Inventory Behavior and the Cost Channel of Monetary Transmission

Gewei Wang*

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Abstract

We extend a dynamic New Keynesian model by introducing inventories and convex adjustment costs to study the cost channel of monetary transmission. We focus on three empirical observations following a monetary policy shock: (1) swift changes of the interest rate; (2) slow adjustment of output and inventories; and (3) slow adjustment of aggregate price. In a model without adjustment costs, the cost channel implies that a decline in interest rates should reduce firms’ financing costs and motivate them to build up inventories. Therefore, in order to bring the model’s inventory predictions in line with the data, we need to assume high costs in capacity adjustment. As a result, the cost channel leads to a surge in the marginal cost. Calibrating the benchmark model with the cost channel and adjustment frictions, we find that the resulting impact of monetary policy on macroeconomic variables is strong in the short run and nonpersistent over the cycle. We show that two sources of real rigidity help to reconcile high adjustment costs and price stickiness. These two sources of real rigidity are both relevant to adjustment frictions. One arises from firms’ motives for dynamic cost smoothing. The other is related to endogenous marginal cost and strategic complementarity.

*Department of Economics, University of California, Berkeley (email: geweiwang@gmail.com). I am grateful to Professor Yuriy Gorodnichenko, Professor Pierre-Olivier Gourinchas, Professor Maurice Obstfeld, Professor David Romer, and all the participants in the Graduate Student Mini Symposium for helpful comments and advice.

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1 Introduction

The demand-side transmission mechanism has been explored extensively to identify whether shocks in monetary policy exert real effects on the economy. Alternatively, some researchers proposed that the cost-side, or supply-side, channel may be also important\(^1\).

The cost channel is analyzed by most of the general equilibrium models\(^2\) with the assumption of intra-period financing: firms must borrow to finance the payments of working capital before they receive revenues from sales. When, for example, an expansionary shock of monetary policy occurs, the nominal interest rate declines and financing costs become lower. As a result, the marginal cost tends to be countercyclical or acyclical. If markups are also countercyclical due to moderate nominal rigidity, the models imply sluggish price adjustment and large real effects of monetary policy shocks.

This paper seeks to rethink the cost channel by considering the role of interest rates in the decision of inventory stocks\(^3\). Inventory behavior has implications for monetary transmission by its very nature. In a theoretical economy where the market clears for each firm’s product, output always equals demand, so it is difficult to identify whether a change in output is driven by a mechanism from the demand side or from the supply side. In contrast, inventory investment represents the difference between sales and output. Investigating inventories thus helps to disentangle these two transmission channels. In fact, empirical evidence shows that the ratio of inventory to sales is countercyclical and inventory investment is acyclical the short run, but the cost channel implies that lower costs should lead to a much higher level of inventory holdings. The inconsistency suggests that either the cost channel may not be effective or there are strong frictions on the supply side.

We present a New Keynesian model with inventory holdings and adjustment costs to shed light on the point. We find that high adjustment costs reconcile two empirical observations: swift changes of financing costs and sluggish adjustment in production and inventories. Inventories can be viewed as the working capital held and financed for a long period\(^4\). In a dynamic model, a decline in the interest rate raises a firm’s valuation of future production costs and current costs become relatively low. Therefore, whether for short-term or for long-term financing, interest rate changes have same effects on production costs and the use of working capital. For example, a decline in the interest rate due to a monetary expansion should motivate firms to build up inventories. Short-run adjustment costs thus must be high to reconcile our model with the cyclical behavior of inventories. Otherwise, if current adjustment costs are low, cost smoothing suggests that future adjustment costs must be even lower, which cannot be justified in the model with an expansionary shock.

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\(^1\)See Barth and Ramey (2001) for evidence and more references.

\(^2\)For example, see Christiano et al. (2005).

\(^3\)There are mainly two measures of working capital: gross working capital, which is equal to the value of inventories plus trade receivables; and net working capital, which nets out trade payables.

\(^4\)The turnover period of inventories (the average time a good is held in inventory) used by NIPA is 4 months.
We find that the effect of the traditional cost channel on the marginal cost depends on the level of adjustment costs. The marginal cost is not necessarily high in the presence of high adjustment costs. It also depends on how strong a firm’s incentive is to adjust output. In a model without adjustment costs, a decline in interest rates lowers the marginal cost, so the cost channel plays a cost-restraining role. In a model with adjustment costs, the larger decreases in interest rates, the larger marginal cost is. Instead, if we shut down the financing cost channel in a model with adjustment costs, the movement of marginal cost is much less excessive. Our calibration shows that the responses of macroeconomic variables are less persistent in the benchmark model compared to the model where inventory holdings are not affected directly by the cost channel of interest rates.

We focus on two sources of real rigidity resulting from adjustment costs. High marginal cost in the short run pose a challenge to explaining the empirical observation of inflation inertia. However, the real rigidity discussed in this paper does help to reconcile high adjustment costs with price stickiness. We find that a transitory rise of marginal cost does not lead to aggressive changes in price.

We find a new source of real rigidity in the model from the behavior of dynamic cost smoothing. To our knowledge, this source of real rigidity has not been documented before. In order to reduce the adjustment costs incurred in the future, firms choose to smooth the process of expanding production. They start to produce more in order to be prepared to produce more in the future. For this reason, firms do not have strong incentive to raise price. The nature of adjustment costs leads to sluggish movement of output, which means that the marginal cost is persistent. In a model without inventories, we find that this source of real rigidity contributes to both inertia and persistence of price adjustment. In the inventory model, however, the cyclical behavior of inventories requires high contemporary costs, so cost smoothing does not play a role in raising real rigidity. Therefore, if the traditional cost channel through interest rates is not as effective as the model indicates, adjustment frictions should exert persistent effects on output and inflation through a new cost channel.

We find that the other real rigidity arising from firm-specific convex adjustment costs plays an important role in the model. In a Calvo world with pricing frictions, the firms that do not adjust price in response to rising demand produce less than their expected sales and cut down inventories. The firms that reoptimize and raise price, meanwhile, curtail sales and build up inventories. Therefore, the firms with high marginal cost stick to their prices and the firms with relatively low marginal cost adjust price. This selection effect magnifies countercyclical markups for aggregate price. The model uses large curvatures of adjustment costs and large price elasticities of product demand to show how endogenous marginal cost is an important source of large real rigidity. We show in our calibration that the conflict between high adjustment costs and price stickiness can be remedied significantly by this source of real rigidity. We solve the model analytically by linearizing the system of non-linear equations. Because of adjustment frictions and idiosyncratic
shocks, different firms have different states. In our model, the optimal behavior of firms depends on four individual state variables: labor input, the beginning-of-period inventory stock, the end-of-period inventory stock, and output price. Although the equation system becomes complicated with more individual state variables, it can be solved by an extension of the undetermined coefficients method. The approximation procedure clarifies those intuitions, especially the one behind pricing behavior.

Our model features a motive of stockout avoidance to justify inventory holdings on steady state, but the main force that determines inventory holdings is through cost smoothing. The reason is that the depreciation rate of inventories is rather small in calibration and the benefit of stockout avoidance only accounts for a small part in determining inventory holdings. Our results are robust to the parameterization because due to a shock of demand boom the motive of stockout avoidance becomes also stronger, albeit not associated with the traditional cost channel.

The paper is organized as follows. Section 2 summarizes related literature. Section 3 reports basic findings of inventory behavior conditional on a monetary policy shock. Section 4 discusses the relationship between adjustment costs and pricing behavior by presenting a baseline model that introduces convex adjustment costs of labor input to an otherwise standard New Keynesian model. Section 5 develops the baseline model by adding to the model inventory holdings. Section 6 describes calibrated results and compares them with other models. This section also discusses some results of robustness checks and possible extensions. Section 7 concludes.

2 Related literature

This paper is related to a large body of literature that studies the behavior of price rigidity, inventories\(^5\), and costs over the business cycle. Our starting point is the observation of sluggish output adjustment in the short run from recent evidence of VARs and identified monetary shocks. This can be seen as indirect evidence of countercyclical inventory movement because inventory investment accounts for the difference between sales and output. Standard recursive vector autoregressions (VARs) indicate that real GDP, hours worked, and investment barely move in the first quarter in response to a monetary policy shock, but sales and consumption do (for example, see figure 3 in Christiano, Trabandt, and Walentin, 2010). The output adjustment estimated with an identified shock is even more sluggish. Figure 2 in Romer and Romer (2004) shows that industrial production has not started to fall until six months after a monetary contractionary. Direct evidence by including inventory explicitly in the VAR also supports this result. Figure 2 in Bernanke and Gertler (1995) shows that inventories appear to build up for 8 months before beginning to decrease.

