Inflation Dynamics During the Financial Crisis

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Abstract

Using (confidential) product-level price data underlying the U.S. Producer Price Index (PPI), this paper analyzes the effect of changes in firms' financial conditions on their price-setting behavior during the "Great Recession." The evidence indicates that during the height of the crisis in late 2008, firms with "weak" balance sheets increased prices significantly, whereas firms with "strong" balance sheets lowered prices, a response consistent with an adverse demand shock. These start differences in price-setting behavior are consistent with the notion that financial frictions may significantly influence the response of aggregate inflation to macroeconomic shocks. We explore the implications of these empirical findings within the New Keynesian general equilibrium framework that allows for customer markets and departures from the frictionless financial markets. In the model, firms have an incentive to set a low price to invest in market share, though when financial distortions are severe, firms forgo these investment opportunities and maintain high prices in an effort to preserve their balance-sheet capacity. Consistent with our empirical findings, the model with financial distortions—relative to the baseline model without financial distortions—implies a substantial attenuation of price dynamics in response to contractionary demand shocks.

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1 Introduction

How do fluctuations in firms' financial conditions over the course of a business cycle affect their price-setting behavior? We investigate this question through the lenses of customer-markets theory, focusing in particular on the 2007–09 financial crisis. As formalized by Bils (1989), the key idea behind customer markets is that pricing decisions are a form of investment that builds the future customer base. In the presence of financial market frictions, however, firms experiencing a deterioration in the quality of their balance sheets may find it optimal to increase prices—relative to financially healthy firms—and sacrifice future sales in order to boost current cash flows (cf. Gottfries (1991); Bucht, Gottfries, and Lundin (2002); and Chevalier and Scharfstein (1996)). This suggests that changes in financial conditions may have a direct effect on aggregate inflation dynamics, especially during financial crises. Importantly, the interaction of financial factors with the price-setting behavior of firms may limit the deflationary pressures that are often associated with acute financial distress, periods in which a significant proportion of firms may be facing financing constraints. It may also help explain the fact that despite the substantial and persistent economic slack—as well a significant tightening of financial conditions—the U.S. economy has experienced only a mild disinflation during the "Great Recession."

As a first step in our analysis, we construct a novel data set by merging a subset of monthly *product-level* prices from the U.S. Producer Price Index (PPI), constructed and published by the Bureau of Labor Statistics (BLS), with the respondents' quarterly income and balance sheet data from Compustat. The micro-level aspect of our data allows us to analyze how changes in financial conditions of these large publicly-traded firms affect their price-setting behavior during the 2005–12 period. Our results indicate that at the peak of the crisis in late 2008—after the collapse of Lehman Brothers investment bank—financially vulnerable firms, on average, dramatically increased prices, whereas their financially healthy counterparts lowered prices in response to the ensuing collapse in aggregate demand. During this period, the price increases by firms with "weak" balance sheets generate a differential of 10 percentage points in the monthly producer price inflation relative to firms with "strong" balance sheets, and this differential is highly persistent over time.

Formal regression analysis also indicates that financially weak firms were significantly more likely to increase prices during the height of the financial crisis. At the same time, these firms were less likely to lower prices before the crisis and in its aftermath. These results strongly suggest firms with weak balance sheets actively manage their prices to maintain cash flows in the face of declining demand and not because they are less well managed and hence less responsive to changes in economic conditions.[1]

[1]Christiano, Eichenbaum, and Evans (2005), Christiano, Gust, and Roldos (2004), and the empirical work of Barth and Ramey (2002) all emphasize a "cost channel," whereby firms borrow to finance inputs to production. To the extent that firms with weak balance sheets face higher borrowing costs, which during the crisis increase more sharply than those for firm with strong balance sheet, financially vulnerable firms may pass those cost increases on to their customers in the form of higher prices. Note that both mechanisms imply less price-cutting for financially

To explore the macroeconomic and policy consequences of financial distortions in a customer-markets framework, we build a general equilibrium model, the essential feature of which is that firms face costly price adjustment, while setting prices to actively manage current versus future expected demand. We do so in the context of the "deep habits" framework formulated by Ravn, Schmitt-Grohe, and Uribe (2006), which is augmented with a tractable model of costly external finance. As in Gourio and Rudanko (2011), customer base in our model is a form of investment. The investment literature has long emphasized the notion that financial distortions may create a debt-overhang problem, which leads firms to pass up otherwise positive net present value projects (Myers (1977)).[2] The presence of financial distortions may similarly influence the incentive to invest into customers via price reductions, implying a sensitivity of price-setting decisions to changes in balance sheet conditions—when cash flow is low or external finance is very costly, firms will "disinvest" by maintaining high prices. In this sense, our framework echoes the theoretical insights of Chevalier and Scharfstein (1996) regarding the role of financial market frictions on the cyclical variation in the mark-up but generalizes their results to a fully dynamic general equilibrium setting. More generally, the framework presented in this paper can be viewed as a special application of liquidity-based asset pricing (Holmstrom and Tirole (2001)) to the New Keynesian pricing theory.

