

# Input-Output Structure and New Keynesian Phillips Curve

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## Abstract

I show that an input-output production structure reinforces persistence in the pricing behavior of firms using a Calvo mechanism. In particular, the optimal price today depends upon the expected optimal prices in the infinite future and those set in the infinite past. This is due to a part of a firm's marginal cost being represented by other firms' price. It follows that the effect of the marginal cost on inflation in the new Keynesian Phillips curve is dampened by the presence of the input-output structure. This helps in explaining the difference between the most recent empirical evidence on price adjustment frequency in the U.S. (Bils and Klenow, 2004) and structural estimates of the new Keynesian Phillips curve.

**JEL Classification:** E30, E31, E39.

**Keywords:** Pricing under Uncertainty, Inflation, Phillips Curve.

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# 1 Introduction

Recent empirical evidence on the frequency of price adjustment, provided by Bils and Klenow (2004), shows that the time length prices remain fixed is much shorter than the one used to calibrate dynamic macroeconomic models. These authors show that, according to their dataset, the median firm changes prices every 4.3 months, compared to previous findings of around one year, as in Taylor (1999). A higher frequency of price adjustment implies that in the standard New Keynesian Model inflation is more sensitive to marginal cost movements. This is in contrast with empirical estimates of the new Keynesian Phillips curve, according to which the coefficient of marginal cost is small. In fact, the estimation of the curve is consistent with an average price stickiness of more than one year. Here I show that, when an input-output structure of the economy is considered, a higher frequency of price changes may still be consistent with empirical estimates of the new Keynesian Phillips curve.

Most modern macroeconomic models consider production functions with only two inputs, namely capital and labor. Intermediate goods do not usually enter the production function. This is a shortcut, as this specification of production maps the use of capital and labor into net output.<sup>1</sup> However simple, this sort of modelling can have serious implications when considering firms' pricing behavior. The point has been stressed by Basu (1995). He shows that the presence of intermediate inputs acts as a multiplier for price stickiness. The Basu model is static and the analysis is performed using comparative statics as in Blanchard and Kiyotaki (1997). Bergin and Feenstra (2000) extend the analysis using a dynamic setting with Taylor pricing, combining the input-output structure with translog preferences. The result is a higher degree of persistence in pricing behavior with respect to the standard Taylor model of price staggering. Huang and Liu (2004) show that the input-output structure makes price staggering able to generate as much persistence as wage staggering. Bouakez, Cardia and Ruge-Murcia (2005) estimate a multi-sector input-output model and obtain different impulse response functions across sectors. Other related works, stressing the impor-

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<sup>1</sup>An intermediate good is represented by any kind of good used as an input in the production of a final good. These inputs are not only raw materials, but also final goods themselves. They enter production as a flow, being completely destroyed in the production process. Alternatively, intermediate goods can be seen as differentiated capital goods as in Romer (1990). In this view, capital and consumer goods should be seen as identical commodities, differing only in their utilization. Then, capital goods are subject to full depreciation and the measure of the set they belong to is constant over time and equal to one.

tance of intermediate goods for inflation and marginal cost determination are, respectively, Dotsey and King (2006) and Rotemberg and Woodford (1999).

In this paper I extend the analysis in Bergin and Feenstra (2000) replacing the Taylor (1980) pricing behavior with the Calvo (1983) mechanism. This is done for two reasons: first, it has been shown that the two mechanisms imply different responses of the model for similar parameter values.<sup>2</sup> Second, the use of the Calvo mechanism allows me to derive a new Keynesian Phillips curve and compare it with the standard one used in the literature. The findings suggest that the new Keynesian Phillips curve, as obtained by introducing intermediate goods into the production function, may account for observed inflation, even for high frequencies of price adjustment.

The paper is organized as follows: sections 2 to 4 present the theoretical model; section 5 shows how the input-output structure can be used to reconcile the micro evidence on price adjustment and the new Keynesian Phillips curve estimates; section 6 discusses some features of the model proposed; section 7 makes a comparison between intermediate goods and capital accumulation in the determination of marginal cost; section 8 concludes.

## 2 Pricing behavior with intermediate goods

In the model presented here, each existing good is both consumed and used in the production of all other goods in the economy. I refer to this environment as an input-output economy (IO model hereafter) or, alternatively, as an economy with intermediate inputs in production.