\(^5\)Inventory movements play a major role in business cycle fluctuations although the level of inventory investment is less than 0.5% of GDP in developed countries. For example, Ramey and West (1999) document that, for quarterly US data, the decline of inventory investment accounts for 49 percent of the fall in GDP for the 1990-1991 recession and on average 69 percent of the fall in GDP for the postwar recessions during the period from 1948 to 1991.
following an unanticipated tightening of monetary policy. Gertler and Gilchrist (1994), Jung and Yun (2005) and many others have all confirmed countercyclical or acyclical movement of inventory holdings over the business cycle. Bils and Kahn (2000) emphasize countercyclical inventory-to-sales ratios. They find in the long run inventories do track sales one for one, but the ratio of inventory to sales is highly persistent and countercyclical, which implies output does not keep pace with sales in the short run\(^6\).

For the traditional cost channel, previous literature mainly studies the effect of intra-period financing, so the change of interest rates directly affects marginal cost. Christiano et al. (2005) argue that the cost decline from intra-period borrowing of payroll helps to explain the odd behavior of inflation after a monetary policy shock\(^7\). The credit channel of financial accelerator proposed by Bernanke and Gertler (1989) has been tested extensively using the evidence from inventory behavior over the business cycle. Gertler and Gilchrist (1994) find that financial factors play a prominent role in the slowdown of inventory demand as monetary policy tightens. They compare inventory behavior across size classes and confirm that small firms exhibit a greater propensity to shed inventories as sales drop. This suggests that financial costs are at work through the effect of net worth when firms make decisions on their inventory holdings. Kashyap, Stein, and Wilcox (1993) and Kashyap, Lamont, and Stein (1994) provide time-series and cross-sectional empirical evidence that a significant number of firms are bank-dependent and therefore have inventory behavior that is sensitive to bank lending conditions.

The literature that studies the incentives to hold inventories has evolved substantially since the 1980s. In general, the incentives in most models are cost reduction, sales benefit, or both. After noticing the empirical inconsistency of the production smoothing theory, one strand of inventory research is to add to the model a targeted inventory level or inventory-to-sales ratio; for example, the target can be determined by the motive of stockout avoidance (Kahn, 1987), direct sales promotion (Bils and Kahn, 2000), or cost uncertainty (Wang and Wen, 2009). The alternative explanation is the \((S,s)\) theory first brought into the macroeconomic scope by Caplin (1985)\(^8\). Khan and Thomas (2007) develop an equilibrium business cycle model driven by technology shocks where nonconvex delivery costs lead firms to follow \((S,s)\) inventory policies. In such a real model, markups are constant. As Kryvtsov and Midrigan (2010b) argue, if markups are constant, monetary shocks can

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\(^6\) The main difference between VAR results and that of Bils and Kahn is that they use a partial equilibrium model of inventories to reveal the cyclicality of real marginal cost over the business cycle, not specific to a monetary shock.

\(^7\) A dip during the first several quarters.

\(^8\) The \((S,s)\) theory considers adjustment behavior in the presence of non-convex costs. If adjustment costs is simply fixed costs incurred at any time a firm wishes to adjust its inventories, Scarf (1960) shows that the firm’s optimal decision rule takes a one-sided \((S,s)\) form. On the one hand, \((S,s)\) policy has different implication from inventory targeting in that high or low inventory levels do not pertain to the marginal cost of inventory. On the other hand, inventory targeting with convex adjustment costs indicates that if inventory cannot keep pace with sales, the marginal cost of replenishing inventories must increase. Although the \((S,s)\) model has also received considerable attention, due to the cumbersome heterogeneity across firms, it was not until Khan and Thomas (2007) and Kryvtsov and Midrigan (2009) that \((S,s)\) inventory policy is incorporated into a general equilibrium model to analyze business cycles. However, the models must be solved using numerical methods.
only generate real effects only if nominal costs are sticky, which gives rise to strong variability in inventories due to intertemporal substitution in production; this result, however, is at odds with the data.

Sluggish output adjustment implies the existence of adjustment frictions. Most macroeconomic research, until recently, has used convex cost functions to slow down changes with rising marginal cost\(^9\). Although some microeconomic studies argue that firm-level lumpy adjustment of capital and inventory stocks may favor the explanation of non-convex costs, or in a narrower sense, fixed costs, the results in Kryvtsov and Midrigan (2009, 2010a) seem to suggest this choice of cost functions does not affect price stickiness significantly\(^10\). After all, it is hard to think that adjustment frictions are irrelevant to a firm’s marginal cost. Our New Keynesian model assumes a convex cost function to represent the source of all frictions in production adjustment.

Recent attempts to include inventory in a standard New Keynesian model focus on the nominal and real rigidity required to achieve observed inflation inertia. Jung and Yun (2005) develops a general equilibrium model that follows Bils and Kahn (2000), in which the motive of holding inventories is to promote sales. Their model also includes a sector which does not use inventories. They find that very high nominal rigidity is required to accommodate both countercyclical inventory-to-sales ratios and price rigidity in the model.

Our inventory model is based on Kryvtsov and Midrigan (2009, 2010a,b), which provide a thorough study of inventory behavior and real rigidity. They construct a model of stockout avoidance to rationalize inventory holdings, together with Calvo pricing, or menu cost. They conclude that the interest rate change in response a monetary policy shock invokes a strong motive of intertemporal substitution and that standard parameterization cannot reconcile inventory behavior and price rigidity. Kryvtsov and Midrigan (2010b) introduce firm-level decreasing returns to generate sufficient real rigidity and focus on the measure of how much nominal cost rigidity and countercyclical markups account for the bulk of the real effects of monetary policy shocks. We place emphasis on the implication for the traditional cost channel of monetary transmission. Inventory behavior suggests that the cost channel may not be effective or there are frictions on the supply side. Our model focuses on heterogeneous adjustment costs among firms. We show that in a Calvo world with pricing frictions, the firms that do not adjust price in response to rising demand produce less than their expected sales and cut down inventories. The firms that reoptimize and raise price, meanwhile, curtail sales and build up inventories. Therefore, the firms with high marginal cost stick to their prices and the firms with relatively low marginal cost adjust price. This selection effect implies that a large nominal rigidity may not be required to reconcile real rigidity.

In stockout avoidance models, holding more inventories increases expected sales. \textit{Ex post} stockout happens for only a few firms and inventory stocks are exhausted only for these firms. However,

\(^9\)For a survey for theoretical applications and empirical performance of convex costs, see Khan and Thomas (2008).

\(^{10}\)See Kryvtsov and Midrigan (2009, 2010a) for detailed discussion.
the *ex ante* benefit of inventory for sales is the same for all firms. In this sense, inventory behavior in the models of sales promotion and stockout avoidance does not make much difference. In this paper, it turns out that, after an expansionary monetary policy shock, the shadow value of inventory stock is primarily determined by the motive of inter-temporal substitution, not by any additional form of benefit.

Recent work of New Keynesian models introduces real rigidity in two ways. The first is internal real rigidity characterized by a price increase associated with a decline in marginal cost at the firm level. Several examples include countercyclical price elasticity (Kimball, 1995; Eichenbaum and Fisher, 2007), diminishing returns to scale (Gali, 2008; Kryvtsov and Midrigan, 2010b), firm-specific capital (Altig et al., 2011), and firm-specific labor (Woodford, 2003). The second approach is external real rigidity that reduces the responsiveness of real marginal cost at the aggregate level. One widely used approach is sticky wages (Erceg et al., 2000; Christiano et al., 2005; Smets and Wouters, 2007). As a matter of fact, medium-sized dynamic stochastic general equilibrium (DSGE) models usually include both sources of real rigidity. Two sources of real rigidity in our model fall into the first category. The first is firm-specific convex costs, which exerts a effect similar to firm-specific factors. The second is dynamic adjustment friction that is distinct from all other real rigidity.

### 3 Evidence from identified monetary policy shocks

Since the focus of this paper is on the real effect of monetary policy shocks, we document the behavior of inventory and sales in the wake of monetary expansions and contractions. A necessary step here is to identify these monetary disturbances. We use the monthly NIPA data which contain high-frequency observations. Output is computed as the sum of real sales and inventory investment for the manufacturing and sales industry. The price level is measured using implicit price deflators for sales. Our measure of monetary shocks represents innovations to the intended fed funds rate due to Romer and Romer (2004) (R&R), which is based on narrative records of FOMC meetings and Federal Reserve’s internal forecasts.

Responses of output, price levels, inventory investment and inventory-sales ratios are obtained by estimating the following OLS regression:

\[
\Delta y_t = a_0 + \sum_{k=1}^{11} a_k D_{kt} + \sum_{i=1}^{24} b_i \Delta y_{t-i} + \sum_{j=1}^{36} c_j S_{t-j} + e_t,
\]

where \( y_t \) is the dependent variable, \( D_k \)'s are a full set of monthly dummies, \( S \) is the measure of Romer-Romer shocks, and \( e_t \) is the zero-mean normally distributed error term, which is assumed to be serially uncorrelated. This specification is used by R&R and implies policy shocks have no contemporary effect on macroeconomic variables. To be consistent with this assumption, the same
timing restriction will be applied in our model. Our analysis for robustness check in section 5 shows that this assumption is essentially innocuous for the responses of most variables.

