac{\gamma}{\psi_k}-1} Z_{k,t}^{-\frac{\gamma}{\psi_k}} C_t^{\frac{\gamma}{\psi_k}}$$

Then, the second derivative at the stationary point is:

$$\frac{\partial^2 \pi_{kj,t}}{\partial p^2_{kj,t}}(p^s_{kj,t}) = (\varepsilon - 1)\Big[\varepsilon - \big(\frac{\varepsilon\gamma}{\psi_k} + 1\big)\Big] A_{k,t} C_t (p^s_{kj,t})^{-\varepsilon-1}.$$

With $\varepsilon - 1 > 0$, $A_{k,t}$ and $C_t$ being positive, and $p^s_{kj,t} > 0$, the second derivative of the profit function at the stationary point is negative if and only if:

$$\Big[\varepsilon - \big(\frac{\varepsilon\gamma}{\psi_k} + 1\big)\Big] < 0 \quad \Leftrightarrow \quad \psi_k < \frac{\varepsilon\gamma}{\varepsilon - 1} = \psi^{max}$$

As long as returns to scale are below $\psi^{max}$, the profit function remains concave.

# B Approximation of scaled profit, $g$

Substituting Eq.15 into Eq.13 (and using $P_{kj,t}/P_t = (P_{kj,t}/P^*_{kj,t})(P^*_{kj,t}/P_t)$) yields

$$\pi(\hat{p}_{kj,t}, C_t) = \alpha\left[\frac{\alpha\varepsilon\gamma}{\psi_k(\varepsilon-1)}\right]^{\frac{-\varepsilon\gamma}{\psi_k(1-\varepsilon)+\varepsilon\gamma}} C_t^{\frac{(1-\varepsilon)\psi_k+\gamma}{\psi_k(1-\varepsilon)+\varepsilon\gamma}}\; e^{-\frac{\varepsilon\gamma}{\psi_k}\hat{p}_{kj,t}}\left[\frac{\varepsilon\gamma}{\psi_k(\varepsilon-1)}e^{(1-\varepsilon+\frac{\varepsilon\gamma}{\psi_k})\hat{p}_{kj,t}} - 1\right].$$

In turn, $g(\hat{p}_{kj,t}, C_t)(= \pi(\hat{p}_{kj,t}, C_t)/\bar{r}_{kj})$ is given as:

$$g(\hat{p}_{kj,t}, C_t) = \frac{\psi_k(\varepsilon-1)}{\varepsilon\gamma}\left[\frac{C_t}{\bar{C}}\right]^{\frac{(1-\varepsilon)\psi_k+\gamma}{\psi_k(1-\varepsilon)+\varepsilon\gamma}}\; e^{-\frac{\varepsilon\gamma}{\psi_k}\hat{p}_{kj,t}}\left[\frac{\varepsilon\gamma}{\psi_k(\varepsilon-1)}e^{(1-\varepsilon+\frac{\varepsilon\gamma}{\psi_k})\hat{p}_{kj,t}} - 1\right].$$

We approximate the function $g$ around the flexible-price equilibrium where $C_t = \bar{C}$ and $\hat{p}_{kj,t} = 0$. As in Alvarez and Lippi (2014), we use the second-order Taylor approximation:

$$\begin{aligned}
g(\hat{p}_{kj,t}, C_t) =& g(\bar{C}, 0) + \frac{\partial g}{\partial \hat{p}}(\bar{C}, 0)\hat{p}_{kj,t} + \frac{\partial g}{\partial C}(\bar{C}, 0)(C_t - \bar{C}) \\
&+ \frac{1}{2}\left[\frac{\partial^2 g}{\partial\hat{p}\partial\hat{p}}(\bar{C}, 0)\hat{p}^2_{kj,t} + \frac{\partial^2 g}{\partial C\partial C}(\bar{C}, 0)(C_t - \bar{C})^2\right] \\
&+ \frac{\partial^2 g}{\partial\hat{p}\partial C}(C_t, 0)\hat{p}_{kj,t}(C_t - \bar{C}) + o(||\hat{p}^2_{kj,t}, C_t - \bar{C}||^2) \\
=& 1 + \frac{(1-\varepsilon)\psi_k + \gamma}{\varepsilon\gamma}\frac{C_t - \bar{C}}{\bar{C}} + \frac{1}{2}(1-\varepsilon)\left[1 - \varepsilon + \frac{\varepsilon\gamma}{\psi_k}\right]\hat{p}^2_{kj,t} \\
&+ \frac{1}{2}\frac{(1-\varepsilon)\psi_k + \gamma}{\varepsilon\gamma}\left[\frac{(1-\varepsilon)\psi_k + \gamma}{\psi_k(1-\varepsilon) + \varepsilon\gamma} - 1\right]\left[\frac{C_t - \bar{C}}{\bar{C}}\right]^2 + o(||\hat{p}^2_{kj,t}, C_t - \bar{C}||^2).
\end{aligned}$$