Relative to the baseline model with frictionless financial markets, our model implies a significant attenuation of the response of prices to contractionary demand shocks. Moreover, in a calibration where external finance is extremely costly—as was likely the case at the nadir of the 2007–09 financial crisis—our model implies that inflation rises rather than falls in response to a contractionary demand shock. These theoretical results are consistent with the apparent lack of significant deflationary pressures during the recent recession, and they also suggest that financial factors may help explain sluggish price responses more generally. In fact, our results offer one potential explanation for the well-known "price-puzzle," the empirical regularity that shows that inflation appears to increase—at least initially—in response to an unanticipated tightening of monetary policy.

One of the defining features of the recent macroeconomic experience is the fact that since the end of 2008, the federal funds rate has been stuck at its effective lower bound. The implications of our model for macroeconomic outcomes at the zero lower bound (ZLB) are striking. In a model with financial distortions, the attenuation of deflationary pressures implies that the ZLB is both harder to achieve, and when achieved, the economy is likely to exit the ZLB environment sooner. In other words, the sharp contractionary nature of a deflationary spiral at the zero lower bound is mitigated to a great extent by the presence of financial distortions. This finding suggests that in a customer-markets model, financial frictions may paradoxically improve overall economic outcomes in an environment where the zero lower bound is binding. This echoes recent findings of Denes, Eggertsson, and Gilbukh (2013) and Eggertsson (2011), who argue that certain forms of

constrained firms relative to their unconstrained counterparts.

[2]See Fazzari, Hubbard, and Petersen (1988), Chirinko (1993), and Gilchrist and Himmelberg (1995) for related empirical evidence and discussion.

taxation may improve economic outcomes in situations where short-term interest rates are stuck at their effective lower bound.

We also consider an extension of our benchmark model that allows for heterogeneity in fixed operating costs across firms. The resulting differences in operating efficiency translate directly into differences in financial conditions: A firm with low operating efficiency (i.e., high fixed operating costs) is in a much more precarious financial position because, on average, it will have a more difficult time meeting its liquidity needs using internally-generated funds and, therefore, will face a higher external finance premium. In such context, an adverse financial shock causes financially healthy firms to aggressively cut prices in an effort to gain a market share, whereas their financially constrained counterparts increase prices to avoid relying on costly external finance. The resulting "price war" induces countercyclical dispersion in firm-level inflation rates—as well as in output and employment—a pattern consistent with that reported by Vavra (2011). However, it is important to emphasize that in our framework the countercyclical dispersion in inflation rates (and other variables) arises endogenously in response to differences in financial conditions across firms, whereas Vavra (2011) generates the countercyclical dispersion in inflation rates using an exogenous countercyclical second-moment shock.

The theoretical mechanism that we study has broader implications for the conduct of monetary policy. The standard New Keynesian framework analyzes optimal policy from the perspective of the welfare losses induced by output fluctuations and price dispersion owing to nominal rigidities. In the standard framework, demand shocks imply the so-called divine coincidence, the fact that countercyclical monetary policy achieves the joint stabilization of output and inflation. The trade-off between inflation and output stabilization only arises in circumstances where the "cost-push" shocks move inflation and output in opposite directions. In our model, demand shocks may also lead to opposing movements in inflation and output. However, when firms face varying costs of external finance, demand shocks also lead to increased dispersion in prices, even in the absence of large swings in aggregate inflation. These results suggest that customer-markets models with financial distortions may have starkly different implications for the inflation-output tradeoff—and therefore for the conduct of monetary policy—especially at times of significant distortions in financial markets.

The remainder of the paper is organized as follows. Section 2 describes the micro-levelprice data and the matching process with firm-level balance sheet data. Section 3 provides empirical results on aggregate price dynamics and explores the effect of firm-level balance sheet conditions on price-setting at the level of the firm. Section 4 presents the general equilibrium model and simulation results. Section 5 concludes.

2 Data Sources and Methods

To understand the interaction between price-setting behavior of firms and the condition of their balance sheets, we construct a new firm-level data set using two sources: (1) *product-level* price data underlying the Producer Price Index published by the Bureau of Labor Statistics; and (2) *firm-level* income and balance sheet date from Compustat.