Markets are complete, which permits to deal with a representative agent environment. I omit the consumer's problem, which is standard.<sup>3</sup> There is a continuum of goods  $i \in [0, 1]$  in the economy. The household's demand function for good  $i$  at time  $t$  is

$$c_{it} = \left( \frac{p_{it}}{P_t} \right)^{-\theta} C_t, \quad (1)$$

where  $c_{it}$  is consumer's demand for good  $i$ ,  $p_{it}$  is the price of product  $i$ ,  $P_t$  is the economy price index,  $C_t = \left[ \int_0^1 c_{it}^{\frac{\theta-1}{\theta}} di \right]^{\frac{\theta}{\theta-1}}$  is a Dixit-Stiglitz aggregator of consumption entering the consumer's utility function and  $\theta$  represents the elasticity of substitution among differentiated goods.

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<sup>2</sup>Kyley (2002).

<sup>3</sup>See Walsh (2003), chapter 5.

Each firm  $i \in [0, 1]$  produces its own differentiated good according to a Cobb-Douglas production function<sup>4</sup>

$$y_{it} = M_{it}^\alpha N_{it}^{1-\alpha}, \quad (2)$$

where  $\alpha \in [0, 1]$ ,  $N_{it}$  is labor used in production and  $M_{it}$  is an aggregator of intermediate goods defined in the same fashion as the consumption aggregator<sup>5</sup>

$$M_{it} = \left[ \int_0^1 (m_{jt}^i)^{\frac{\theta-1}{\theta}} dj \right]^{\frac{\theta}{\theta-1}}, \quad (3)$$

over all goods in the economy, here denoted by  $j \in [0, 1]$ . This specification implies the demand function for the intermediate good  $j$  from firm  $i$

$$m_{jt}^i = \left( \frac{p_{jt}}{P_t} \right)^{-\theta} M_{it}, \quad (4)$$

and integrating over  $i$  the total demand as an investment good for firm  $j$  is obtained

$$m_{jt} = \left( \frac{p_{jt}}{P_t} \right)^{-\theta} M_t, \quad (5)$$

where  $M_t = \int_0^1 M_{it} di$  is the total demand of intermediate goods in the economy at time  $t$ . Total demand for good  $i$  at  $t$  is then

$$D_{it} = \left( \frac{p_{it}}{P_t} \right)^{-\theta} D_t, \quad (6)$$

where  $D_{it} = c_{it} + m_{it}$  and  $D_t = C_t + M_t$ .

Firms adjust prices according to the Calvo (1983) mechanism. Each period, a proportion  $\omega$  of randomly chosen firms is not allowed to change prices. Firms in the remaining  $1-\omega$  measure maximize the stream of present and future real profits by solving

$$\max_{p_t} E_t \sum_{k=0}^{\infty} \omega^k Q_{t,t+k} \left[ \frac{p_t}{P_{t+k}} - \varphi_{t+k} \right] D_{it+k}, \quad (7)$$

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<sup>4</sup>Although Woodford (2003), p. 170, criticizes the use of the Cobb-Douglas production function for intermediate goods and labor, here I follow Basu (1995) and Bergin and Feenstra (2000) who first showed, using a Cobb-Douglas production function, that an input-output structure matters for price determination.

<sup>5</sup>The parameter  $\theta$ , which governs the elasticity of substitution of goods inside the Dixit-Stiglitz aggregator, is assumed to be the same for consumers and firms. This is done for exposition purposes as the results of the paper would be unchanged assuming a different  $\theta$  for the two categories.

where  $E_t(\cdot)$  is the mathematical expectation at  $t$ ,  $Q_{t,t+k} = \beta^k \left(\frac{C_{t+k}}{C_t}\right)^{-\sigma}$  is the stochastic discount factor derived from the household problem,<sup>6</sup>  $\beta$  is the subjective discount factor,  $\sigma$  is the inverse of the intertemporal elasticity of substitution, and  $\varphi_{t+k}$  is the firm's real marginal cost. The price index  $P_{t+k}$  is defined as

$$P_{t+k} = \left[ \int_0^1 p_{it+k}^{1-\theta} di \right]^{\frac{1}{1-\theta}}. \quad (8)$$