Figure 1 reports impulse responses to R&R shocks. The solid lines in the figure denote point estimates of the different response functions, and the dashed lines report respective 95% confidence intervals computed by bootstrapping. Output responses are negative between 4 and 36 months, with the trough at around 24 months after the shock. The response of inventory investment is countercyclical for about one year after the shock, reflecting the fact that inventory stocks are adjusted with a lag. We corroborating the result of countercyclical inventory-sales ratios conditional on a monetary policy shock: after a contractionary monetary shock, the ratio rises until one and a half year later.

Figure 2 and Figure 3 show the responses for the manufacturing industry and the trade industry separately. Inventory investment is countercyclical for the manufacturing industry during the first 18 months, but only acyclical for the trade industry during the first year after the shock. Figure 4 breaks down inventories according to three processing stages. Basically, the patterns are similar across different stages.

[Figure 1, 2, 3, and 4 here]

[Figure 5 here]

4 Adjustment costs and pricing in a baseline model

4.1 A simple example

This section illustrates the relationship between adjustment costs and pricing behavior. We start with a stylized example showing how heterogeneous adjustment costs across firms contributes higher real rigidity at the aggregate level. Consider an economy with a continuum of firms, whose optimal pricing decisions are characterized by the following log-linearized best-response:

\[ p_i - p = mc_i \]

where \( p_i \) denotes firm \( i \)'s optimal price, \( p = \int p_i \, di \) denotes the average price of all firms, and \( mc_i \) denotes firm \( i \)'s marginal cost. This equation can be derived from a static pricing strategy with a constant markup. When individual marginal cost is determined only by aggregate output \( y \), that is, \( mc_i = \xi y \), the equation can be rewritten as

\[ p_i = \xi (p + y) + (1 - \xi) p, \quad \xi > 0 \]

Given a certain level of nominal rigidity, after a shock of nominal spendings, the closer \( \xi \) is to zero, the more sluggish price adjustment is. When individual marginal cost is a decreasing function of
relative product price: $mc_i = \xi y - \eta (p_i - p)$, $\eta > 0$, we have

$$p_i = \frac{\xi}{1 + \eta} (p + y) + \frac{1 + \eta - \xi}{1 + \eta} p, \quad \xi > 0 \text{ and } \eta > 0$$

which implies that if a firm’s marginal cost is sensitive to its relative product price, large real rigidity is possible. In our model to be formulated below, this measure $\eta$ essentially depends on the price elasticity of demand and the curvature of cost functions. Because aggregate marginal cost $mc \equiv \int mc_i di$, defined here as the average of individual marginal cost, still equals $\xi y$, we call $\xi$ a measure of external real rigidity and $\eta$ a measure of internal real rigidity.

Consider adjustment costs in the model. If individual adjustment costs are completely determined at the industry level when $mc_i$ does not depend on $p_i$, price stickiness requires that aggregate adjustment costs must be low (small $\xi$). However, if adjustment costs are heterogeneous across firms, they decrease with relative price ($\eta > 0$). Each reoptimizing firm sets price based on individual marginal cost, which will be unambiguously lower than aggregate marginal cost if price is lifted up.

We continue to explain this selection effect in this section by presenting a general equilibrium model. All elements in the model follow medium-sized New Keynesian models such as in Christiano et al. (2005), except for convex adjustment costs of labor inputs to shed light on our intuition.

### 4.2 A New Keynesian model with labor adjustment costs

In the baseline model with two factors in production, differentiated goods are produced by a continuum of monopolistically competitive firms, indexed by $i \in [0, 1]$, using a Cobb-Douglas production function:

$$Y_t (i) = K_t^\alpha (i) L_t (i)^{1-\alpha}$$

where $Y_t (i)$ denotes individual output of firm $i$ at period $t$, $L_t (i)$ denotes labor input in production, and $K_t (i)$ denotes the input of capital service. A firm needs to hire $\Upsilon \left( \frac{L_t (i)}{L_{t-1} (i)} \right) L_t (i)$ units of labor to adjust employment in production. $\Upsilon (\cdot)$ is a convex cost function of labor adjustment such that $\Upsilon (1) = \Upsilon' (1) = 0$ and $\Upsilon'' (1) > 0$. The real cost function therefore includes a component of labor adjustment costs:

$$\frac{W_t}{P_t} L_t (i) + \frac{W_t}{P_t} \Upsilon \left( \frac{L_t (i)}{L_{t-1} (i)} \right) L_t (i) + R_{K,t} K_t (i)$$

where $P_t$ is the price index, $W_t$ is nominal wage, and $R_{K,t}$ is the rental rate of capital service. The demand curve for one firm is given by

$$Y_t (i) = \left( \frac{P_t (i)}{P_t} \right)^{-\theta} C_t$$

where $C_t$ denotes aggregate consumption.
Firm $i$’s objective function is given by
\[
E_t \sum_{j=0}^{\infty} D_{t,t+j} \left[ \frac{P_{t+j}(i)}{P_{t+j}} Y_{t+j} (i) - \frac{W_{t+j}}{P_{t+j}} L_{t+j} (i) - \frac{W_{t+j}}{P_{t+j}} \Upsilon \left( \frac{L_{t+j} (i)}{L_{t+j-1} (i)} \right) L_{t+j} (i) - R_{K,t+j} \right] \]
\[
+ Q_{t+j} (i) \left( K_{t+j}^\alpha (i) L_{t+j} (i) ^{1-\alpha} - Y_{t+j} (i) \right)
\]
where $Q_t (i)$ is the Lagrangian multiplier and the marginal cost (also known as the shadow value of time $t$ inventories) for firm $i$ and $D_{t,t+j}$ is the stochastic discount factor for evaluating real income streams received at period $t+j$. $D_{t,t+j}$ is defined as $\beta \Lambda_{t+j} / \Lambda_t$, where $0 < \beta < 1$ is the discount factor of the representative household and $\Lambda_t$ is the Lagrangian multiplier of the budget constraint for consumption optimization.

The first-order conditions for $K_t^* (i)$, $L_t^* (i)$, and $P_t^* (i)$ are stated in Appendix A. Following standard literature, the household problem determines demand for varieties, aggregate consumption, labor supply, and capital accumulation. See Appendix A for more details.

### 4.3 Log-linearization and the New Keynesian Phillips Curve

In this paper, unless otherwise noted, an English/Greek letter in lower case indicates deviation from steady state, expressed as a fraction of steady state. That is $x_t \equiv dX_t / X_t$, where $X$ is the steady state value of $X_t$ and $dX_t$ is a small deviation, $X_t - X$. We refer to $x_t$ as the log deviation of $X_t$ from steady state, or, simply, as the “log deviation”. We also denote $\tilde{x}_t (i) \equiv x_t (i) - x_t$, the log deviation of $X_t(i)$ from its aggregate level $X_t$.

The equation for labor demand after linearization is given by
\[
\omega_t - p_t + F_t \cdot (l_t (i) - l_{t-1} (i) - \beta (E_t l_{t+1} (i) - l_t (i))) = \frac{q_t (i) - \alpha r_{K,t+j}}{1 - \alpha}
\]
where $F_t \equiv \Upsilon'' (1)$ is the curvature of adjustment costs. Subtracting the aggregate equation for $q_t$
\[
q_t = (1 - \alpha) \left( \omega_t - p_t + F_t \cdot (l_t - l_{t-1} - \beta (E_t l_{t+1} - l_t)) \right) + \alpha r_{K,t+j}
\]
from $q_t (i)$ gives
\[
q_t (i) - q_t = \tilde{q}_t (i) = (1 - \alpha) F_t \cdot \left( l_t (i) - \tilde{l}_{t-1} (i) - \beta \left( E_t \tilde{l}_{t+1} (i) - \tilde{l}_t (i) \right) \right),
\]
which suggests that the deviation of individual marginal cost depends on (1) the curvature of adjustment costs, (2) the contemporaneous input change, and (3) the input change in the next period.