2.1 Producer Price Data

The confidential PPI micro-level price data from the BLS form the cornerstone of our analysis for two reasons.[3] First, they allow us to construct firm-level inflation rates, thereby overcoming the limitations of working with aggregate price indices. And second, they allows us to analyze firm-level price dynamics directly in conjunction the respondents' corresponding financial data. Both of these features represent an important advance over any analysis that employs aggregate price series—even if narrowly defined—because price dynamics at the product and firm levels are subject to large idiosyncratic shocks (cf. Nakamura and Steinsson (2008); Bils and Klenow (2004); and Gopinath and Itskhoki (2011)). Moreover, prices at the level of individual products contain potentially important information to understand the economics of price adjustment at the firm level.

From a practical perspective, we focus on the PPI data because they yield a much broader match with the data set of publicly-traded Compustat firms. Economic considerations also point to studying producer prices as they most directly reflect the response of production unit to changes in the underlying economic fundamentals. The CPI data, in contrast, reflect the pricing behavior of non-producing retailers—the so-called outlets—which are subject to price responses by the entire distribution network and therefore may exhibit quite different price-setting behavior. Moreover, the PPI data exclude prices of imported goods, which are an important part of the CPI, but for which data on financial conditions of the underlying production units are not readily available. All told, our sample contains about 100,000 monthly producer price quotes collected by the BLS from 28,300 production units. The time-series range of our data runs from January 2005 through September 2012 and thus fully includes the 2007-09 financial crisis and its aftermath.

Our measure of firm-level inflation—denoted by $\pi_{j,k,t}$—is given by the weighted monthly average price changes of goods produced by each firm, after filtering out monthly industry-level (2-digit

[3]The PPI data are described at length for example in Nakamura and Steinsson (2008), Bhattarai and Schoenle (2010) and Goldberg and Hellerstein (2009). The data are representative of the entire U.S. production structure and have the important quality that they are carefully and consistently sampled. In particular, goods within a firm are uniquely identified according to several consistent criteria: their "price-determining" characteristics such as the type of buyer, the type of market transaction, the method of shipment, the size and units of shipment, the freight type, and the day of the month of the transaction. Once a good is identified, prices are consistently collected each month for that very same good and the same customer. Such consistent sampling avoids the problem of having to compute unit prices as is given with many micro data sets. All prices are transaction prices, not list prices as critiqued by Stigler and Kindahl (1970).

NAICS) inflation rates (denoted by $\pi_{k,t}$). Formally,

$$\pi_{j,k,t} = \frac{1}{n_j} \sum_{i=1}^{n_j} w_{i,j,k,t}(\Delta p_{i,j,k,t} - \pi_{k,t}), \tag{1}$$

where $\Delta p_{i,j,k,t}$ denotes monthly log price changes for each good i produced by firm j that operates in an industry k, and n_j the number of goods produced by that firm.[4] Importantly, we use *quality-adjusted* prices when constructing these inflation rates. For each item, the quality-adjusted price in month t is defined as the ratio of the recorded price $p^*_{i,j,k,t}$ to the base price $p^b_{i,j,k,t}$, where the latter takes into account changes in the item's quality over time: $p_{i,j,k,t} = \frac{p^*_{i,j,k,t}}{p^b_{i,j,k,t}}$. The fraction of firm-level price changes is constructed analogously using a quarterly price change indicator variable instead of the monthly log price difference but without filtering.

We construct weights very carefully based on the relative importance weights used by the BLS and firm-level value of shipments data recorded by the BLS for computation of the aggregate PPI. We define the within-firm good-level weight $w_{i,j,k,t}$ as follows:

$$w_{i,j,k,t} = \bar{w}_{i,j,k,t} \times \omega_{j',t}, \tag{2}$$

where $\bar{w}_{i,j,k,t}$ denotes the relative weight for good i in the production structure of firm j, according to the BLS definition. The second term in the expression is an adjustment factor that takes into account the fact that in our merge with Compustat data more than one BLS respondent may fall within the Compustat firm definition j. The adjustment factor is therefore defined as the relative value of shipments weight of one BLS firm with respect to all other BLS firms within the same Compustat firm unit.

2.2 Indicators of Financial and Product Market Frictions

We use quarterly Compustat data to characterize the firms' financial conditions and product market characteristics. Our primary measure of financial conditions is the liquid-asset ratio, defined as

$$LIQUIDITY_{j,t} = \frac{Cash\ and\ other\ Liquid\ Assets_{j,t}}{Total\ Assets_{j,t}}, \tag{3}$$

where cash (and other liquid assets) and total assets are measured at the end of month t corresponding to the firm's fiscal quarter, which is properly aligned with the calendar month and thus each monthly inflation rate.[5] As a robustness check, we also consider two alternative financial

[4]Note that taking out "industry inflation" does not take into account the weight assigned to each industry for a firm if the firm operates across multiple industries. This is not a problem for our data. The reason is the the BLS defines firms as price-setting units in one production unit, which is usually unique to a NAICS code, especially at 2-digit level of filtering. We drop the handful of cases where a firm operates across multiple industries.