Denoting $\chi = \frac{\psi_k(1-\varepsilon)+\varepsilon\gamma}{\varepsilon\gamma}$ and $\delta = \frac{(1-\varepsilon)\psi_k+\gamma}{\psi_k(1-\varepsilon)+\varepsilon\gamma}$, and plugging the above into Eq.20, the firm's problem can be written as the following minimization problem:

$$\begin{aligned}
\min_{\boldsymbol{\tau}, \triangle\hat{\boldsymbol{p}}_{\boldsymbol{kj}}} \; \bar{r}_{kj}\; \mathbf{E}\Big[&\int_0^\infty \frac{1}{2}(\varepsilon-1)(1-\varepsilon+\frac{\varepsilon\gamma}{\psi_k})\hat{p}^2_{kj,t}e^{-\rho t}dt + \sum_{i=1}^\infty e^{-\rho\tau_i}\varphi \\
&- \int_0^\infty \big[\chi\frac{C_t - \bar{C}}{\bar{C}} + \frac{1}{2}\chi(\delta-1)(\frac{C_t - \bar{C}}{\bar{C}})^2\big]e^{-\rho t}dt \\
&+ \int_0^\infty o(||\hat{p}^2_{kj,t}, C_t - \bar{C}||^2)e^{-\rho t}dt \mid \hat{p}_{kj,0} = \hat{p}_{kj}\Big].
\end{aligned} \tag{31}$$

In Eq.31, only the first line of the problem depends on firm $kj$'s choice of the pricing policy $(\boldsymbol{\tau}, \triangle\hat{\boldsymbol{p}}_{\boldsymbol{kj}})$ Thus, the firm's problem simply becomes:

$$\min_{\boldsymbol{\tau}, \triangle\hat{\boldsymbol{p}}_{\boldsymbol{kj}}} \mathbf{E}\left[\int_0^\infty \frac{1}{2}(\varepsilon-1)(1-\varepsilon+\frac{\varepsilon\gamma}{\psi_k})\hat{p}_{kj,t}^2 e^{-\rho t}dt + \sum_{i=1}^{\infty} e^{-\rho\tau_i}\varphi \mid \hat{p}_{kj,0} = \hat{p}_{kj}\right]. \tag{32}$$

# C Price gap following Browning motion

Assuming that money supply is constant over time, i.e., $M_t = \bar{M}$, Eqs.6, 7, and 16 indicate that in the flexible price equilibrium, aggregate price is also constant at:

$$\bar{P} = \frac{\rho\bar{M}}{\kappa\bar{C}}.$$

Then, in the flexible-price equilibrium, a nominal price set by firm $kj$, $P^*_{kj,t}$ is given as (cf. Eq.15):

$$P^*_{kj,t} = \frac{1}{Z_{k,t}}\left[\frac{\alpha\gamma}{\psi_k}\frac{\varepsilon}{\varepsilon-1}\bar{C}^{\frac{\gamma}{\psi_k}}\right]^{\frac{1}{1-\varepsilon+\frac{\varepsilon\gamma}{\psi_k}}} \frac{\rho\bar{M}}{\kappa\bar{C}}.$$

Taking the log of this equation and differentiating it (with respect to time) yields $\mathrm{dlog}P^*_{kj} = -\mathrm{dlog}Z_k$. Further, taking the log of Eq.10 and differentiating it gives $\mathrm{dlog}Z_k = \sigma \mathrm{d}x_k$, where $x_k$ follows standard Brownian motion. We thus have

$$\mathrm{dlog}P^*_{kj} = -\sigma \mathrm{d}x_k. \tag{33}$$

Next, given that a price gap, $\hat{p}_{kj,t} = \log(\frac{P_{kj,t}}{P^*_{kj,t}})$, we have $\mathrm{d}\hat{p}_{kj} = \mathrm{dlog}P_{kj} - \mathrm{dlog}P^*_{kj}$. Since price $P_{kj,t}$ is constant between two consecutive price changes *by definition*, $\mathrm{dlog}P_{kj} = 0$ between those changes. This means that:

$$\mathrm{d}\hat{p}_{kj} = -\mathrm{dlog}P^*_{kj}. \tag{34}$$

Last, combining Eqs.33 and 34 yields:

$$\mathrm{d}\hat{p}_{kj} = \sigma \mathrm{d}x_k.$$

A price gap $\hat{p}_{kj,t}$ follows Brownian motion with the volatility parameter of $\sigma$.

# D Derivation of the expected duration of inaction

Denote $q_t = \hat{p}^2_{kj,t}$, and $\bar{q} = h^2_k$. Proposition 1 shows that a firm changes its price whenever $q_t$ reaches $\bar{q}$. For a starting price gap $\hat{p}_{kj}$, and $q = \hat{p}^2_{kj}$, we define $T(q)$ as the expected time required for $q_t$ to reach $\bar{q}$ when starting from $q$. The function $T$ satisfies the following Bellman equation:

$$T(q) = dt + \mathbf{E}[T(q + dq)] \Rightarrow 0 = dt + \mathbf{E}[dT(q)] \tag{35}$$

Given that a price gap $\hat{p}_{kj,t}$ follows Brownian motion (i.e. $\mathrm{d}\hat{p}_{kj} = \sigma \mathrm{d}x_k$ where $x_k$ is standard Brownian motion), and using Ito's Lemma, it is straightforward to prove that $dq = \sigma^2 dt + 2\sigma\sqrt{q}dx_k$. Similarly, using Ito's lemma on function $T(q)$, we have:

$$dT(q) = (T^{'}(q)\sigma^2 + 2\sigma^2 qT^{''}(q))dt + (2\sigma\sqrt{q}T^{'}(q))dx_k \tag{36}$$