The pricing equation after linearization is given by
\[ p_t^i - p_t \equiv \tilde{p}_t^i = (1 - \alpha_p \beta) E_t^P \sum_{j=0}^{\infty} (\alpha_p \beta)^j q_{t+j}^i + E_t^P \sum_{j=1}^{\infty} (\alpha_p \beta)^j \Delta_p \pi_{t+j}. \] (2)

The inflation rate is denoted by \( \pi_t \equiv \log P_t - \log P_{t-1} \). If a firm does not change price during the period from \( t \) to \( t+j \), since \( q_{t+j}^i \) is determined by \( l_{t+j}^i \), and then \( p_{t-1}^i \), \( p_t^i \) is a function of \( p_{t-1}^i \). We posit that

\[ \tilde{p}_t^i = \psi \tilde{p}_{t-1}^i + p_t^* \]

Intuitively, \( \psi \) is larger than zero because if input is low in last period, to avoid high adjustment costs, input today still stays low; \( \psi \) should also be less than one because of the requirement of system stationarity. It follows that individual marginal cost is determined by

\[ \tilde{q}_t^i = (1 - \alpha) F_t^i (\tilde{p}_{t-1}^i - \phi \tilde{p}_t^i) \]

where

\[ \phi \equiv 1 + \beta (1 - \alpha_p - (1 - \alpha_p) \psi) \]

We find that the function of individual marginal cost is decreasing with individual product price as \( \phi > 0 \), which is consistent with our stylized example. Therefore, aggregating the re-optimized prices gives

\[ p_t^* = E_t^P \sum_{j=1}^{\infty} (\alpha_p \beta)^j \Delta_p \pi_{t+j} \]

\[ + (1 - \alpha_p \beta) E_t^P \sum_{j=0}^{\infty} (\alpha_p \beta)^j q_t \]

\[ \text{new} \left\{ - \varepsilon (1 - \alpha) F_t^i (\phi - \alpha_p \beta) \left( p_t^* - E_t^P \sum_{j=1}^{\infty} (\alpha_p \beta)^j \Delta_p \pi_{t+j} \right) \right\} \] (3)

where the third line is new due to the introduction of adjustment costs. After simplification, the New Keynesian Phillips Curve is given by

\[ \Delta_p \pi_t = \frac{(1 - \alpha_p \beta)(1 - \alpha_p)}{\alpha_p} \frac{1}{1 + \kappa} q_t + \beta E_t \Delta_p \pi_{t+1}, \]

where

\[ \kappa \equiv \varepsilon (1 - \alpha) F_t \cdot (\phi - \alpha_p \beta) \]

Here \( \kappa \) is a measure of real rigidity resulted from adjustment costs. \( \kappa \) has a lower bound of zero when there are no adjustment costs. It depends basically on the value of \( \varepsilon \) and \( F_t \) since \( \phi - \alpha_p \beta \) is close to 1 in our calibration. Because \( F_t < 5 \) is fairly reasonable, \( \kappa \) can be considerably large.
Figure 6 shows the relationship between $\kappa$ and $F_l$. When $F_l$ is above 1, $\kappa$ is approximately more than 4.

[Figure 6 here]

The intuition of the selection effect can be seen in equation (3). A firm’s price is based on its own marginal cost. As individual marginal cost is endogenous, it increases with output, thereby decreases with relative price. When output is elastic with price and adjustment friction is high, individual marginal cost is responsive to product price, which thereby responds less to aggregate marginal cost.

The effect of large firm-specific adjustment costs on the inflation response is through two channels. The first is through higher $\kappa$, which increases strategic complementarity in pricing and therefore inflation responds less to a change of aggregate marginal cost. The second is through $q_t$: the higher individual adjustment costs, the higher aggregate marginal cost is. Figure 8 shows the impulse responses after an expansionary monetary policy shock$^{11}$. The inflation response with a larger cost curvature is even flatter. Because aggregate price is determined by re-optimizing firms, this means they charge even lower prices when they face higher wage rates and adjustment costs. The selection effect cannot explain this puzzling behavior. However, we can find clues from the dynamic structure of adjustment costs. Equation (1) shows firms need to take into consideration future adjustment costs. When firms are sluggish in adjusting price, they wish to adjust input quickly in order to reduce expected adjustment costs in the future. In our calibration, the optimal price is even lower for larger adjustment costs. As a result, the effect of enlarged real rigidity dominates the effect of rising aggregate marginal cost, and price adjustment is more sluggish.

The source of real rigidity arising from dynamic cost smoothing is a novel idea. In order to smooth adjustment costs, firms choose to increase input purchase immediately after an expansionary shock instead of raising price. They start to produce more in order to be prepared to produce more in the future. This motive for inter-temporal substitution is different from other sources of real rigidity like strategic complementarity among firms or counter-cyclical markups that works intra-temporally$^{12}$.

[Figure 8 here]

5 A model with inventories

We formulate in this section a New Keynesian model with inventories. The motive of stockout avoidance is introduced to justify positive inventory holdings on steady state. We solve the model analytically by linearizing the system of non-linear equations. Adjustment frictions imply different firms have different states. In our model, the optimal behavior of firms depends on four individual

$^{11}$See Appendix A for the parametrization based on quarterly data

$^{12}$The selection effect is one example of this.
state variables: labor input, the beginning-of-period inventory stock, the end-of-period inventory stock, and output price. Although the equation system becomes complicated with more individual state variables, it can be solved by an extension of the undetermined coefficients method. The benefit of this approximation procedure is to clarify intuitions, especially the one behind pricing behavior.

5.1 Household

We denote \( v_t(i) \) as a preference shock specific to each good in the CES aggregator. Assume \( \log(v_t) \sim N \left(-\frac{\sigma_v^2}{2}, \sigma_v^2 \right) \). The preference shocks at each period unfold to all firms after they make decisions on the quantity of goods supplied to the market. Therefore, in this economy the representative consumer’s demand will occasionally be satisfied in part by firms with insufficient inventory available. We let \( Z_t(i) \) be each firm’s available stock of inventories: the consumer cannot buy more than \( Z_t(i) \) units. The consumer’s optimization problem is defined as

\[
\max E_0 \sum_{t=0}^{\infty} \beta^t U(C_t, N_t) \\
\text{st.} \quad \int_0^1 P_t(i) C_t(i) \, di + E_t D_{t,t+1} B_{t+1} \leq B_t + W_t N_t + \Pi_t
\]

where

\[
C_t(i) \leq Z_t(i) \\
C_t = \left( \int_0^1 v_t(i)^{\frac{1}{\sigma}} C_t(i)^{\frac{\sigma+1}{\sigma}} \, di \right)^{\frac{\sigma}{\sigma+1}}
\]

\( B_{t+1} \) denotes a portfolio of nominal state contingent claims in the complete contingent claims market, \( D_{t,t+1} \) denotes the stochastic discount factor for computing the nominal value in period \( t \) of one unit of consumption goods in period \( t+1 \), \( W_t \) denotes aggregate nominal wage, \( N_t \) denotes labor supply, and \( \Pi_t \) denotes a lump-sum transfer.

The inter-temporal Lagrangian is given by

\[
\mathcal{L} = E_0 \sum_{t=0}^{\infty} \beta^t \left( U(C_t, N_t) + \Lambda_t \left( W_t N_t - \int_0^1 P_t(i) C_t(i) \, di \right) + \int_0^1 \mu_t(i) (Z_t(i) - C_t(i)) \, di \right)
\]

where \( \Lambda_t \) is the multiplier on the consumer’s budget constraint and \( \mu_t(i) \) are the multipliers on the constraint \( C_t(i) \leq Z_t(i) \) for all \( i \).
The first order condition for consumption varieties yields the price index:

\[ P_t \equiv \frac{U_{c,t}}{\Lambda_t} = \left( \int_0^1 v_t(i) \left( P_t(i) + \frac{\mu_t(i)}{\Lambda_t} \right)^{1-\theta} \right)^{1/\theta} \]

For goods that happen to be out of stock, shadow prices are higher than market prices such that demand equals supply. The demand function for a variety \( i \) is given by

\[
C_t(i) = \begin{cases} 
  v_t(i) \left( \frac{P_t(i)}{P_t} \right)^{-\theta} C_t & \text{if } v_t(i) \left( \frac{P_t(i)}{P_t} \right)^{-\theta} C_t < Z_t(i) \\
  Z_t(i) & \text{otherwise}
\end{cases}
\]

Labor supply is determined by the standard intra-temporal equation:

\[ U_{n,t} = -U_{c,t} \frac{W_t}{P_t} \]

Note that \( P_tC_t \neq \int_0^1 P_t(i) C_t(i) \, di \), so the consumer cannot merely optimize with respect to \( C_t \) while keeping the shares of \( C_t(i) \) fixed. The reason is that \( P_t \) now is not exogenous but contains information about stockout, which in turn relates to demand. Hence, when the consumer solves the problem, \( P_t \) cannot be taken as the unit price of \( C_t \). Some of goods are out of stock. As a result, even if \( P_t \) is paid at the margin, one cannot get the same consumption basket as before. Instead, with extra payment of \( P_t \), the consumer needs to reallocate consumption across goods in stock and reckons marginal utility from this new consumption basket.