[5] Other widely used indicators to measure the degree of financial frictions faced by firms include the dividend payout behavior (Carpenter, Fazzari, and Petersen (1994)); firm size (Gertler and Gilchrist (1994) and

indicators: cash-flow ratio and interest coverage. We define the cash-flow ratio as:

$$CASH\text{-}FLOW_{j,t} = \frac{Operating\ Income_{j,t}}{Total\ Assets_{j,t-1}}; \tag{4}$$

and the interest coverage ratio as:

$$INTEREST\text{-}COVERAGE_{j,t} = \frac{Interest\ Expense\ _{j,t}}{Total\ Sales_{j,t}}. \tag{5}$$

To measure product-market characteristics motivated by the customer-markets theory, which emphasizes the idea that price setting is a form of investment that builds the future customer base, we include into our analysis sales and general administrative expenses (SG&A), a commonly-used indicator of frictions in product markets. We normalize SG&A expenditures by sales:

$$SGAXR_{j,t} = \frac{SGAX_t}{Total\ Sales_{j,t}}. \tag{6}$$

It is important to emphasize that the intensity of SG&A spending can have opposite implications for pricing decisions. On the one hand, for a firm with a relatively high SG&A ratio—an indication that the firm is likely operating in a customer market environment (e.g., Gourio and Rudanko (2011))—one would expect a stronger incentive to lower prices today in order to expand market share tomorrow. On the other hand, due to the quasi-fixed nature of SG&A expenses, a high ratio of SG&A to sales may be associated with low operating efficiency. In turn, this would force firms to set higher prices today to boost current cash flow, a dynamic that would be exacerbated during periods of financial stress when external financing is very costly. In the empirical analysis, we let the data speak for themselves to see which force dominates the pricing dynamics during the financial crisis.

2.3 Matched Compustat-PPI Sample

To link the BLS micro-level research database with the firm-level Compustat, we use the matching algorithm developed by Schoenle (2010). The algorithm works by running a fuzzy match of the names of firms in the PPI and Compustat databases.[6] After sorting all nonperfect matches in

Carpenter, Fazzari, and Petersen (1998)); the reliance of trade credit (Nilsen (2002)); the presence (or absence) of an external credit rating (Gilchrist and Himmelberg (1995)); the length and/or number of banking relationships Petersen and Rajan (1994); and industrial effects arising from factor intensity differentials (Rajan and Zingales (1998)).

[6]The steps of the algorithm can be summarized as follows: First, firm names in the PPI and Compustat data are assimilated through a series of string manipulations by means of capitalization, punctuation removal, standardization of terms, and removal of generic terms. Second, a modified string similarity algorithm computes a measure of similarity between base and target firm names. It summarizes the quality of matches using Dice's coefficient $s = 2c/(x_1 + x_2)$ where c is the number of common bigrams, x_1 the number of bigrams in the first string and x_2 the number of bigrams in the second string. Note that when $s = 1$, we have a perfect match.

decreasing order of similarity, we then manually select "good" matches in addition to perfect matches.

After applying the algorithm to the two data sets over the 2005-12 period, we successfully matched 780 Compustat firms, on average, per quarter. Given that we have information on almost 5,000 Compustat firms in an average quarter, this implies a matching rate of 16%. In terms of basic characteristics, the firms in the matched sample tend to be larger, a result that is not at all surprising because large firms are more likely to be sampled by the BLS. In terms of their price-setting behavior, we find that there are no significant differences between average monthly inflation rates in the full PPI data set and the matched subsample. At the same time, the frequency of price changes in the matched sample is significantly higher than in the full sample (see Table 1).

Figure 1 plots the aggregate inflation rates for the full and matched sample of firms. The two series are highly correlated, an indication that our matched sample is broadly representative of the economy as a whole. And lastly, as indicted in Table 2, our matched sample of firms exhibits somewhat lower liquidity, SG&A and interest expense ratios, on average, compared with the sample of all U.S. publicly-traded nonfinancial corporations.

3 Inflation Dynamics and Financial Conditions

To analyze the role of financial distortions in determining inflation dynamics, we first compute industry-adjusted firm-level inflation rates as described above. Then for each month t, we sort firms into financially "weak" and "strong" categories based on whether a specified financial indicator in month $t-1$ (i.e., liquid asset ratio, cash flow ratio, or interest coverage ratio) is below/above the median of its distribution in that period. To minimize the switching of firms between the two categories, we use a rolling 12-month backward moving average of financial ratios when sorting firms into financially weak and strong categories. We use the same method to identify firms with a high (low) intensity of SG&A spending. Finally, we compute average weighted monthly inflation for each category using firms sales as weights.