Plugging Eq.36 into Eq.35, and using the fact that $\mathbf{E}[dx_k] = 0$, we derive:

$$0 = dt + (T^{'}(q)\sigma^2 + 2\sigma^2 qT^{''}(q))dt$$

Dividing this by $dt$ gives an Ordinary Differential Equation (ODE):

$$0 = 1 + T^{'}(q)\sigma^2 + 2\sigma^2 qT^{''}(q) \tag{37}$$

Using the boundary condition $T(\bar{q}) = 0$, the solution for the ODE in Eq.37 is $T(q) = \frac{\bar{q}-q}{\sigma^2}$. Thus, the expected duration of inaction of a firm in sector $k$, $D_k$ is equal to:

$$D_k = T(0) = \frac{\bar{q}}{\sigma^2} = \frac{h_k^2}{\sigma^2}$$

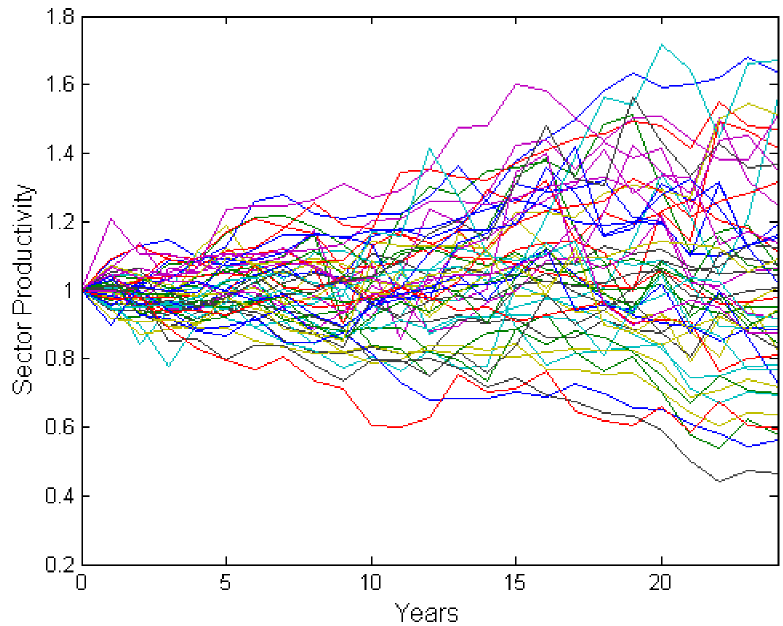
# E Estimation of the volatility parameter, $\sigma$

Here, we estimate the volatility parameter $\sigma$ of sectoral productivity shocks, modeled as the exponential of Brownian motion, i.e., geometric Brownian motion. First, in line with the estimation of returns to scale (Eqs.27 and 28), we assume that the production function of firms in sector $k$ is given as:

$$Y_{k,t} = Z_{k,t}(L_{k,t}^{cL_{k,t}} K_{k,t}^{cK_{k,t}} M_{k,t}^{cM_{k,t}})^{\psi_k},$$

where $Y_{k,t}$ is gross output (in sector $k$ in year $t$); $Z_{k,t}$ is total factor productivity; $L_{k,t}$, $K_{k,t}$, and $M_{k,t}$ are labor, capital, and intermediate inputs; $cL_{k,t}$, $cK_{k,t}$, and $cM_{k,t}$ are the cost shares of respective inputs; $\psi_k$ is returns to scale. Then, using the data from NBER-CES manufacturing industry and BLS multifactor productivity databases, and our estimates for returns to scale (see Figure 1), we compute $Z_{k,t}$ for each year from 1987 to 2011 for the 447 sectors. To normalize the initial value of geometric Brownian motion to its standard value of 1, we divide $Z_{k,t}$ by $Z_{k,1987}$. Figure 6 presents the realized path of $Z_{k,t}$ for 50 (of 447) sectors from $t = 0$ (1987) to $t = 24$ (2011).

Figure 6: Sector Productivity shocks $Z_{k,t}$




Note: Normalized paths of $Z_{k,t}$ for 50 6-digit US manufacturing sub-sectors. Year $t = 0$ corresponds to year 1987. Sources: Authors' calculation using data from NBER-CES Manufacturing Industry and BLS Multifactor Productivity databases.

We regard these 447 normalized paths of $Z_{k,t}$ as a set of *realizations* of geometric Brownian motion, $Z_t$. To incorporate the possibility that there is a trend to sectoral total factor productivity in reality, we assume that $Z_t$ is geometric Brownian motion with drift, characterized by a volatility parameter $\sigma$ and a drift parameter $\mu$. Thus, the mean and variance of this stochastic process at time $t$ are given as:

$$E(Z_t) = e^{(\mu+(1/2)\sigma^2)t} \text{ and } Var(Z_t) = e^{(2\mu+\sigma^2)t}(e^{\sigma^2 t} - 1) = E(Z_t)^2(e^{\sigma^2 t} - 1),$$

which, in turn, yields:

$$\frac{Var(Z_t)}{E(Z_t)^2} = e^{\sigma^2 t} - 1.$$

Then, using the 447 realizations of $Z_t$, we obtain the estimate of the volatility parameter $\sigma$ for each year $t$ ($t = 1, ..., 24$), and we find that the average of these 24 estimated values is 0.105. This is our estimate for $\sigma$ (Eq.10) for the case where the unit of time is a year. Interestingly, this estimated value of volatility parameter is quite close to the parameter of 0.1 used by Dixit (1991a) and Alvarez and Lippi (2014) who assume that the unit of time is a year.