We specify that

\[ U(C_t, N_t) = \frac{C_t^{1-\sigma} - 1}{1-\sigma} - \frac{N_t^{1+\chi}}{1+\chi} \]

which implies labor supply is given by

\[ N_t = \frac{W_t}{P_t} \]

The optimization condition for bonds holding is

\[ D_{t,t+1} = \beta \frac{\Lambda_{t+1}}{\Lambda_t} \]

We denote \( D_{t,t+j} = \beta \frac{\Lambda_{t+j}}{\Lambda_t} \). Hence, if \( R_t \) represents the gross nominal interest rate in period \( t \), absence of arbitrage gives the following Euler equation:

\[ E_t(D_{t,t+1}R_t) = 1 \]
5.2 Firms

5.2.1 Production function, inventory, and goods demand

Storable final goods are produced by monopolistically competitive firms using a production function linear in labor:

$$Y_t(i) = \exp(\epsilon^A_t) L_t(i)$$

where $Y_t(i)$ denotes individual output of firm $i$ at period $t$, $L_t(i)$ denotes labor input, and $\epsilon^A_t$ represents the technology shock with zero mean. Goods are storable and can be held as finished goods inventory. A firm needs to hire $\Upsilon \left( \frac{L_{t+1}(i)}{L_{t+j-1}(i)} \right) L_t(i)$ units of labor to adjust employment in production. $\Upsilon(\cdot)$ is a convex cost function of labor adjustment such that $\Upsilon(1) = \Upsilon'(1) = 0$ and $\Upsilon''(1) > 0$. Hence, the cost function of production is given by

$$C(Y_t(i)) = W_t \left( L_t(i) + \Upsilon \left( \frac{L_t(i)}{L_{t+j-1}(i)} \right) L_t(i) \right)$$

Firms cannot observe idiosyncratic demand shocks before production, therefore, inventory can be used to ensure market clearing. Denote sales by $S_t$. It is possible that sales do not equal output for individual firms and the economy: $S_t(i) \neq Y_t(i)$ and $S_t \neq Y_t$. The demand function for firm $i$ is given by

$$S_t(P_t(i), Z_t(i)) = \min \left( \nu_t(i) \left( \frac{P_t(i)}{P_t} \right)^{-\theta} C_t, Z_t(i) \right)$$

The beginning-of-period inventory stock of firm $i$ evolves over time according to

$$Z_t(i) = (1 - \delta) (Z_{t-1}(i) - S_{t-1}(i)) + Y_t(i) - \Xi \left( \frac{Z_t(i)}{Z_{t-1}(i)} \right) Z_t(i)$$

where $Z_t(i)$ is defined as inventory holdings at the beginning of period $t$ after production, and $\delta$ is the constant marginal cost of inventory stocks measured in the form of iceberg loss. $\Xi \left( \frac{Z_t(i)}{Z_{t-1}(i)} \right) Z_t(i)$ is a convex function of inventory adjustment costs such that $\Xi(1) = \Xi'(1) = 0$ and $\Xi''(1) > 0$. Inventory costs can take several forms. Besides natural attrition, storage and maintenance costs are incurred when a firm stocks and moves inventory. External financing premium is also one main type of inventory costs if a firm borrows short-term loans to finance inventory holdings.

Consumers cannot resell the goods purchased, thus they do not choose to store goods because the expected return is negative while we assume the riskfree rate is always positive. In the literature, there are basically two benefits to induce firms to hold inventories on steady state when firms may face idiosyncratic shocks but no aggregate shocks: cost reduction and sales promotion. The DSGE inventory models of cost reduction include idiosyncratic cost uncertainty (Wang and Wen, 2009) and $(S,s)$ policy for fixed ordering cost (Khan and Thomas, 2007). Sales promotion models can be specified with the motive of stockout avoidance (Kryvtsov and Midrigan, 2009, 2010a,b) by
idiosyncratic demand uncertainty, which our model is based upon. Because the rate of inventory depreciation cannot be very large, after an expansionary monetary policy shock, the increase of benefit from sales promotion is relatively small and it turns out that the shadow value of inventory stock is primarily affected by the decline of interest rates. In this case, the motive of (aggregate) cost smoothing dominates any other incentives for firms to determine the optimal level of inventory stocks. As we will see, this cost structure has profound implications on inventory behavior.

5.2.2 Objective function and optimal conditions

Firms set prices according to a variant of the mechanism spelled out by Calvo (1983). In each period, a firm faces a constant probability, \( \alpha_p \), of not being able to re-optimize its nominal price.

\[
\mathcal{L} = E_t \sum_{j=0}^{\infty} D_{t,t+j} \left[ P_{t+j} (i) S_{t+j} (i) - W_{t+j} (i) L_{t+j} (i) - W_{t+j} (i) \gamma \left( \frac{L_{t+j} (i)}{L_{t+j-1} (i)} \right) L_{t+j} (i) \right. \\
\left. + Q_{t+j} (i) \left( (1 - \delta) (Z_{t+j-1} (i) - S_{t+j-1} (i)) + L_{t+j} (i) - Z_{t+j} (i) - \Xi \left( \frac{Z_{t+j} (i)}{Z_{t+j-1} (i)} \right) Z_{t+j} (i) \right) \right]
\]

where \( Q_t (i) \) is the Lagrangian multiplier and the shadow value of time \( t \) inventory for firm \( i \).

Here we have two types of convex adjustment costs: \( \Upsilon (\cdot) \) for labor input adjustment and \( \Xi (\cdot) \) for inventory stock adjustment. \( \delta \) denotes the rate of one-period inventory depreciation.

The first-order conditions for \( Z_t (i) \), \( L_t (i) \), and \( P_t (i) \) can be summarized as follows. Firms that do not re-optimize prices simply follow the indexation rule. Therefore, the optimal condition of pricing is only applied to those firms that re-optimize.

The first-order condition for inventory holdings \( Z_t (i) \) is given by

\[
Q_t (i) \left( 1 + \Xi' \left( \frac{Z_t (i)}{Z_{t-1} (i)} \right) \frac{Z_t (i)}{Z_{t-1} (i)} + \Xi \left( \frac{Z_t (i)}{Z_{t-1} (i)} \right) \right) - E_t D_{t,t+1} Q_{t+1} (i) \Xi' \left( \frac{Z_{t+1} (i)}{Z_t (i)} \right) \left( \frac{Z_{t+1} (i)}{Z_t (i)} \right)^2 = P_t (i) \frac{\partial E_t S_t (i)}{\partial Z_t (i)} + E_t (1 - \delta) D_{t,t+1} Q_{t+1} (i) \left( 1 - \frac{\partial E_t S_t (i)}{\partial Z_t (i)} \right)
\]

This equation defines a dynamic equation for inventory holdings. The left hand side is the marginal cost of accumulating one unit of inventory at period \( t \). The right hand side comes from the benefit of sales promotion and the discounted marginal cost at period \( t + 1 \). If demand is less than stocks, inventory leftovers must be restocked. Intertemporal cost smoothing considers the future shadow value of inventory which reflects the storage role of inventory. The first-order conditions for labor input \( L_t (i) \) is given by

\[
Q_t (i) = W_t \left( 1 + \Upsilon' \left( \frac{L_t (i)}{L_{t-1} (i)} \right) \frac{L_t (i)}{L_{t-1} (i)} + \Upsilon \left( \frac{L_t (i)}{L_{t-1} (i)} \right) \right) - E_t D_{t,t+1} W_{t+1} \Upsilon' \left( \frac{L_{t+1} (i)}{L_t (i)} \right) \left( \frac{L_{t+1} (i)}{L_t (i)} \right)^2
\]

which shows that the shadow value of production equals marginal cost. In our model, marginal
cost of production also includes adjustment costs of labor input. The first-order conditions for price-setting $P_t(i)$ is given by

$$E_t^p \sum_{j=0}^{\infty} \alpha_j(t) D_{t+j} S_{t+j} \left( \frac{P_{t+j}(i)}{P_t(i)} - \frac{\varepsilon_{t+j}(i)}{\varepsilon_{t+j}(i)} - 1 \right) (1 - \delta) D_{t+j} \pi_{t+j+1} Q_{t+j+1}(i) = 0$$

where $\varepsilon_{t+j}(i) \equiv -\frac{P_{t+j}(i) E_t^{p_t+i}(i)}{R_{t+j}(i)}$. This equation describes a standard pricing equation with Calvo frictions. The markup becomes time-varying when inventory is considered. In addition, pricing is based on the discounted marginal cost of the following period in the equation because of cost smoothing indicated in equation (4).

Note that $E_t$ and $E_t^p$ are different operators because the expectations are conditional on different events. $E_t^p X_{t+k}(i)$ denotes the expectation of the random variable $X_{t+k}(i)$, condition on date $t$ information and on the event that firm $i$ optimizes its price in period $t$, but does not do so in any period up to and including $t + k$. For any aggregate state variable $X_{t+k}$, $E_t^p X_{t+k} = E_t X_{t+k}$. However, the two conditional expectations differ for firm $i$'s individual variables. This distinction is emphasized in Woodford (2005).

### 5.3 Social resource constraint and monetary policy

The aggregate production equation and labor market clearing imply that

$$Y_t + \int_0^1 \Upsilon \left( \frac{Y_t(i)}{Y_{t-1}(i)} \right) Y_t(i) \, di = N_t$$

Aggregating individual inventory holdings gives us the law of motion for aggregate inventory stock

$$Z_t = (1 - \delta) (Z_{t-1} - S_{t-1}) + Y_t - \int_0^1 \Xi \left( \frac{Z_t(i)}{Z_{t-1}(i)} \right) Z_t(i) \, di.$$  \hspace{1cm} (5)

One can see that the aggregate market clearing condition can be written as

$$Y_t = S_t + I_{Z,t}$$  \hspace{1cm} (6)

where $I_{Z,t} \equiv Z_t - S_t - (1 - \delta) (Z_{t-1} - S_{t-1}) - \int_0^1 \Xi \left( \frac{Z_t(i)}{Z_{t-1}(i)} \right) Z_t(i) \, di$ denotes inventory investment.