The top panel of Figure 2 shows the industry-adjusted inflation rates for firms with weak balance sheets, while the bottom panel depicts the the same information for firms in a strong financial position. Regardless of the financial indicator used to sort firm into financially weak and strong categories, a strikingly similar picture emerges: At the peak of the crisis in the fourth quarter of 2008, firms with weak balance sheets significantly increased—relative to their industry trend—prices, whereas their financially healthy counterparts substantially lowered prices, a response consistent with the sharp drop in demand that was occuring at that time. Note that such differences in price-setting behavior in response to a contractionary demand shock will lead to a persistent and long-lasting dispersion in prices.

Our next empirical exercise focuses on firms with different product-market characteristics. The top panel of Figure 3 shows the industry-adjusted inflation rates for firms with different intensities

of SG&A spending. The bottom panel focuses on a subset of SG&A expenses, namely advertising expense, a narrower indicator of whether a firm is operating in a customer-markets environment. According to both panels, firms that likely operate in the customer-markets environment significantly increased prices in the latter part of 2008. In contrast, firms that likely operate in competitive markets lowered their prices significantly, a response consistent with the concommitant drop in demand.

The results in Figures 2 and 3 are difficult to reconcile with the standard price-adjustment mechanism emphasized by the New Keynesian literature, a paradigm where firms' financial conditions play no role in determining their price-setting behavior. In general, we would expect that firms hit by an adverse demand shock—they kind the U.S. economy experienced in the latter part of 2008—should induce firms to lower prices. Moreover, if the proxies used to measure the strength of firms' balance sheets were also indicative of the weakness in demand, we would expect financially vulnerable firms to lower prices even more relative to financially strong firms. However, we observe exactly the opposite reaction in the data.

As emphasized by Bils, Klenow, and Malin (2012), disinflationary pressures during the "Great Recession" were most pronounced in nondurable goods industries. The top panel of Figure 4 shows inflation rates of financially strong and weak firms within the durable and nondurable goods sectors, while the bottom panel contains inflation rates for firms with varying intensity of SG&A spending, again within the durable and nondurable goods sectors. According to both panels, the deflationary pressures during the recent financial crisis were concentrated primarily in the nondurable goods sector, a result consisted with that reported by Bils, Klenow, and Malin (2012).

However, within the nondurable goods sector, price deflation reflects solely the massive price cut by financially healthy firms or firms that are unlikely to operate within the customer-markets environment. In contrast, nondurable goods producers with weak balance sheets or those with a high SG&A expense ratio significantly increased prices during the height of the crisis. The fact that inflation dynamics in nondurable goods industries during the financial crisis appear to be shaped significantly by financial conditions and SG&A expenditures is consistent with the notion that nondurable goods are typically frequently-purchased items, subject to habits and past experience, factors at the center of the customer-markets theory. In contrast, we expect customers to be less loyal to past purchase habits when buying large-item durable goods that are purchased relatively infrequently.

3.1 Extensive Margin of Price Adjustment

In this section, we provide new evidence on the importance of the strength of firm balance sheets and the intensity of SG&A spending for price adjustment at the extensive margin—that is, the frequency of price adjustment. As Bhattarai and Schoenle (2010), we estimate a multinomial logit

of the form:

$$\Pr(Y_{i,j,t+1} = \{-1, 0, 1\} | X_{i,j,t} = x) = \Lambda(\beta_t' X_{i,j,t}), \tag{7}$$

where $Y_{i,j,t+1}$ is an indicator variable for price changes at time $t+1$ of good i produced by firm j: -1 = price decrease; 0 = no change (base category); and 1 = price increase. The set of firm-level explanatory variables $X_{i,j,t}$ includes the liquidity ratio, the SG&A-to-sales ratio, and sales growth at time t. In addition, the specification includes time and (3-digit NAICS) industry fixed effects.

To allow for time-series variation in the response coefficients β_t, we estimate the multinomial logit specification using a four-quarter rolling window. The resulting (time-varying) estimates are used to compute the elasticity of the response variable—that is, the percent change in the probability of a price adjustment for a given percent change in a variable of interest, evaluated at the sample mean of the explanatory variables.