# F Matching product categories with NAICS 6-digit manufacturing sector

| Code | Prod. description | 6-digits NAICS description | NAICS |
|---|---|---|---|
| 278 | Shortening and cooking oil | Fats and Oils Refining and Blending | 311225 |
| 641 | Fats and oils, inedible | Fats and Oils Refining and Blending | 311225 |
| 255 | Confectionery end Prod.s | Confectionery | 311330 |
| 254 | Confectionery materials | Chocolate and Confectionery | 311320 |
| 253 | Refined sugar | Cane Sugar Refining | 311312 |
| 242 | Frozen fruits, juices and ades | Frozen Fruit, Juice, and Vegetable Mfg. | 311411 |
| 282 | Pickles and pickle Prod.s | Fruit and Vegetable Canning | 311421 |
| 284 | Canned specialties | Specialty Canning | 311422 |
| 281 | Jams, jellies, and preserves | Fruit and Vegetable Canning | 311421 |
| 244 | Canned vegetables and juices | Fruit and Vegetable Canning | 311421 |
| 285 | Frozen specialties | Frozen Specialty Food Mfg. | 311412 |
| 241 | Canned fruits and juices | Fruit and Vegetable Canning | 311421 |
| 245 | Frozen vegetables | Frozen Fruit, Juice, and Vegetable Mfg. | 311411 |
| 235 | Condensed and evaporated milk | Dry, Condensed, and Evaporated Dairy | 311514 |
| 234 | Ice cream and frozen desserts | Ice Cream and Frozen Dessert Mfg. | 311520 |
| 232 | Butter | Creamery Butter Mfg. | 311512 |
| 233 | Natural and processed cheese | Cheese Mfg. | 311513 |
| 221 | Meats | Animal (except Poultry) Slaughtering | 311611 |
| 222 | Processed poultry | Poultry Processing | 311615 |
| 286 | Meat sauces | Mayonnaise, Dressing, and Other Sauce | 311941 |
| 283 | Processed eggs | All Other Miscellaneous Food Mfg. | 311999 |
| 262 | Soft drinks | Soft Drink Mfg. | 312111 |
| 391 | Textile fibers, yarns and fabrics, n.e.c. | Yarn Spinning Mills | 313111 |
| 326 | Yarns | Yarn Spinning Mills | 313111 |
| 327 | Threads | Thread Mills | 313113 |
| 345 | Nonwovens and felt goods | Nonwoven Fabric Mills | 313230 |
| 347 | Embroideries and lace goods | Schiffli Machine Embroidery | 313222 |
| 337 | Broadwovens | Broadwoven Fabric Mills | 313210 |
| 342 | Broadwovens | Broadwoven Fabric Mills | 313210 |
| 339 | Other fabrics | Other Knit Fabric and Lace Mills | 313249 |
| 344 | Narrow fabrics | Narrow Fabric Mills | 313221 |
| 348 | Knit fabrics,finished in knitting mills | Weft Knit Fabric Mills | 313241 |
| 338 | Knits | Weft Knit Fabric Mills | 313241 |
| 346 | Coated fabrics, not rubberized | Fabric Coating Mills | 313320 |
| 393 | Other finishing of textiles | Textile and Fabric Finishing Mills | 313312 |
| 382 | Textile housefurnishings | Curtain and Drapery Mills | 314121 |
| 1214 | Bedding | Curtain and Drapery Mills | 314121 |
| 442 | Gloves | Glove and Mitten Mfg. | 315992 |
| 427 | Finished and unfinished leather | Leather and Hide Tanning and Finishing | 316110 |
| 419 | Hides and skins, incl. cattle | Leather and Hide Tanning and Finishing | 316110 |
| 432 | Women's footwear | Women's Footwear (except Athletic) Mfg. | 316214 |
| 439 | All other footwear | Other Footwear Mfg. | 316219 |
| 431 | Men's footwear | Men's Footwear (except Athletic) Mfg. | 316213 |
| 437 | Athletic footwear | Rubber and Plastics Footwear Mfg. | 316211 |
| 441 | Luggage and small leather goods | Women's Handbag and Purse Mfg. | 316992 |
| 445 | Leather/leather-like goods, n.e.c. | All Other Leather Good Mfg. | 316999 |
| 871 | Treated wood and contract wood preserving | Wood Preservation | 321114 |
| 851 | Logs, bolts, timber and pulpwood | Sawmills | 321113 |
| 849 | Other sawmill planing mill Prod.s | Sawmills | 321113 |
| 832 | Hardwood plywood and related Prod.s | Hardwood Veneer and Plywood Mfg. | 321211 |
| 831 | Softwood plywood | Softwood Veneer and Plywood Mfg. | 321212 |
| 922 | Hardboard, particleboard fiberboard prods. | Reconstituted Wood Prod. Mfg. | 321219 |
| 834 | Hardwood plywood veneer | Hardwood Veneer and Plywood Mfg. | 321211 |
| 833 | Softwood plywood veneer | Softwood Veneer and Plywood Mfg. | 321212 |