Finally, the monetary policy rule is assumed to follow a variant of Taylor (1993) rule with partial adjustment of the form

$$\log \left( \frac{R_t}{R} \right) = \rho_r \log \left( \frac{R_{t-1}}{R} \right) + (1 - \rho_r) \left( \rho \pi \pi_t + \rho_y \log \left( \frac{Y_t}{Y} \right) \right) + e_t^r,$$  \hspace{1cm} (7)

where $\rho_r$ is the partial adjustment parameter, $\rho \pi$ measures the responsiveness of the policy interest rate with respect to inflation rate, $\rho_y$ measures the responsiveness of the policy interest rate with
respect to real output, and \( e^r_t \) is an exogenous (possible stochastic) component with zero mean. It is also assumed that it takes one period for private agents to observe monetary shocks, so \( e^r_t \) is not included in the period \( t \) information set of the agents in the model. This ensures that the model satisfies the restriction used in the empirical analysis to identify a monetary policy shock.

5.4 Log-linearization and aggregation

Denote the end-of-period inventory stock for firm \( i \) at period \( t \) by \( X_t(i) \equiv Z_t(i) - S_t(i) \). At period \( t \), re-optimizing firms choose different prices and inputs, depending on individual state variables \( \hat{x}_{t-1}(i) \), \( \hat{z}_{t-1}(i) \), \( \hat{l}_{t-1}(i) \), and \( \hat{p}_{t-1}(i) \). This is a complication that is absent in the usual Calvo setting, where all price-optimizing firms choose the same price. It turns out that, following the logic laid out in Woodford (2005), if we assume only first moments matter for all stochastic processes, every choice variable for firm \( i \) at period \( t \), \( \hat{l}^*_t(i) \), \( \hat{z}^*_t(i) \), and \( \hat{p}^*_t(i) \), is a linear function of the state variable plus a term which only depends on aggregate variables. In other words, we assume that according to the distributions of firm variables, the aggregate shocks in consideration do not change any moments other than first moments. The strategy for computing the parameters of the linear policy functions is based on the undetermined coefficient method. This method has been extended in several recent papers. For example, Altig et al. (2011) features a model with firm-specific capital and thereby individual marginal cost is a function of individual capital stock for each period.

Denote

\[
\Delta_{\rho} \pi_t \equiv \pi_t - \rho \pi_{t-1} \\
\Delta_{\rho} w_t \equiv w_t - w_{t-1} - \rho w_t (w_{t-1} - w_{t-2})
\]

where \( \rho \) and \( \rho_w \) are two indexation parameters in price and wage setting\(^{13} \). Then we posit (and later verify) linear policy functions for a firm’s labor hiring, pricing, and inventory holdings decision under four specific states as in Table 1.

\(^{13}\)As in Christiano et al. (2005), we assume a firm which cannot re-optimize its price sets \( P_t(i) \) according to: \( P_t(i) = \left( \frac{P_{t-1}(i)}{P_{t-2}} \right)^\rho P_{t-1}(i) \), \( 0 \leq \rho \leq 1 \), where \( \rho \) controls the degree of lagged inflation indexation. Firms and the representative household all take the market nominal wage as given for each period. The labor contract stipulates that the nominal wage rate is indexed with lagged inflation by the rule if it is not to be changed

\[
W_t(i) = \left( \frac{W_{t-1}(i)}{W_{t-2}} \right)^{\rho_w} W_{t-1}(i), \quad 0 \leq \rho_w \leq 1,
\]

where \( \rho_w \) controls the degree of wage indexation. This indexation rule differs from Christiano et al. (2005) in that the index is aggregate nominal wage, not the level of aggregate price.
The linearized discount factor is obtained by log-linearizing the Euler equation around the steady state with a zero inflation rate

$$E_t d_{t,t+1} + r_t - \pi_{t+1} = 0.$$  \hfill (10)

The equation for the stochastic discount factor gives

$$E_t d_{t,t+1} = E_t \lambda_{t+1} - \lambda_t$$ \hfill (11)

With habit formation, consumption dynamics is

$$c_t = \frac{1 - \beta}{(1 + \beta b) \sigma} \lambda_t + \frac{b}{1 + \beta b^2} c_{t-1} + \frac{\beta b}{1 + \beta b^2} E_t c_{t+1}. \hfill (12)$$

Following Erceg et al. (2000), labor supply is given by

$$\Delta_{\hat{w}} w_t = \frac{(1 - \alpha_l)}{\alpha_l} (1 - \alpha_l \beta) v_t + \beta E_t \Delta_{\hat{w}} w_{t+1}, \hfill (13)$$

where $v_t = \chi_l - \lambda_t - w_t^p$ is the deviation from the Pareto-optimal allocation, in which $v_t = 0$. Without the Calvo-style adjustment of labor input, labor supply is given by $w_t^p = \chi_{t+1} - \lambda_t$, which is equivalent to $v_t = 0$. The law of motion for aggregate real wage is given by

$$w_t^p = w_{t-1}^p + w_t - w_{t-1} - \pi_t. \hfill (14)$$

---

**Table 1: Linear policy functions**

<table>
<thead>
<tr>
<th>State A</th>
<th>State B</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1 - \alpha_p$</td>
<td>$\alpha_p$</td>
</tr>
<tr>
<td>$\hat{I}<em>t (i) = \psi_1^0 \hat{x}</em>{t-1} (i) + \psi_1^1 \hat{l}<em>{t-1} (i) + \psi_2^1 \hat{z}</em>{t-1} (i) + \psi_4^1 \hat{p}_t (i)$</td>
<td>$\psi_1^0 \hat{x}<em>{t-1} (i) + \psi_1^1 \hat{l}</em>{t-1} (i) + \psi_2^1 \hat{z}_{t-1} (i) + \psi_4^1 \hat{p}_t (i)$</td>
</tr>
<tr>
<td>$\hat{p}<em>t (i) = \psi_3^0 \hat{x}</em>{t-1} (i) + \psi_3^1 \hat{l}<em>{t-1} (i) + \psi_3^2 \hat{z}</em>{t-1} (i) + \psi_4^2 \hat{p}_t (i)$</td>
<td>$\hat{p}<em>t (i) - \Delta</em>{\hat{p}} \pi_t$</td>
</tr>
<tr>
<td>$E_t \hat{x}<em>{t} (i) = \psi_1^0 \hat{x}</em>{t-1} (i) + \psi_1^1 \hat{l}<em>{t-1} (i) + \psi_2^1 \hat{z}</em>{t-1} (i) + \psi_4^1 \hat{p}_t (i)$</td>
<td>$\psi_1^0 \hat{x}<em>{t-1} (i) + \psi_1^1 \hat{l}</em>{t-1} (i) + \psi_2^1 \hat{z}_{t-1} (i) + \psi_4^1 \hat{p}_t (i)$</td>
</tr>
<tr>
<td>$\hat{z}<em>t (i) = \psi_1^0 \hat{x}</em>{t-1} (i) + \psi_1^1 \hat{l}<em>{t-1} (i) + \psi_2^1 \hat{z}</em>{t-1} (i) + \psi_4^1 \hat{p}_t (i)$</td>
<td>$\psi_1^0 \hat{x}<em>{t-1} (i) + \psi_1^1 \hat{l}</em>{t-1} (i) + \psi_2^1 \hat{z}_{t-1} (i) + \psi_4^1 \hat{p}_t (i)$</td>
</tr>
<tr>
<td>$\hat{q}<em>t (i) = \psi_1^0 \hat{x}</em>{t-1} (i) + \psi_1^1 \hat{l}<em>{t-1} (i) + \psi_2^1 \hat{z}</em>{t-1} (i) + \psi_4^1 \hat{p}_t (i)$</td>
<td>$\psi_1^0 \hat{x}<em>{t-1} (i) + \psi_1^1 \hat{l}</em>{t-1} (i) + \psi_2^1 \hat{z}_{t-1} (i) + \psi_4^1 \hat{p}_t (i)$</td>
</tr>
</tbody>
</table>
The linearized aggregate equation for inventory is

\[ z_t = (1 - \delta) \left( z_{t-1} - \frac{S}{Z} s_{t-1} \right) + \frac{Y}{Z} y_t. \tag{15} \]

It is obtained directly from (5).