As all firms changing price at  $t$  will post the same price, because they face the same maximization problem, the subscript  $i$  is omitted and  $p_t$  represents the price set by all firms adjusting at  $t$ . The problem of the firm coincides with a standard problem, in which labor is the only input of a constant returns to scale production (SD model hereafter), except for two features: first, the demand function  $D_{it+k}$  is now the sum of consumption and intermediate goods demand; second, from the cost minimization problem, in which firms take factor prices as given, I can write real marginal cost as

$$\varphi_{t+k} = \frac{1}{\Phi} \frac{P_{t+k}^\alpha W_{t+k}^{1-\alpha}}{P_{t+k}} = \frac{1}{\Phi} \left( \frac{W_{t+k}}{P_{t+k}} \right)^{1-\alpha}, \quad (9)$$

where  $\Phi = \alpha^\alpha (1-\alpha)^{1-\alpha}$  and  $W_{t+k}$  is the nominal wage rate at  $t+k$ . The labor market is competitive. Then, the relevant marginal cost for the firm is measured by the real wage rate to the power of  $1-\alpha$ , which governs the importance of labor in the production function (2).<sup>7</sup> In the SD model the real marginal cost is simply given by  $\varphi_{t+k} = \frac{W_{t+k}}{P_{t+k}}$ .

### 3 Implications for the price level

By log-linearizing the first order condition of problem (7) around a flexible price steady state with zero inflation it is possible to derive an expression relating the optimal price with the current and the expected future nominal marginal costs

$$\hat{p}_t = (1-\omega\beta) E_t \left\{ \sum_{k=0}^{\infty} (\omega\beta)^k \left( \hat{\varphi}_{t+k} + \hat{P}_{t+k} \right) \right\}. \quad (10)$$

Here a variable  $\hat{x}_t$  is defined as  $\hat{x}_t = \log x_t - \log x^{ss}$ , where  $x^{ss}$  is the steady state value of  $x_t$ . Using the log-linearization of the real marginal cost in (9)

<sup>6</sup>See Walsh (2003), chapter 5.

<sup>7</sup>In perfect competition  $1-\alpha$  coincides with the labor share of total output. In sticky price models with monopolistic competition this is not the case.

I obtain

$$\hat{\varphi}_{t+k} + \hat{P}_{t+k} = (1 - \alpha) \hat{w}_{t+k} + \alpha \hat{P}_{t+k}. \quad (11)$$

Then, (10) becomes

$$\hat{p}_t = (1 - \omega\beta) E_t \left\{ \sum_{k=0}^{\infty} (\omega\beta)^k \left( (1 - \alpha) \hat{w}_{t+k} + \alpha \hat{P}_{t+k} \right) \right\}. \quad (12)$$

The optimal price depends on the present and the expected future values of the nominal wage rate and the price index in the proportions, respectively,  $1 - \alpha$  and  $\alpha$ . When  $\alpha \rightarrow 0$ ,  $\hat{p}_t$  depends only on the nominal wage rate, as in the SD model.<sup>8</sup>

The law of motion of the price index can now be used to characterize  $\hat{p}_t$ . Using (8) together with Calvo price-setting this is equal to

$$P_t^{1-\theta} = \omega P_{t-1}^{1-\theta} + (1 - \omega) p_t^{1-\theta}, \quad (13)$$

and in log-deviations

$$\hat{P}_t = \omega \hat{P}_{t-1} + (1 - \omega) \hat{p}_t. \quad (14)$$

Using (12) and (14) I can write

$$\hat{p}_t = \Gamma (1 - \alpha) \hat{w}_t + \Gamma \alpha \omega \hat{P}_{t-1} + \Gamma E_t \left\{ \sum_{k=1}^{\infty} (\omega\beta)^k \left( (1 - \alpha) \hat{w}_{t+k} + \alpha \hat{P}_{t+k} \right) \right\}, \quad (15)$$

where  $\Gamma = (1 - \omega\beta) [1 - \alpha(1 - \omega\beta)(1 - \omega)]^{-1}$  is a positive constant. From (15) it is evident how the optimal price at  $t$  depends on the price index at  $t - 1$ . This effect is present only when intermediate goods are considered in production,  $\alpha > 0$ . This is due to part of a firm's cost being represented by other goods price. As a proportion  $\omega$  of firms is not allowed to change prices at  $t$ , the marginal cost in that period, and then the optimal price, will be anchored to the previous period price index. This backward-looking dependence of the optimal price grows together with  $\alpha$  because, the larger this parameter, the larger the share of marginal cost depending on the previous period price index. In the limit, when  $\alpha \rightarrow 1$ , the optimal price is not linked anymore to the nominal wage and depends only on past and future values of the price index.