| | | | |
|---|---|---|---|
| 923 | Building board, const. paper felt stock | Reconstituted Wood Prod. Mfg. | 321219 |
| 1553 | Mobile homes, residential, double wide | Manufactured Home (Mobile Home) Mfg. | 321991 |
| 823 | Miscellaneous millwork Prod.s | Other Millwork (including Flooring) | 321918 |
| 1552 | Mobile homes, residential, single wide | Manufactured Home (Mobile Home) Mfg. | 321991 |
| 842 | Boxes | Wood Container and Pallet Mfg. | 321920 |
| 822 | Prefabricated structural members | Prefabricated Wood Building Mfg. | 321992 |
| 861 | Prefabricated wood buildings components | Prefabricated Wood Building Mfg. | 321992 |
| 812 | Hardwood lumber | Cut Stock, Resawing Lumber, and Planing | 321912 |
| 841 | Wood pallets and skids | Wood Container and Pallet Mfg. | 321920 |
| 821 | General millwork | Cut Stock, Resawing Lumber, and Planing | 321912 |
| 811 | Softwood lumber | Cut Stock, Resawing Lumber, and Planing | 321912 |
| 1556 | Mobile homes, nonresidential | Manufactured Home (Mobile Home) Mfg. | 321991 |
| 911 | Woodpulp | Pulp Mills | 322110 |
| 913 | Paper | Paper (except Newsprint) Mills | 322121 |
| 914 | Paperboard | Paperboard Mills | 322130 |
| 915 | Converted paper and paperboard Prod.s | All Other Converted Paper Prod. Mfg. | 322299 |
| 916 | Pressure sensitive Prod.s | Coated and Laminated Paper Mfg. | 322222 |
| 937 | Commercial printing | Commercial Gravure Printing | 323111 |
| 931 | Newspapers | Commercial Gravure Printing | 323111 |
| 935 | Manifold business forms | Manifold Business Forms Printing | 323116 |
| 934 | Book printing | Books Printing | 323117 |
| 932 | Periodicals | Commercial Gravure Printing | 323111 |
| 938 | Blankbooks, binders, and bookbinding work | Tradebinding and Related Work | 323121 |
| 1361 | Prep. asphalt tar roofing siding prod. | Asphalt Shingle and Coating Materials Mfg. | 324122 |
| 561 | Crude petroleum (domestic Prod.ion) | Petroleum Refineries | 324110 |
| 574 | Residual fuels | Petroleum Refineries | 324110 |
| 1394 | Paving mixtures and blocks | Asphalt Paving Mixture and Block Mfg. | 324121 |
| 571 | Gasoline | Petroleum Refineries | 324110 |
| 581 | Petroleum and coal Prod.s, n.e.c. | All Other Petroleum and Coal Prod.s Mfg. | 324199 |
| 1362 | Other asphalt roofing | Asphalt Shingle and Coating Materials Mfg. | 324122 |
| 573 | Light fuel oils | Petroleum Refineries | 324110 |
| 512 | Bituminous coal and Lignite | All Other Petroleum and Coal Prod.s Mfg. | 324199 |
| 614 | Basic organic chemicals | Gum and Wood Chemical Mfg. | 325191 |
| 551 | Residential natural gas | Cyclic Crude and Intermediate Mfg. | 325192 |
| 532 | Liquefied petroleum gas | Industrial Gas Mfg. | 325120 |
| 613 | Basic inorganic chemicals | Alkalies and Chlorine Mfg. | 325181 |
| 531 | Natural gas | Cyclic Crude and Intermediate Mfg. | 325192 |
| 552 | Commercial natural gas | Cyclic Crude and Intermediate Mfg. | 325192 |
| 553 | Industrial natural gas | Cyclic Crude and Intermediate Mfg. | 325192 |
| 662 | Thermoplastic resins | Plastics Material and Resin Mfg. | 325211 |
| 663 | Thermosetting resins | Plastics Material and Resin Mfg. | 325211 |
| 652 | Fertilizer materials | Nitrogenous Fertilizer Mfg. | 325311 |
| 653 | Other agricultural chemicals | Pesticide and Other Agricultural Chemical Mfg. | 325320 |
| 637 | Biological Prod.s | Biological Prod. (except Diagnostic) Mfg. | 325414 |
| 631 | Medicinal and botanical chemicals | Medicinal and Botanical Mfg. | 325411 |
| 638 | Pharmaceutical preparations | Pharmaceutical Preparation Mfg. | 325412 |
| 634 | Preparations, veterinary | Pharmaceutical Preparation Mfg. | 325412 |
| 622 | Paint materials | Paint and Coating Mfg. | 325510 |
| 623 | Allied and miscellaneous paint Prod.s | Paint and Coating Mfg. | 325510 |
| 621 | Prepared paint | Paint and Coating Mfg. | 325510 |
| 675 | Cosmetics and other toilet preparations | Toilet Preparation Mfg. | 325620 |
| 672 | Specialty cleaning, polish. san. prods. | Toilet Preparation Mfg. | 325620 |
| 679 | Misc. chemical prod. and preparations | All Other Miscellaneous Chemical Prod. | 325998 |
| 723 | Laminated plastic sheets, rods, and tubes | Unsupported Plastics Packaging Film. | 326112 |
| 725 | Plastic packaging | Unsupported Plastics Packaging Film | 326112 |
| 721 | Plastic construction Prod.s | All Other Plastics Prod. Mfg. | 326199 |
| 729 | Other plastic Prod.s | All Other Plastics Prod. Mfg. | 326199 |
| 722 | Unsupp. plastic film/sheet/other shapes | Unsupported Plastics Packaging Film | 326112 |
| 713 | Miscellaneous rubber Prod.s | All Other Rubber Prod. Mfg. | 326299 |
| 711 | Crude rubber | Rubber and Plastics Hoses and Belting Mfg. | 326220 |