A, B, C, D, E, G, H in the following are functions of structural parameters. The law of motion for the average shadow value of inventory is

\[ z_t - c_t - AC F_z (z_t - z_{t-1} - \beta (E_t z_{t+1} - z_t)) = AC q_t - BC E_t (d_{t,t+1} + q_{t+1}) \tag{16} \]

The input dynamics for labor demand is given by

\[ q_t = w_t - p_t + F_l (l_t - l_{t-1} - \beta (E_t l_{t+1} - l_t)) \tag{17} \]

Inflation dynamics has a slightly different form compared to standard New Keynesian models because of staggered adjustment of inputs and the existence of inventories.

\[ \Delta_{\rho} \pi_t = \beta E_t \Delta_{\rho} \pi_{t+1} + \frac{(1 - \alpha_p)(1 - \alpha_p \beta)}{\alpha_p H} \frac{1}{1 + \kappa} (z_t - c_t) \]

\[ + \frac{(1 - \alpha_p)(1 - \alpha_p \beta)}{\alpha_p G} \frac{1}{1 + \kappa} E_t (d_{t,t+1} + q_{t+1}) \tag{18} \]

where \( \kappa \) is a non-linear function of the parameters of the model, so \( \kappa \) can be viewed as a measure of real rigidity. The parameter \( \kappa \) are the only thing that is new to this extended model. Specifically, in an inventory model without adjustment costs, \( F_z = F_l = 0 \), we have \( \kappa = 0 \). We can numerically make plots to see how real rigidity is affected by structural parameters. Figure 7 shows that \( \kappa \) increases with cost curvature.

Here, it should be noted that up to first-order log-linear approximations, measures of relative price and input distortions turn out to be zero, following the literature. Thus, log-linearizing the aggregate production function yields

\[ y_t = l_t + e_t^A. \tag{19} \]

The equilibrium is goods market results in

\[ s_t - c_t = \left( \frac{\varepsilon \theta (1 - \varepsilon \psi)}{1 - \theta + \theta \varepsilon \phi} + \varepsilon \phi \right) (z_t - c_t) \tag{20} \]

in which it should be noted that \( s_t \neq c_t \) in a model with stockout avoidance. Besides, the Taylor rule leads to

\[ r_t = \rho_r r_{t-1} + (1 - \rho_r) (\rho \pi_t + \rho_y y_t) + e_t^r. \tag{21} \]
This completes the equation system of our linearized economy.

**Proposition 1.** An equilibrium is a stochastic process for the prices and quantities which has the property that the household and firm problems are satisfied, and goods and labor markets clear. If there is an equilibrium in the linearized economy, then the following 14 unknowns

\[ z_t, y_t, l_t, q_t, \pi_t, s_t, c_t, r_t, w_t, w_{t+1}^r, d_{t,t+1}, \lambda_t, \Delta \rho \pi_t, \Delta \rho w_t \]


### 6 Calibration

We evaluate the model’s quantitative implications by calibrating parameter values to match empirical impulse functions obtained above. Following the empirical analysis, we set the length of the period as one month and therefore choose a discount factor of \( \beta = .96^{1/12} \). The utility function is assumed to be logarithmic (\( \sigma = 1 \)) and the inverse of Frisch labor supply elasticity is one (\( \chi = 1 \)).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values</th>
<th>Description and definitions</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \sigma )</td>
<td>1</td>
<td>Inverse of inter-temporal substitution</td>
</tr>
<tr>
<td>( \chi )</td>
<td>1</td>
<td>Inverse of labor supply elasticity</td>
</tr>
<tr>
<td>( \beta )</td>
<td>0.96(^{1/12} )</td>
<td>Time discount factor</td>
</tr>
<tr>
<td>( \varrho )</td>
<td>1</td>
<td>Degree of inflation indexation</td>
</tr>
<tr>
<td>( \varrho_w )</td>
<td>0.6</td>
<td>Degree of wage indexation</td>
</tr>
<tr>
<td>( 1 - \alpha_p )</td>
<td>1/8</td>
<td>Frequency of price changes in each month</td>
</tr>
<tr>
<td>( 1 - \alpha_l )</td>
<td>1/12</td>
<td>Frequency of wage changes in each month</td>
</tr>
<tr>
<td>( Z )</td>
<td>1.9</td>
<td>Beginning-of-month inventory-sales ratio</td>
</tr>
<tr>
<td>( \theta )</td>
<td>6</td>
<td>Elasticity of substitution across good varieties</td>
</tr>
<tr>
<td>( \varepsilon_w )</td>
<td>6</td>
<td>Elasticity of substitution across labor varieties</td>
</tr>
<tr>
<td>( \sigma_v )</td>
<td>.5406</td>
<td>Standard deviation of the logarithm of demand shocks</td>
</tr>
<tr>
<td>( \delta )</td>
<td>.0078</td>
<td>Rate of inventory depreciation</td>
</tr>
<tr>
<td>( b )</td>
<td>0.95</td>
<td>Degree of habit persistence</td>
</tr>
<tr>
<td>( \rho_\pi )</td>
<td>1.5</td>
<td>Responsiveness to inflation</td>
</tr>
<tr>
<td>( \rho_y )</td>
<td>0.5/4</td>
<td>Responsiveness to output gap</td>
</tr>
</tbody>
</table>

Table 2 reports the parameter values we used in our quantitative analysis. We set the elasticity of substitution across good and labor varieties, \( \theta = \varepsilon_w = 6 \). This implies the steady-state demand elasticity equals 5.43, a markup of 23%, in the range of estimates in existing work. We assume a frequency of wages changes of once a year, \( 1-\alpha_l = 1/12 \), consistent with what is typically assumed in existing studies. Our model requires the same nominal rigidity used by other literature to generate inflation inertia. Specifically, we assume that the average of price durations lasts for 8 months.
This is consistent with recent empirical findings on the frequency of price adjustment\textsuperscript{14}.

The calibration of inventory parameters follows Kryvtsov and Midrigan (2010b). Specifically, we calibrate two parameters, the rate of inventory depreciation $\delta$ and the standard deviation of the logarithm of demand shocks $\sigma_v$, to ensure that the model accounts for two facts about inventories and stockouts in the data: a 5% frequency of stockouts and a 1.4 inventory-sales ratio. We assume a smooth turnover of production and sales, so the calibrated beginning-of-period inventory ratio is 1.9.

### 6.1 Adjustment costs and inventory behavior

In calibration, we only consider input adjustment costs and fix the curvature of stock adjustment costs to zero. Therefore, we have one free parameter, the curvature of input adjustment costs. The difference between input adjustment costs and stock adjustment costs can be observed in equation \textsuperscript{(16)}. Stock adjustment costs merely smoothes inventory adjustment, but doesn’t change marginal cost of production directly. In contrast, input adjustment costs is one component of marginal cost and determines inventory holdings through the sluggish adjustment of output. Hence, inventory investment can be negative in the short run if output does not keep pace with sales.

Figure 9 and Figure 10 show the impulse responses without adjustment costs and with adjustment costs. They are shown separately in two graphs because without adjustment costs, the incentive to increase inventory stocks is so strong that output is raised dramatically. If adjustment costs is large enough, the output change is smoothed and inventory accumulation slows down. As a result, the inventory-sales ratio becomes countercyclical. The response of inflation is not strong, however. This is not a result of declining real wage because the share of wage in the marginal cost becomes small when the cost curvature is large.

[Figure 9 and Figure 10 here]

### 6.2 Adjustment costs and real rigidity

We can conduct an experiment of removing real rigidity by setting $\kappa = 0$. Figure 11 shows that in this case inflation rises quickly due to high aggregate marginal cost. Firm-specific adjustment costs reduce a firm’s response to aggregate marginal cost and the calibration indicates that the peak of inflation is nearly a third of the peak of inflation response without this source of real rigidity.

[Figure 11 here]

\textsuperscript{14}For example, Nakamura and Steinsson (2008) find an uncensored median duration of regular prices of 8–11 months and 7–9 months including substitutions.
6.3 Adjustment costs and the cost channel

We also see that the working capital channel through low pricing is not present in our model. The decline in interest rates do not lower a firm’s marginal cost of production, but only changes the motive for inter-temporal substitution. We conduct an experiment of removing the working capital channel, in which we assume there is no interest rate effect in inventory decisions. Figure 12 shows the impulse responses from this experiment. Because the incentive of cost smoothing disappears, inventory becomes more countercyclical. We can also observe that inflation becomes more persistent. The reason is that without the working capital channel, output adjustment is smoother and marginal cost actually is lower compared to the case with the working capital channel. The motive of inter-temporal incentive in this way decreases price stickiness, in contrast to the channel through intra-temporal financing costs.

[Figure 12 here]

6.4 Robustness check

There is a debate about whether it is valid to assume that monetary policy shocks do not have contemporaneous effect on macroeconomic variables. The evidence from R&R identified shocks actually shows dropping this assumption only changes the response of Federal funds rates to a hump shaped curve (see Figure 5). Figure 13 shows that the calibration also supports that our result for inventory behavior is robust for this assumption. Inflation rises to a higher level because the change of interest rates is larger.

[Figure 13 here]

7 Conclusions

Cost structure is closely related to a firm’s production and pricing behavior. This paper examines the quantitative information on output to infer the cost structure that a firm is likely to have. The information on costs then can be used to test different hypotheses about pricing. Because the demand of a firm’s product is determined by consumer preference and product price, we need to find more information to disentangle different channels from the demand side and the supply side.

The information on inventories serves to satisfy our needs because inventory investment represents the difference between sales and output. Empirical evidence shows that the ratio of inventory to sales is countercyclical and inventory investment is acyclical the short run, but the cost channel implies that lower costs should lead to a much higher level of inventory holdings. The inconsistency suggests that either the cost channel may not be effective or there are strong frictions on the supply side.