Solving (14) backwards it is possible to write (12) in terms of the optimal prices set in the infinite past and expected optimal prices in the infinite

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<sup>8</sup>In the SD model total factor productivity (TFP) is also a component of the marginal cost. As pointed out above, I consider TFP constant and equal to one in the production function (2).

future

$$\begin{aligned} \hat{p}_t = & \Lambda (1 - \omega^2\beta) (1 - \alpha) E_t \left\{ \sum_{k=0}^{\infty} (\omega\beta)^k \hat{w}_{t+k} \right\} + \Lambda (1 - \omega) \alpha \omega \sum_{k=0}^{\infty} \omega^k \hat{p}_{t-1-k} + \\ & + \Lambda \alpha (1 - \omega) E_t \left\{ \sum_{k=1}^{\infty} (\omega\beta)^k \hat{p}_{t+k} \right\}, \end{aligned} \quad (16)$$

where  $\Lambda = (1 - \omega\beta) [1 - \omega^2\beta - \alpha(1 - \omega\beta)(1 - \omega)]^{-1}$ . Details of the derivation are given in the appendix. From (16) it is clear the dependence of optimal prices across time. The use of intermediate goods provides then a clear mechanism through which the pricing behavior of firms in the IO model is more persistent than in the Calvo pricing mechanism alone. In this context, the frequency of price adjustment is less decisive for price determination. The reason is that adjusting firms will anyway set a closer price to those remaining fixed than in the SD model. Thus, even when the frequency of price adjustment increases, each time a firm faces the possibility to adjust its price, it will choose not to deviate much from the previous level of the price.

## 4 Implications for the inflation rate

The Phillips Curve derived in the SD New Keynesian Models takes the simple form<sup>9</sup>

$$\pi_t = \beta E_t \pi_{t+1} + \kappa \hat{\varphi}_t, \quad (17)$$

where  $\kappa = (1 - \omega\beta)(1 - \omega)\omega^{-1}$ , and  $\hat{\varphi}_t$  is the real marginal cost. It is easy to show that in the IO model the Phillips curve takes the same form as in (17). The only difference is the real marginal cost. Using the definition of real marginal cost from the SD and the IO model, the new Keynesian Phillips curve in (17) becomes, respectively<sup>10</sup>,

$$\pi_t = \beta E_t \pi_{t+1} + \kappa (\hat{w}_t - \hat{P}_t), \quad (18)$$

and

$$\pi_t = \beta E_t \pi_{t+1} + \kappa(1 - \alpha) (\hat{w}_t - \hat{P}_t). \quad (19)$$

The parameter  $\alpha$  is crucial in determining the difference in the impact of the marginal cost on inflation between the two models. In the standard

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<sup>9</sup>Strictly speaking, the new Keynesian Phillips curve is expressed in terms of the output-gap instead of the real marginal cost. The choice of the latter will be made clear below.

<sup>10</sup>Recall that the production technology is constant over time.

model, the real wage is the unique component of the real marginal cost, so the impact of shocks on the real wage is entirely transmitted to inflation, as made clear by equation (18). In the input-output model, two are the components of the real marginal cost, the ratio of intermediate inputs price and the nominal marginal cost deflator and the real wage. However, as the price of intermediate goods is equal to the nominal marginal cost deflator, it turns out that the relevant component of the real marginal cost to inflation is still the real wage. As the latter is only a part of the real marginal cost, the impact on inflation is reduced to the proportion  $1 - \alpha$  of the shock on the real wage. The intuition is the same as for the pricing equation (15): when firms set new prices, there is a component of the pricing rule, given by the part of marginal cost due to non-adjusting firms, suggesting to set the optimal price at the same level as the price index of the previous period.

Equation (19) can be solved forward to obtain

$$\pi_t = E_t \sum_{k=0}^{\infty} \beta^k \kappa (1 - \alpha) (\hat{w}_{t+k} - \hat{P}_{t+k}). \quad (20)$$

Consequently, inflation is represented by the discounted sum of expected future real wages, weighted by  $\kappa(1 - \alpha)$ . In the limit, were the intermediate goods the only input in production, inflation would tend to zero. This would imply complete price stickiness and zero inflation over time. The economic intuition for this result is the following. When  $\alpha = 1$  the real marginal cost of the firm is given by the price of intermediate goods divided by the nominal marginal cost deflator. In the model, the nominal marginal cost deflator is the price of output, which is equal to the price of intermediate goods, as all goods in the economy are both consumed and used as intermediate inputs. Thus, by definition, the real marginal cost is always constant when  $\alpha = 1$ . As inflation depends on real marginal cost movements, it is zero when intermediate goods are the only input in production.<sup>11</sup>

## 5 Reconciling the micro and macro evidence on price adjustments

Recently, [Bils and Klenow \(2004\)](#) provided micro evidence on the frequency of price adjustment in the U.S. This evidence appears in contrast with empirical estimates of the new Keynesian Phillips curve based on the SD model.