The top panel of Figure 5 depicts the time-varying elasticity estimates of price djustment with respect to financial conditions, as measured by the liquid-asset ratio; the left panel depicts the elasticity of downward price adjustment, while the right panel depicts the elasticity of upward price adjustment. According to these estimates, firms with weak balance sheets became significantly more likely to increase prices during the financial crisis, as evidenced by the fact that the estimated elasticity of upward price adjustment with respect to liquidity ratio (right panel) dropped noticeably into the negative territory in the latter half of 2008; conversely, financial healthy firms were less likely to increase prices during that period.

In economic terms, an increase in the liquidity ratio of one percentage points in the second half of 2008 is estimated to lower—ceteris paribus—the probability of upward price adjustment 16 basis points relative to no price change. At the same time, the results in the left panel indicate that a high liquidity ratio is consistently associated with a greater likelihood of downward price adjustment. In sum, these results suggest that financial strong firms face lower downward price rigidity—at least at the extensive margin—compared with their weaker counterparts.

The bottom panel of Figure 5 presents the elasticities of price adjustment with respect to the SG&A ratio. The fact that both directional elasticities are consistently negative indicates that firms with a high intensity of SG&A spending are less likely to change their prices—either up or down—relative to no price change. Moreover, there is little evidence to suggest that this pattern has changed apprecibly during the financial crisis; at the same time, there is a sizable drop—at least in economic terms—in the elasticity of downward price adjustment during the crisis, an indication that firms with lower SG&A-to-sales ratio were more likely to lower their prices during that period.

4 Model

In this section, we construct a general equilibrium model aimed at explaining two key empirical findings:

1. Firms with weak balance sheets significantly increased prices at the height of the 2007–09 financial crisis, while the financially strong firms lowered prices.

2. Firms with a high SG&A-to-sales ratio—a likely indication that they operate in a customer-markets environment—increased prices significantly during the nadir of the recent financial crisis, while firms with a low SG&A ratio lowered their prices.

The main idea of our model involves monopolistically-competitive firms that set prices in a customer-markets environment, whereby their current pricing decisions influence future market shares. To motivate the competition for market shares implied by the customer-markets hypothesis, we specify preferences that allow for the formation of a *customer base*—that is, "low" prices today are a form of investment in a future market share (Rotemberg and Woodford (1991)).[7] Specifically, we adopt the good-specific habit model developed by Ravn, Schmitt-Grohe, and Uribe (2006), which we augment with nominal rigidities in the form of quadratic costs to changing prices.[8] Because our empirical analysis indicates that financial factors primarily affect the price-setting behavior of firms in nondurable goods industries, we consider only perishable goods in our model formulation. To explore the influence of financial distrortion on price-setting behavior, we augment the framework with a stylized but tractable model of costly external finance.

4.1 Preferences and Technology

The model contains a continuum of households indexed by $j \in [0, 1]$. Each household consumes a variety of consumption goods indexed by $i \in [0, 1]$. The preferences of households are defined over a habit-adjusted consumption bundle x_t^j and labor h_t^j as follows:

$$\mathbb{E}_t \sum_{s=0}^{\infty} \beta^s U(x_{t+s}^j - \delta_{t+s}, h_{t+s}^j). \tag{8}$$

The consumption/habit aggregator is defined as

$$x_t^j \equiv \left[\int_0^1 \left(\frac{c_{it}^j}{s_{it-1}^{\theta}} \right)^{1-1/\eta} di \right]^{1/(1-1/\eta)}, \tag{9}$$

while the demand shock δ_t in equation (8) alters the marginal utility of consumption today and hence the final demand. The good-specific habit stock is assumed to be external and thus taken as

[7] Switching cost models of the type considered by Klemperer (1987) would serve the same purpose. We chose the good-specific habit model because of its tractability in a dynamic general equilibrium setting.

[8] In standard New Keynesian models the quadratic cost of price adjustment is equivalent to a Calvo price-setting mechanism.

given by consumers. We assume that the habit evolves according to

$$s_{it} = \rho s_{it-1} + (1-\rho)c_{it}, \tag{10}$$

where $1-\rho$ denotes the depreciation rate for the current stock of habit. The dual problem of cost minimization gives rise to a good-specific demand,

$$c_{it}^{j} = \left(\frac{p_{it}}{\tilde{p}_t}\right)^{-\eta} s_{it-1}^{\theta(1-\eta)} x_t^j, \tag{11}$$

where $p_{it} \equiv P_{it}/P_t$ is the relative price of variety i in terms of $P_t \equiv \left[\int_0^1 P_{it}^{1-\eta} di\right]^{1/(1-\eta)}$, and the externality-adjusted composite price index $\tilde{p}_t$ is given by

$$\tilde{p}_t \equiv \left[\int_0^1 (p_{it} s_{it-1}^{\theta})^{1-\eta} di\right]^{1/(1-\eta)}. \tag{12}$$