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| 712 | Tires, tubes, tread, repair materials | Tire Mfg. (except Retreading) | 326211 |
| 1052 | Vitreous china fixtures | Vitreous China Plumbing Fixture | 327111 |
| 1352 | Clay refractories | Clay Refractory Mfg. | 327124 |
| 1345 | Structural clay Prod.s, n.e.c. | Other Structural Clay Prod. Mfg. | 327123 |
| 1342 | Brick and structural clay tile | Brick and Structural Clay Tile Mfg. | 327121 |
| 1353 | Refractories, non clay | Nonclay Refractory Mfg. | 327125 |
| 1261 | Tableware, kitchenware and other pottery | Vitreous China and Other Pottery | 327112 |
| 1313 | Other finished glassware | Other Glass and Glassware Mfg. | 327212 |
| 1265 | Mirrors | Glass Prod. Mfg. | 327215 |
| 1262 | Household glassware | Other Glass and Glassware Mfg. | 327212 |
| 1311 | Flat glass | Flat Glass Mfg. | 327211 |
| 1335 | Prestressed concrete Prod.s | Other Concrete Prod. Mfg. | 327390 |
| 1332 | Concrete pipe | Concrete Pipe Mfg. | 327332 |
| 1333 | Ready-mixed concrete | Ready-Mix Concrete Mfg. | 327320 |
| 1322 | Cement | Cement Mfg. | 327310 |
| 1331 | Concrete block and brick | Concrete Block and Brick Mfg. | 327331 |
| 1334 | Precast concrete Prod.s | Other Concrete Prod. Mfg. | 327390 |
| 1371 | Gypsum Prod.s | Gypsum Prod. Mfg. | 327420 |
| 1395 | Cut stone and stone Prod.s | Cut Stone and Stone Prod. Mfg. | 327991 |
| 1392 | Insulation materials | Mineral Wool Mfg. | 327993 |
| 1136 | Abrasive Prod.s | Abrasive Prod. Mfg. | 327910 |
| 1321 | Construction sand, gravel, and crushed stone | All Other NonMt.lic Mineral Mfg. | 327999 |
| 1399 | NonMt.lic minerals and Prod.s, n.e.c. | All Other NonMt.lic Mineral Mfg. | 327999 |
| 1016 | Blast and electric furnace Prod.s | ElectroMt.lurgical Ferroalloy Prod. Mfg. | 331112 |
| 1012 | Iron and steel scrap | Iron and Steel Mills | 331111 |
| 1017 | Steel mill Prod.s | Iron and Steel Mills | 331111 |
| 1011 | Iron ore | Iron and Steel Mills | 331111 |
| 1022 | Primary nonferrous Mt.s | Smelting and Refining of Nonferrous Mt. | 331419 |
| 1025 | Nonferrous mill shapes | Smelting and Refining of Nonferrous Mt. | 331419 |
| 1026 | Nonferrous wire and cable | Smelting and Refining of Copper | 331411 |
| 1028 | Nonferrous foundry shop Prod.s | Smelting and Refining of Nonferrous Mt. | 331419 |
| 1023 | Nonferrous scrap | Smelting and Refining of Nonferrous Mt. | 331419 |
| 1021 | Nonferrous Mt. ores | Smelting and Refining of Nonferrous Mt. | 331419 |
| 1027 | Nonferrous forage shop Prod.s | Smelting and Refining of Nonferrous Mt. | 331419 |
| 1024 | Secondary nonferrous Mt.s | Smelting and Refining of Nonferrous Mt. | 331419 |
| 1042 | Hand and edge tools | Hand and Edge Tool Mfg. | 332212 |
| 1267 | Cutlery, razors and razor blades | Cutlery and Flatware (except Precious) Mfg. | 332211 |
| 1076 | Fabricated steel plate | Plate Work Mfg. | 332313 |
| 1073 | Sheet Mt. Prod.s | Sheet Mt. Work Mfg. | 332322 |
| 1071 | Mt. doors, sash, and trim | Mt. Window and Door Mfg. | 332321 |
| 1079 | Prefabricated Mt. buildings | Prefabricated Mt. Building and Component Mfg. | 332311 |
| 1072 | Mt. tanks | Mt. Tank (Heavy Gauge) Mfg. | 332420 |
| 1077 | Steel power boilers | Power Boiler and Heat Exchanger Mfg. | 332410 |
| 1032 | Barrels, drums, and pails | Other Mt. Container Mfg. | 332439 |
| 1075 | Heat exchanges and condensers | Power Boiler and Heat Exchanger Mfg. | 332410 |
| 1041 | Hardware, n.e.c. | Hardware Mfg. | 332510 |
| 1088 | Fabricated ferrous wire Prod.s | Other Fabricated Wire Prod. Mfg. | 332618 |
| 1081 | Bolts, nuts, screws, rivets, and washers | Bolt, Nut, Screw, Rivet, and Washer Mfg. | 332722 |
| 1195 | Machine shop Prod.s | Machine Shops | 332710 |
| 1089 | Other miscellaneous Mt. Prod.s | All Other Fabricated Mt. Prod. Mfg. | 332999 |
| 1056 | Mt. sanitary ware | All Other Fabricated Mt. Prod. Mfg. | 332999 |
| 1054 | Brass fittings | Plumbing Fixture Fitting and Trim Mfg. | 332913 |
| 112G | Parts for construction Mch. | Construction Mch. Mfg. | 333120 |
| 1192 | Mining Mch. and Eq. | Mining Mch. and Eq. Mfg. | 333131 |
| 1191 | Oil field and gas field Mch. | Oil and Gas Field Mch. and Eq. Mfg. | 333132 |
| 1114 | Agricultural Mch. and Eq. | Farm Mch. and Eq. Mfg. | 333111 |
| 1266 | Lawn and garden equip., ex. garden tractors | Lawn and Garden Tractor and Eq. Mfg. | 333112 |
| 112D | Off-highway Eq., excluding parts | Construction Mch. Mfg. | 333120 |
| 112I | Construction Mch. and Eq. sold | Construction Mch. Mfg. | 333120 |
| 1164 | Paper industries Mch. | All Other Industrial Mch. Mfg. | 333298 |