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<sup>11</sup>However, it must be noted that this is only a hypothetical situation, as a productive input-output structure requires the utilization of a positive amount of at least one of the primary inputs, capital and labor.



In particular, estimations of the curve for the U.S. imply a frequency of price adjustment which is too low compared to the micro evidence. In this section I put forth the following question: is it possible to use the IO model presented in this paper to reconcile the micro and macro evidence on the frequency of price adjustment?

Bils and Klenow (2004), using U.S. Bureau of Labor Statistics data, present evidence on the frequency of price adjustment for 350 categories of consumer goods and services which cover 70% of total consumption expenditure. They show that the median firm in their dataset changes prices every 4.3 months, which implies a value of  $\omega$  around 0.3.<sup>12</sup> This evidence represents the benchmark for calibrating New Keynesian Models and adds to the previous one, due to Taylor (1999), suggesting an average duration of around one year. Gali and Gertler (1999), using U.S. data, show that the marginal cost fits the data, when estimating the new Keynesian Phillips curve, better than the output gap. They explain the difference arguing that the measure of marginal cost they employ does not commove with output over the business cycle, but it responds with some delay. Comparing Bils and Klenow (2004) and Gali and Gertler (1999) it appears that the estimates of the parameter  $\omega$  are remarkably different. Gali and Gertler (1999) estimate  $\omega$  to be between 0.83 and 0.88, depending on the different normalizations of the orthogonality conditions of the GMM estimation, implying an average price stickiness ranging from one year and a half to two years. Although the same authors argue that the estimation might be upward biased, these values are extremely far from 0.3, which implies an average duration slightly longer than four months, as in Bils and Klenow (2004).

Consider the implications of a high frequency of price adjustment for the new Keynesian Phillips curve in the SD model. When setting a value of 0.3 for  $\omega$  and one of 0.99 for  $\beta$ , the implied value of  $\kappa$  in (18) is 1.64, much higher than the 0.023 Gali and Gertler report for the coefficient of marginal cost in their estimation of the New Keynesian Phillips Curve.<sup>13</sup> A  $\kappa$  of 1.64 implies that inflation responds more than proportionally to changes in the marginal cost. Consider now the IO model presented in this paper. In this model, equation (18) is replaced by equation (19).<sup>14</sup> This requires to calibrate  $\alpha$ , as

<sup>12</sup>To see this, note that the average duration of a Poisson process with mean  $1 - \omega$  is  $(1 - \omega)^{-1}$ . In the Calvo mechanism, this represents the average waiting time before changing price. Then,  $(1 - 0.3)^{-1} = 1.42$ . As the model time period is one quarter this implies an expected duration slightly longer than four months.

<sup>13</sup>Recall that  $\kappa = (1 - \omega\beta)(1 - \omega)\omega^{-1}$ .

<sup>14</sup>Gali, Gertler and Lopez-Salido (2001) assume a decreasing returns to scale production function in labor only to obtain a lower impact of the real wage on inflation. Here I obtain

**Table 1**

$\omega$	Average Duration in quarters	$\kappa(1-\alpha)$						
		$\alpha=0$	$\alpha=0.1$	$\alpha=0.3$	$\alpha=0.5$	$\alpha=0.7$	$\alpha=0.8$	$\alpha=0.9$
0.01	1.01	98.02	88.22	68.61	49.01	29.41	19.60	9.80
0.10	1.11	8.11	7.30	5.68	4.05	2.43	1.62	0.81
0.20	1.25	3.21	2.89	2.25	1.60	0.96	0.64	0.32
0.30	1.43	1.64	1.48	1.15	0.82	0.49	0.33	0.16
0.40	1.67	0.91	0.82	0.63	0.45	0.27	0.18	0.09
0.50	2.00	0.51	0.45	0.35	0.25	0.15	0.10	0.05
0.60	2.50	0.27	0.24	0.19	0.14	0.08	0.05	0.03
0.70	3.33	0.13	0.12	0.09	0.07	0.04	0.03	0.01
0.80	5.00	0.05	0.05	0.04	0.03	0.02	0.01	0.01
0.90	10.00	0.01	0.01	0.01	0.01	0.00	0.00	0.00
$\beta=0.99$								

the coefficient in (19) is given by  $\kappa(1 - \alpha)$ . For this purpose I use the value proposed in Basu (1995) who suggests a range between 0.8 and 0.9.<sup>15</sup> This calibration implies that the coefficient of real wages on inflation in (19) lies between 0.16 and 0.33, more than 80% smaller than the SD case represented by equation (18). As one may not accept values of  $\alpha$  which are that high, I also calibrate  $\alpha$  between 0.01 and 0.9. The results for the coefficient  $\kappa(1 - \alpha)$  are reported in Table 1. Even for values of  $\alpha$  of 0.5 and 0.7 I obtain low values of  $\kappa(1 - \alpha)$  such as 0.82 and 0.49, respectively. As a result, the IO model proposed helps in explaining the small impact of the marginal cost in the estimated new Keynesian Phillips curve, even for low values of the stickiness parameter  $\omega$ .