We assume that there exists a continuum of monopolistically-competitive firms, producing a differentiated variety of goods indexed by $i \in [0,1]$. The production technology is given by

$$y_{it} = \left(\frac{A_t}{a_{it}} h_{it}\right)^{\alpha} - \phi, \quad 0 < \alpha \leq 1 \tag{13}$$

where A_t is an aggregate productivity shock that follows an AR(1) process, and a_{it} is an idiosyncratic (i.i.d.) productivity shock distributed as $\log a_{it} \sim N(-0.5\sigma^2, \sigma^2)$. As indicated by equation (13), we allow the production technology to exhibit either decreasing or constant returns-to-scale. In addition, we assume that production is subject to fixed operating costs—denoted by ϕ—which makes it possible for firms to incur negative income, thereby creating a liquidity squeeze if external financing is costly.

4.2 Pricing Frictions and Financial Distortions

To allow for nominal rigidities, we assume that firms face a quadratic cost to adjusting nominal prices, specified as $\gamma/2(P_{it}/P_{it-1} - \bar{\pi})^2 c_t = \gamma/2(\pi_t \cdot p_{it}/p_{it-1} - \bar{\pi})^2 c_t$ (see Rotemberg (1982)). It is wortwhile to note that staggered pricing models such as those of Calvo (1983) would not change the main conclusions of our paper. Rather, convex adjustment costs are adopted for the sake of mathematical tractability.

To introduce financial distortions in the model, we assume that firms make pricing and production decisions to maximize the present value of discounted dividends. For simplicity, we focus on equity as the only source of external finance. We assume that firms must commit to pricing decisions—and hence production—based on all aggregate information available within the period, but prior to the realization of their idiosyncratic productivity shock. Based on this aggregate in-

formation, firms post prices, take orders from customers, and plan production based on expected marginal cost. Firms then realize actual marginal cost and hire labor to meet the demand. Labor must be paid within the period, and in the presence of fixed operating costs, ex post profits may be too low to cover the total cost of production, in which case, firms must raise external funds.

External funds are raised by issuing new equity. We assume that equity finance involves a constant per-unit dilution cost per dollar of equity issued.[9] We also abstract from firm savings decisions by assuming that all dividends are paid out within the period.[10] Specifically, we assume that ex post equity finance involves a constant per-unit dilution cost $\varphi \in (0,1)$. This tractable formulation of costly external finance allows us to highlight the basic mechanism within a framework that deviates only slightly from the standard good-specific habit model. In particular, in our framework, all firms are identical ex ante, so that only firms with an idiosyncratic productivity shock below a threshold incur negative profits and issue new equity.

4.3 Profit Maximization Problem

The firm's problem is to maximize the present value of dividend flows, $\mathbb{E}_t[\sum_{s=0}^{\infty} m_{t,t+s} d_{it+s}]$, where d_{it} denotes (real) dividend payouts when positive and equity issuance when negative. The formulation of the dilution costs implies that when a firm issues a notional amount of equity $d_{it}(< 0)$, actual cash inflow from the issuance is reduced to $-(1-\varphi)d_{it}$. The firm's problem is subject to the flow-of-funds constraint:

$$0 = p_{it}c_{it} - w_t h_{it} - \frac{\gamma}{2}\left(\pi_t \frac{p_{it}}{p_{it-1}} - \bar{\pi}\right)^2 c_t - d_{it} + \varphi \min\{0, d_{it}\}; \tag{14}$$

and given the monopolistically competitive product market, to the demand constraint:

$$\left(\frac{A_t}{a_{it}} h_{it}\right)^{\alpha} - \phi \geq c_{it}. \tag{15}$$

[9] As shown by Gomes (2001) and Stein (2003), other forms of costly external financing can be replicated by properly parameterized equity dilution costs.

[10] We are also interested in analyzing a richer model in which firms actively manage their balance sheets and may save or issue debt to meet future financial needs. As in the financial accelerator literature (cf. Bernanke, Gertler, and Gilchrist (1999), Gilchrist, Sim, and Zakrajsek (2013)), this requires introducing a firm-specific financial state variable, such as net worth. Allowing for such financial state variable(s) typically induces more persistence in the dynamics of macroeconomic aggregates, reflecting fluctuations in financial conditions.