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| 1166 | Other special industry Mch. | All Other Industrial Mch. Mfg. | 333298 |
| 1162 | Textile Mch. and Eq. | Textile Mch. Mfg. | 333292 |
| 1163 | Woodworking Mch. and Eq. | All Other Industrial Mch. Mfg. | 333298 |
| 1165 | Printing trades Mch. and Eq. | Printing Mch. and Eq. Mfg. | 333293 |
| 1161 | Food Prod.s Mch. | Food Prod. Mch. Mfg. | 333294 |
| 1541 | Photographic Eq. | Photographic and Photocopying Eq. Mfg. | 333315 |
| 1542 | Photographic supplies | Photographic and Photocopying Eq. Mfg. | 333315 |
| 1168 | Service industry Mch. and parts | Other Commercial and Service Industry Mch. Mfg. | 333319 |
| 1186 | Optical instruments and lenses | Optical Instrument and Lens Mfg. | 333314 |
| 1169 | Commercial laundry dry cleaning equip. | Other Commercial and Service Industry Mch. Mfg. | 333319 |
| 1193 | Office and store machines and Eq. | Office Mch. Mfg. | 333313 |
| 1066 | Water heaters, domestic | Heating Eq. (except Warm Air Furnaces) Mfg. | 333414 |
| 1062 | Warm air furnaces | Air-Conditioning+Warm Air Heating Equip Mfg. | 333415 |
| 1064 | Domestic heating stoves | Heating Eq. (except Warm Air Furnaces) Mfg. | 333414 |
| 1148 | Air conditioning and refrigeration equip | Air-Conditioning+Industrial Refrigeration Equip Mfg. | 333415 |
| 1147 | Fans and blowers, except portable | Industrial and Commercial Fan and Blower Mfg. | 333412 |
| 1061 | Steam and hot water Eq. | Heating Eq. (except Warm Air Furnaces) Mfg. | 333414 |
| 1063 | Conversion burners | Air-Conditioning+Warm Air Heating Equip Mfg. | 333415 |
| 1135 | Cutting tools and accessories | Cutting Tool and Machine Tool Accessory Mfg. | 333515 |
| 113A | Mt.working Mch. n. e. c. | Other Mt.working Mch. Mfg. | 333518 |
| 1139 | Tools, dies, jigs, fixtures ind. molds | Industrial Mold Mfg. | 333511 |
| 1138 | Mt. forming machine tools | Cutting Tool and Machine Tool Accessory Mfg. | 333515 |
| 1137 | Mt. cutting machine tools | Cutting Tool and Machine Tool Accessory Mfg. | 333515 |
| 1194 | Internal combustion engines | Turbine and Turbine Generator Set Units Mfg. | 333611 |
| 1196 | Steam, gas, hydraulic turbines parts | Turbine and Turbine Generator Set Units Mfg. | 333611 |
| 1145 | Mechanical power transmission Eq. | Mechanical Power Transmission Eq. Mfg. | 333613 |
| 1197 | Turbine generator sets and parts | Turbine and Turbine Generator Set Units Mfg. | 333611 |
| 1141 | Pumps, compressors, and Eq. | Pump and Pumping Eq. Mfg. | 333911 |
| 1132 | Power driven hand tools | Power-Driven Handtool Mfg. | 333991 |
| 112A | Tractors and attachments, excluding parts | Industrial Truck, Tractor Mch. Mfg. | 333924 |
| 1133 | Welding machines and Eq. | Welding and Soldering Eq. Mfg. | 333992 |
| 112B | Power cranes, excavators and Eq. | Overhead Traveling Crane, Hoist Mfg. | 333923 |
| 1142 | Elevators, escalators, and other lifts | Elevator and Moving Stairway Mfg. | 333921 |
| 1144 | Industrial material handling Eq. | Conveyor and Conveying Eq. Mfg. | 333922 |
| 1149 | Miscellaneous general purpose Eq. | All Other Miscellaneous General Purpose Mch. Mfg. | 333999 |
| 1167 | Packing and packaging Mch. | Packaging Mch. Mfg. | 333993 |
| 1146 | Scales and balances | Scale and Balance (except Laboratory) Mfg. | 333997 |
| 1143 | Fluid power Eq. | Fluid Power Cylinder and Actuator Mfg. | 333995 |
| 1134 | Industrial process furnaces and ovens | Industrial Process Furnace and Oven Mfg. | 333994 |
| 1152 | Computer storage devices | Computer Storage Device Mfg. | 334112 |
| 1153 | Computer terminals and parts | Computer Terminal Mfg. | 334113 |
| 1154 | Computer peripheral Eq. and parts | Other Computer Peripheral Eq. Mfg. | 334119 |
| 1151 | Electronic computers | Electronic Computer Mfg. | 334111 |
| 1176 | Communication and related Eq. | Other Communications Eq. Mfg. | 334290 |
| 1252 | Television receivers | Radio and Television Eq. Mfg. | 334220 |
| 1257 | Speakers and commercial sound Eq. | Audio and Video Eq. Mfg. | 334310 |
| 1178 | Electronic components and accessories | Other Electronic Component Mfg. | 334419 |
| 1181 | Environmental controls | Automatic Environmental Control Mfg. | 334512 |
| 1172 | Integrating and measuring instruments | Instruments+Related Measuring Mfg | 334513 |
| 1184 | Fluid meters and counting devices | Totalizing Fluid Meter and Counting Device Mfg. | 334514 |
| 1182 | Process control instruments | Instruments Controlling Industrial Process Variables | 334513 |
| 1189 | Measuring and controlling devices, n.e.c. | Other Measuring and Controlling Device Mfg. | 334519 |
| 1185 | Engineering and scientific instruments | Analytical Laboratory Instrument Mfg. | 334516 |
| 159C | Precorded cd/tape/record producing | Prerecorded Compact Disc | 334612 |
| 1245 | Electric lamps | Electric Lamp Bulb and Part Mfg. | 335110 |
| 1177 | Electric lamps/bulbs and parts | Electric Lamp Bulb and Part Mfg. | 335110 |
| 1083 | Lighting fixtures | Residential Electric Lighting Fixture Mfg. | 335121 |
| 1243 | Household vacuum cleaners, parts, attach. | Household Vacuum Cleaner Mfg. | 335212 |
| 1258 | Other home electronic Eq. | Electric Housewares and Household Fan Mfg. | 335211 |
| 1244 | Electric housewares and fans | Electric Housewares and Household Fan Mfg. | 335211 |