It must be noted that even with the IO model it is hard to calibrate the model to obtain 0.023 as in Gali and Gertler (1999). However, intermediate goods represent only one of the mechanisms that provide price stickiness at the firm level. It is likely that, combining intermediate goods with other mechanisms might provide a coefficient of the magnitude estimated in Gali and Gertler (1999). In section 7, I will compare one of these mechanisms, capital accumulation, with intermediate goods.

a similar effect using constant returns and intermediate goods.

<sup>15</sup>Note that this calibration is reasonable because the static model in Basu (1995) coincides with the steady state equilibrium of the IO model proposed here.

## 6 Discussion

The IO model adds several implications to the standard New Keynesian Model. The most apparent implication is that the frequency of price adjustment becomes less important for inflation dynamics. Although a firm may change price frequently, it will not set a price too different from previous periods optimal prices and expected future optimal prices. This occurs because a part of the firm's marginal cost is represented by other firms' price. If the importance of intermediate goods in production is high, this fact will have a countervailing effect on inflation with respect to the frequency of price adjustment. The model proposed is then qualitatively consistent with the apparent conflict between the observed sluggishness of aggregate inflation and the high frequency of price adjustment at the firm level observed in the U.S.<sup>16</sup>

Another feature of the model emerges when one considers the dependence of inflation on the parameter  $\alpha$ , the exponent of intermediate goods in the Cobb-Douglas production function. This parameter is strictly related to the share of intermediate goods in gross output in the economy. Thus, if the share of intermediate goods is not constant, structural inflation might change over time.<sup>17</sup> In Moro (2009) I show that the share of intermediate goods in gross output is larger in manufacturing than in services. This fact, together with the increase of the services share in the economy's output, implies a decline in the overall share of intermediate goods in the U.S. during the 1960-2005 period. Thus, according to the model presented in this paper, the structural inflation is becoming more responsive to marginal cost movements. A natural direction for future research is to study, through simulations, how much the change occurred in the share of intermediate goods over time affected inflation in the U.S.

Typically, there are several difficulties in the estimation of the new Keynesian Phillips curve. In particular, it is hard to find appropriate measures of the output gap and the marginal cost. The problem with the output gap is that it is not clear which is the measure of potential output that should be considered. Instead, measures of the marginal cost must be based on the technology that is assumed in the model. In the IO model presented here, the relevant marginal cost depends crucially on the real wage. Al-

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<sup>16</sup>See Altig et al. (2004).

<sup>17</sup>For instance, the production function in (2) might take the form

$$y_{it} = M_{it}^{\alpha_t} N_{it}^{1-\alpha_t}$$

where  $\alpha_t \in [0, 1]$  follows some stochastic process.

though it is easy to find several measures of the real wage, it is not clear how to choose the relevant one for an estimation of the economy wide new Keynesian Phillips curve. On this point, note that in a GMM estimation of the new Keynesian Phillips curve (19) similar to the one performed in Galí and Gertler (1999), the parameter  $\alpha$  cannot be identified. This fact, together with the limited availability of data on intermediate goods and gross output poses serious problems to pin down the parameter  $\alpha$  through estimation methods. In this sense, the calibration exercise proposed in the previous section represents a useful first step to understand the quantitative properties of the model.

Finally, note that the results obtained for inflation and pricing decisions rely on the assumption that each producer uses all goods in the economy as inputs. This may appear unrealistic. However, the input-output tables of the U.S. economy show only few zeros, as Basu (1995) points out. This observation rationalizes the assumption made to build the model.