In order to bring the model’s inventory predictions in line with the data, we need to assume high
adjustment costs in production. High adjustment costs lead to a surge in marginal cost. Calibrating our benchmark model we find that the resulting impact of monetary policy on macroeconomic variables is stronger in the short run and less persistent, compared with the model without the cost channel of interest rates. Two sources of real rigidities relevant to adjustment costs help to reconcile high adjustment costs and price stickiness. The first is a new source of real rigidity from dynamic cost smoothing. The second, from firm-specific convex adjustment costs, is similar to those documented in the literature of firm-specific factors.

Our findings about the cost channel have implications on the credit channel through firm-level financing. Because we know the interest rate change due to a monetary policy shock is short-lived, if the credit channel is not effective in the short run, the direct impact of a monetary policy shock on a firm’s net worth may not be large. In contrast, the demand-side transmission is persistent. This in turn can change a firm’s finance situation by demand-driven cash flow and the expectation about a firm’s future profitability.

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Figure 1. Response to +1% Romer-Romer shock
Manufacturing and Trade: Jan 1970 - Dec 1996
Figure 2. Response to +1% Romer-Romer shock
Manufacturing industry: Jan 1970 - Dec 1996
Figure 3. Response to +1% Romer-Romer shock
Trade industry: Jan 1970 - Dec 1996
Figure 4. Response to +1% Romer-Romer shock
All types of manufacturing inventories: Jan 1970 - Dec 1996
Figure 5. Response to +1% Romer-Romer shock (with contemporaneous effects on macroeconomic variables)
Manufacturing and Trade: Jan 1970 - Dec 1996

Output

Price level

Fed funds rate

Inventory–to–sales ratio
Figure 6. Real rigidity and the curvature of cost functions

![Figure 6](image_url)

Figure 7. Real rigidity and the curvature of cost functions

The model with inventories

![Figure 7](image_url)
Figure 8. Impulse response after an expansionary monetary shock
No inventory, convex adjustment cost of labor

- Inflation Rate
- Marginal cost
- Lambda
- Output
- Labor
- Consumption
- Real Wage
- Nominal Interest Rate

small curvature \((F = 0.001)\)
medium curvature \((F = 1)\)
large curvature \((F = 5)\)
Figure 9. Impulse response after an expansionary monetary shock
With inventory holdings and no adjustment cost
Figure 10. Impulse response after an expansionary monetary shock
With inventory holdings and adjustment cost
**Figure 11.** Impulse response after an expansionary monetary shock
No real rigidity ($\kappa = 0$ but not considering other effects on marginal cost)
With inventory holdings and adjustment cost
Figure 12. Impulse response after an expansionary monetary shock  
With inventory holdings and adjustment cost  
No working capital channel
**Figure 13.** Impulse response after an expansionary monetary shock
With inventory holdings and adjustment cost
Monetary policy has contemporaneous effects on macroeconomic variables
Appendix

A The baseline model

A.1 Household and aggregate resource

The preference in period $t$ of the representative household is given by
\[ E_t \sum_{j=0}^{\infty} \beta^j \left( \frac{(C_{t+j} - bC_{t+j-1})^{1-\sigma} - 1}{1 - \sigma} - \frac{N_{t+j}^{1+\chi}}{1+\chi} \right), \quad \sigma > 0, \quad \chi > 0, \]
where $0 < \beta < 1$ denotes the discount factor, $C_t$ denotes the index of consumption goods and $N_t$ denotes the number of hours worked in period $t$. In equilibrium, consumption $C_t$ is equal to gross sales $S_t$ if without investment and government spending. We assume that the parameter $b$ takes a positive value, in order to allow for habit formation in consumption preferences. $C_t$ is the CES aggregator over different varieties
\[ C_t = \left( \int_0^1 C_t(i)^\frac{\theta-1}{\theta} \, di \right)^\frac{\theta}{\theta-1} \]
Define the price index $P_t$ as
\[ P_t = \left( \int_0^1 P_t(i)^\frac{1-\theta}{\theta} \, di \right)^\frac{\theta}{1-\theta} \]
The budget constraint in period $t$ of the representative household can be therefore written as
\[ C_t + E_t D_{t,t+1} = \frac{B_t}{P_t} + \frac{W_t}{P_t} L_t + \Pi_t, \quad (22) \]
where $B_{t+1}$ denotes a portfolio of nominal state contingent claims in the complete contingent claims market, $D_{t,t+1}$ denotes the stochastic discount factor for computing the real value in period $t$ of one unit of consumption goods in period $t+1$, $W_t$ denotes aggregate nominal wage, and $\Pi_t$ denotes real dividend income and transfers. The first order conditions for consumption and labor supply can be written as
\[ \Lambda_t = E_t \left( (C_t - bC_{t-1})^{-\sigma} - \beta b (C_{t+1} - bC_t)^{-\sigma} \right), \]
\[ N_t^{\chi} = \Lambda_t \frac{W_t^*}{P_t}, \quad (23) \]
where $\Lambda_t$ is the Lagrange multiplier of the budget constraint (22) and $W_t^*$ is the market-clearing wage rate at time $t$. The optimization condition for bonds holding is
\[ D_{t,t+1} = \beta \frac{\Lambda_{t+1}}{\Lambda_t}. \]
Hence, if $R_t$ represents the gross nominal interest rate in period $t$, absence of arbitrage gives the following Euler equation:
\[ E_t \left( D_{t,t+1} R_t \frac{P_t}{P_{t+1}} \right) = 1. \]
The household accumulates capital using the following technology:

\[ K_{t+1} = (1 - \delta) K_t + F (I_t, I_{t-1}) + \Delta_t, \]

where the function for adjustment cost is specified by

\[ F (I_t, I_{t-1}) = \left( 1 - S \left( \frac{I_t}{I_{t-1}} \right) \right) I_t \]

where \( S (\cdot) \) is a convex cost function of investment adjustment such that \( S (1) = S' (1) = 0 \) and \( S'' (1) > 0 \).

The decision of capital accumulation by the household gives us

\[ P_{K,t} = \omega_t \Lambda_t \]

where \( \omega_t \) is the Lagrangian multiplier on the constraint of capital accumulation. The optimal investment is given by

\[ \omega_t \left[ 1 - S \left( \frac{I_t}{I_{t-1}} \right) - S' \left( \frac{I_t}{I_{t-1}} \right) \frac{I_t}{I_{t-1}} \right] + E_t \beta \omega_{t+1} S' \left( \frac{I_{t+1}}{I_t} \right) \left( \frac{I_{t+1}}{I_t} \right)^2 = \Lambda_t \]

and absence of arbitrage for the capital return leads to

\[ E_t D_{t,t+1} \frac{R_{K,t+1} + (1 - \delta_k) P_{K,t+1}}{P_{K,t}} = 1 \]

The aggregate resource constraint is given by

\[ Y_t = C_t + I_t - S \left( \frac{I_t}{I_{t-1}} \right) I_t \]

A.2 A firm’s first-order conditions

The first-order conditions for \( K^*_t (i) \), \( L^*_t (i) \), and \( P^*_t (i) \) can be summarized as follows. Firms set prices according to a variant of the mechanism spelled out by Calvo (1983). In each period, a firm faces a constant probability, \( \alpha_p \), of not being able to re-optimize its nominal price. Firms that do not re-optimize prices simply follow the indexation rule (see footnote 13). Therefore, the optimal conditions for price are only applied to those firms that re-optimize.

The first-order conditions for capital service and labor in production \( K^*_t (i) \) and \( L^*_t (i) \) is given by

\[ R_{K,t,j} = Q_{t,j} (i) \alpha L_{t+j}^{1-\alpha} (i) K_{t+j}^{\alpha-1} (i) \quad (24) \]

and

\[ \frac{W_t}{P_t} \left( 1 + \Upsilon \left( \frac{L_t (i)}{L_{t-1} (i)} \right) \frac{L_t (i)}{L_{t-1} (i)} \right) + \Upsilon \left( \frac{L_t (i)}{L_{t-1} (i)} \right) - E_t D_{t,t+1} \frac{W_{t+1}}{P_{t+1}} \Upsilon' \left( \frac{L_{t+1} (i)}{L_t (i)} \right) \left( \frac{L_{t+1} (i)}{L_t (i)} \right)^2 = Q_{t+j} (i) R_{K,t,j}^{\alpha-1} \alpha (1 - \alpha) \]
where the marginal cost from labor input depends on a firm’s expected labor input changes in current period and next period.

The first-order condition for price-setting $P^*_t (i)$ is given by

$$E_t^E \sum_{j=0}^{\infty} \alpha_j^i P_{t+j} \left( \frac{P_{t+j} (i)}{P_{t+j}} - \frac{\varepsilon}{\varepsilon - 1} Q_{t+j} (i) \right) = 0$$

where marginal cost $Q_{t+j} (i)$ now depends on individual variables.

A.3 Parametrization

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values</th>
<th>Description and definitions</th>
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