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| 1241 | Major appliances | Household Cooking Appliance Mfg. | 335221 |
| 1175 | Switchgear, switchboard, etc. Eq. | Switchgear and Switchboard Apparatus Mfg. | 335313 |
| 1174 | Transformers and power regulators | Power, Distribution, and Specialty Transformer Mfg. | 335311 |
| 1173 | Motors, generators, motor generator sets | Motor and Generator Mfg. | 335312 |
| 1171 | Wiring devices | Current-Carrying Wiring Device Mfg. | 335931 |
| 1416 | Travel trailers and campers | Travel Trailer and Camper Mfg. | 336214 |
| 1413 | Truck and bus bodies | Motor Vehicle Body Mfg. | 336211 |
| 1414 | Truck trailers | Truck Trailer Mfg. | 336212 |
| 1411 | Motor vehicles | Motor Vehicle Body Mfg. | 336211 |
| 1412 | Motor vehicle parts | All Other Motor Vehicle Parts Mfg. | 336399 |
| 1421 | Aircraft | Aircraft Mfg. | 336411 |
| 1423 | Aircraft engines and engine parts | Aircraft Engine and Engine Parts Mfg. | 336412 |
| 1425 | Aircraft parts and auxiliary Eq., nec | Other Aircraft Parts and Auxiliary Eq. Mfg. | 336413 |
| 1442 | Railroad cars and car parts | Railroad Rolling Stock Mfg. | 336510 |
| 1441 | Locomotives and parts | Railroad Rolling Stock Mfg. | 336510 |
| 1431 | Ships | Ship Building and Repairing | 336611 |
| 1432 | Boats | Boat Building | 336612 |
| 1491 | Transportation Eq., n.e.c. | All Other Transportation Eq. Mfg. | 336999 |
| 1212 | Wood household furniture | Nonupholstered Wood Household Furniture Mfg. | 337122 |
| 1213 | Upholstered household furniture | Upholstered Household Furniture Mfg. | 337121 |
| 1216 | Household furniture, n.e.c. | Household Furniture (except Wood and Mt.) Mfg. | 337125 |
| 1211 | Mt. household furniture | Mt. Household Furniture Mfg. | 337124 |
| 1223 | Public building furniture | Institutional Furniture Mfg. | 337127 |
| 1215 | Porch and lawn furniture | Upholstered Household Furniture Mfg. | 337121 |
| 1222 | Mt. office furniture and store fixtures | Office Furniture (except Wood) Mfg. | 337214 |
| 1221 | Wood office furniture and store fixtures | Wood Office Furniture Mfg. | 337211 |
| 1564 | Ophthalmic goods | Ophthalmic Goods Mfg. | 339115 |
| 1571 | Industrial safety Eq. | Surgical Appliance and Supplies Mfg. | 339113 |
| 1565 | Dental Eq. and supplies | Dental Eq. and Supplies Mfg. | 339114 |
| 1563 | Surgical appliances and supplies | Surgical Appliance and Supplies Mfg. | 339113 |
| 1562 | Medical instruments and Eq. | Surgical and Medical Instrument Mfg. | 339112 |
| 1594 | Jewelry and jewelry Prod.s | Jewelry (except Costume) Mfg. | 339911 |
| 1264 | Household flatware | Silverware and Hollowware Mfg. | 339912 |
| 1593 | Musical instruments | Musical Instrument Mfg. | 339992 |
| 1398 | Gaskets, packing, and sealing devices | Gasket, Packing, and Sealing Device Mfg. | 339991 |
| 1512 | Sporting and athletic goods | Sporting and Athletic Goods Mfg. | 339920 |
| 1595 | Pens, pencils, and marking devices | Marking Device Mfg. | 339943 |
| 1532 | Needles, pins, and fasteners | Fastener, Button, Needle, and Pin Mfg. | 339993 |
| 1531 | Buttons, button blanks, and parts | Fastener, Button, Needle, and Pin Mfg. | 339993 |
| 1591 | Caskets | Burial Casket Mfg. | 339995 |
| 1597 | Brooms and brushes | Broom, Brush, and Mop Mfg. | 339994 |
| 1511 | Toys, games, and children's vehicles | Game, Toy, and Children's Vehicle Mfg. | 339932 |
| 1263 | Hollowware | Silverware and Hollowware Mfg. | 339912 |

Abbreviation: Mfg.=Manufacturing, Prod.=Product, Mch.=Machinery, Eq.=Equipment

Notes: Matching of 277 Product code to 202 6-digits NAICS manufacturing. The description of some NAICS industries have been modified to fit into the table. For the full description of the 6-digits 1997 NAICS, visit http://www.nber.org/nberces/.

Sources: Authors' matching using NBER-CES Manufacturing Industry and Product code from Nakamura and Steinsson (2008).

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