## 7 Intermediate Inputs and Capital

Equation (20) shows that inflation is a weighted average of current and expected future real marginal costs. The result holds whenever firms adjust prices in a Calvo fashion. Thus, to understand inflation behavior it is crucial to identify the relevant marginal cost for the firm. The present work stresses the importance of intermediate goods in the determination of the marginal cost. Sveen and Weinke (2004), instead, focus on the importance of capital accumulation. In particular, they show that when firms own the stock of capital they use in production, the effect of a monetary shock on inflation is dampened with respect to the case in which a rental market for capital is assumed. Altig et al. (2005) estimate a model in which capital is firm owned. Exploiting the same mechanism as in Sveen and Weinke (2004) they are able to match post-war aggregate inflation in the U.S. even for a high frequency of price adjustment. Other related works, that look for alternative mechanisms of marginal cost determination are Gilchrist and Williams (2000), who use putty-clay technologies and Christiano et al. (2005), who stress the importance of wage rigidities.

In this section, I compare the importance of capital and intermediate goods for marginal cost determination. Among the mechanisms mentioned above, I focus on capital accumulation for the following reason. Strictly speaking, intermediate goods can be considered a sort of capital that completely depreciates during the production process. Thus, in what follows, I

am interested in stressing the difference between the price stickiness obtained using intermediate goods and that provided by standard capital accumulation decisions. Both intermediate goods and capital contribute to lower the effect of marginal cost on inflation, but the mechanisms through which they work are different. Sveen and Weinke (2004) show that in the absence of a rental market for capital, capital accumulation influences pricing decisions through its impact on the marginal cost when firms set prices in a Calvo fashion. I follow them in defining a Cobb-Douglas production function

$$y_{it} = K_{it}^\alpha N_{it}^{1-\alpha}, \quad (21)$$

where  $K_{it}$  and  $N_{it}$  are the capital stock and the amount of labor used by firm  $i$  at  $t$ . Each firm faces convex adjustment costs in capital accumulation and capital becomes productive with one period delay. This implies that the real marginal cost is given by

$$\varphi_{it} = \frac{W_t}{P_t} \frac{1}{MPL_{it}}. \quad (22)$$

Equation (22) results from the cost minimization problem. The mechanism through which capital accumulation generates persistence in pricing behavior is the following. Capital accumulation affects marginal cost through the marginal productivity of labor in (22). The higher the stock of capital, the higher the marginal productivity of labor and the lower the marginal cost. When allowed to change its price, a firm considers that the chosen price will influence its marginal cost. In particular, when price is higher than average, production will be lower and marginal cost as well. This is what Sveen and Weinke (2004) call "short run" decreasing returns to scale. Then, the equilibrium condition that requires the price to be set as a mark-up over marginal cost will be satisfied at a lower price than in the case where a rental market is assumed. In the latter case the marginal cost is common across firms and it is given by

$$\varphi_t = \frac{W_t}{P_t} \frac{1}{MPL_t}, \quad (23)$$

where  $MPL_t$  is the average marginal product of labor in the economy. In this case the price set by a firm does not influence its marginal cost and the profit maximization condition is met at a higher optimal price. To summarize, decreasing returns to scale in the short run imply a degree of price stickiness which is higher than the case with constant returns to scale. If a monetary shock occurs the firm will have its marginal cost raised only

in the measure labor enters the production function. There is an upward pressure only on real wages and not on the cost of capital because this is firm owned.

Also when intermediate goods are modelled in production the marginal cost reacts in the measure labor enters the production function after a monetary shock. However, the extent to which marginal cost reacts does not depend on the marginal product of labor of the single firm. The relevant marginal cost with intermediate inputs, given by equation (9), is common across firms and it is different with respect to the model with firm specific capital, equation (22). Thus, in the model presented here the stickiness in pricing behavior does not rely on a firm specific input, which is the case in the model with capital accumulation.

To conclude, both intermediate inputs and firm specific capital justify the low coefficient of marginal cost in the new Keynesian Phillips curve. Both inputs dampen the effect of monetary shocks on a firm's marginal cost. Models that avoid using these inputs into the production function may be misleading qualitatively and quantitatively.

## 8 Conclusions

The present work stresses the importance of intermediate goods for inflation behavior. In particular, I nest an input-output production structure into an otherwise standard New Keynesian Model to highlight the higher degree of price stickiness and the different inflation behavior with respect to the latter.

The model is able to help reconciling the most recent empirical evidence on the frequency of price adjustment in the U.S. with estimates of the new Keynesian Phillips curve that imply much lower frequencies. This point is fundamental to understand inflation behavior. What a monetary model should provide is a framework in which firms adjust prices frequently but aggregate inflation is low, as observed in the data. The model presented accomplish this task exploiting intermediate goods. When a part of the marginal cost of the firm is represented by other firms' price, there is an incentive that leads the firm not to change its price to a large extent. This incentive is present each time the firm sets a new price. Thus, even if the frequency of price adjustment increases, the effect on aggregate inflation is limited.

In the framework presented, the parameter governing the importance of intermediate goods in production matters at least as much as the frequency of price adjustment in inflation determination. When this parameter, which

is strictly related to the share of intermediate goods in the economy, is larger, the response of inflation to marginal cost variations is smaller. I study the effects of the change in the share of intermediate goods on inflation in the U.S. in current research.

Additional empirical evidence is needed to check for the validity of the theory proposed. The prediction of the model is that, depending on the value of the parameter governing the importance of intermediate goods in production, the impact of changes in marginal cost on inflation have different magnitudes. Then, it is reasonable to expect that countries with different intermediate goods intensities display different inflation patterns. This point can be of particular importance for the conduct of monetary policy. In countries in which intermediate goods have a low importance in production, inflation should be more sensitive to marginal cost variations, and monetary policy should be more aggressive than in countries where the intensity of intermediate goods in production is larger.

## Appendix

Here I derive equation (16) from (12) and (14). I report the two equations for convenience

$$\hat{p}_t = (1 - \omega\beta) E_t \left\{ \sum_{j=0}^{\infty} (\omega\beta)^j \left( (1 - \alpha) \hat{w}_{t+j} + \alpha \hat{P}_{t+j} \right) \right\},$$

$$\hat{P}_t = \omega \hat{P}_{t-1} + (1 - \omega) \hat{p}_t.$$

First, using (14) I can find an expression for  $\sum_{k=0}^{\infty} (\omega\beta)^k \alpha \hat{P}_{t+k}$  in terms of  $\hat{P}_{t-1}$  and future optimal prices. This is done solving (14) backwards until  $\hat{P}_{t-1}$ , for each  $t + k$ ,  $k = 0, \dots, \infty$  and plugging the resulting expression in  $\sum_{k=0}^{\infty} (\omega\beta)^k \alpha \hat{P}_{t+k}$ . This implies

$$\begin{aligned} \sum_{k=0}^{\infty} (\omega\beta)^k \alpha \hat{P}_{t+k} &= \alpha \left[ \frac{\omega}{(1 - \omega^2\beta)} \hat{P}_{t-1} + \frac{1 - \omega}{(1 - \omega^2\beta)} \hat{p}_t \right] + \\ &+ \alpha (1 - \omega) E_t \left\{ \sum_{k=1}^{\infty} \sum_{s=0}^{\infty} (\omega\beta)^{k+s} \omega^s \hat{p}_{t+k} \right\}. \end{aligned}$$

Equation (14) can then be written as

$$\hat{p}_t = (1 - \omega\beta) E_t \left\{ \sum_{k=0}^{\infty} (\omega\beta)^k (1 - \alpha) \hat{w}_{t+k} \right\} +$$

$$+ \left[ \frac{\alpha (1 - \omega\beta) \omega}{(1 - \omega^2\beta)} \hat{P}_{t-1} + \frac{\alpha (1 - \omega\beta) (1 - \omega)}{(1 - \omega^2\beta)} \hat{p}_t \right] + \\ + \alpha (1 - \omega) (1 - \omega\beta) E_t \left\{ \sum_{k=1}^{\infty} \sum_{s=0}^{\infty} (\omega\beta)^{k+s} \omega^s \hat{p}_{t+k} \right\},$$

which implies, using  $\sum_{k=1}^{\infty} \sum_{s=0}^{\infty} (\omega\beta)^{k+s} \omega^s \hat{p}_{t+k} = \frac{1}{(1 - \omega^2\beta)} \sum_{k=1}^{\infty} (\omega\beta)^k \hat{p}_{t+k}$ ,

$$\hat{p}_t = \Lambda (1 - \omega^2\beta) (1 - \alpha) E_t \left\{ \sum_{k=0}^{\infty} (\omega\beta)^k (1 - \alpha) \hat{w}_{t+k} \right\} + \\ + \Lambda \alpha \omega \hat{P}_{t-1} + \Lambda \alpha (1 - \omega) E_t \left\{ \sum_{k=1}^{\infty} (\omega\beta)^k \hat{p}_{t+k} \right\}. \quad (24)$$

Solving backwards equation (14) at  $t - 1$ , I obtain

$$\hat{P}_{t-1} = \sum_{k=0}^{\infty} (1 - \omega) \omega^k \hat{p}_{t-1-k}.$$

Using the last expression in (24) I obtain equation (16).



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