Formally, the Lagrangean associated with the firms' problem is given by

$$\begin{aligned}\mathcal{L} &= \mathbb{E}_0 \sum_{t=0}^{\infty} m_{0,t} \Bigg\{ d_{it} + \kappa_{it} \left[\left(\frac{A_t}{a_{it}} h_{it} \right)^{\alpha} - \phi - c_{it} \right] \\ &\quad + \xi_{it} [p_{it} c_{it} - w_t h_{it} - \frac{\gamma}{2} \left(\pi_t \frac{p_{it}}{p_{it-1}} - \bar{\pi} \right)^2 c_t - d_{it} + \varphi \min\{0, d_{it}\}] \\ &\quad + \nu_{it} \left[\left(\frac{p_{it}}{\tilde{p}_t} \right)^{-\eta} s_{it-1}^{\theta(1-\eta)} x_t - c_{it} \right] + \lambda_{it} [\rho s_{it-1} + (1-\rho) c_{it} - s_{it}] \Bigg\}, \end{aligned} \tag{16}$$

where κ_{it}, ξ_{it}, ν_{it}, and λ_{it} are the Lagrangean multipliers associated with equations (15), (14), (11), and (10), respectively.

The efficiency conditions are summarized by the following first-order conditions:[11]

$$d_{it} \;:\; \xi_{it} = 1 \text{ if } d_{it} \geq 0; \quad \xi_{it} = 1/(1-\varphi) \text{ if } d_{it} < 0 \tag{17}$$

$$h_{it} \;:\; \kappa_{it} = \xi_{it} a_{it} \frac{w_t}{\alpha A_t} (c_{it} + \phi)^{\frac{1-\alpha}{\alpha}} \tag{18}$$

$$c_{it} \;:\; \mathbb{E}_t^a[\nu_{it}] = \mathbb{E}_t^a[\xi_{it} p_{it}] - \mathbb{E}_t^a[\kappa_{it}] + (1-\rho)\lambda_{it} \tag{19}$$

$$\begin{aligned} s_{it} \;:\; \lambda_{it} &= \rho \mathbb{E}_t \{ m_{t,t+1} \lambda_{it+1} \} \\ &\quad + \theta(1-\eta) \mathbb{E}_t \left\{ m_{t,t+1} \mathbb{E}_{t+1}^a \left[\nu_{it+1} \frac{c_{it+1}}{s_{it}} \right] \right\} \end{aligned} \tag{20}$$

$$\begin{aligned} p_{it} \;:\; 0 &= \mathbb{E}_t^a[\xi_{it}] c_{it} - \eta \frac{\mathbb{E}_t^a[\nu_{it}]}{p_{it}} c_{it} - \gamma \frac{\pi_t}{p_{it-1}} \left(\pi_t \frac{p_{it}}{p_{it-1}} - \bar{\pi} \right) c_t \\ &\quad + \gamma \mathbb{E}_t \left[m_{t,t+1} \mathbb{E}_{t+1}^a [\xi_{it}] \pi_{t+1} \frac{p_{it+1}}{p_{it}^2} \left(\pi_{t+1} \frac{p_{it+1}}{p_{it}} - \bar{\pi} \right) c_{t+1} \right]. \end{aligned} \tag{21}$$

Implict in the last three conditions is the assumption that pricing and production decisions are made prior to the realization of the idiosyncratic productivity shock. Accordingly, these first-order conditions involve the expected value of internal funds $\mathbb{E}_t^a[\xi_{it}] \equiv \int_0^{\infty} \xi_{it} dF(a)$, where the expectations are formed using all aggregate information up to time t, except, of course, the realization of the idiosyncratic shock. In contrast, the realized values ξ_{it} and a_{it} enter the efficiency conditions (17) and (18) without the expectation operator because equity issuance and labor hiring decisions are made after the realization of the idiosyncratic productivity shock.[12]

Under risk-neutrality and with i.i.d. idiosyncratic productivity shocks, the timing convention adopted above implies that firms are identical ex ante. Hence, we focus on a symmetric equilibrium, whereby all monopolistically-competitive firms choose identical relative price ($p_{it} = 1$), production

[11] Note that in equation (18), we replace h_{it} by the conditional labor demand $h_{it} = (c_{it} + \phi)^{1/\alpha} \frac{a_{it}}{A_t}$ *after* we derive the associated first-order condition.

[12] A similar timing convention has been used by Kiley and Sim (2012) in the context of financial intermediation.

scale ($c_{it} = c_t$), and habit stock ($s_{it} = s_t$). However, the distributions of labor inputs, dividend payouts, and equity issuance are non-degenerate and depend on the realization of the idiosyncratic shock.

4.4 Value of Internal Funds and Value of Customer Base

To analyze how distortions in financial markets interact with pricing (mark-up) decisions, we now consider the value of internal funds. Define the equity issuance trigger a_t^E as the level of idiosyncratic productivity that satisfies the flow-of-funds constraint, when dividends are exactly zero:

$$a_t^E = \frac{c_t}{(c_t + \phi)^{1/\alpha}} \frac{A_t}{w_t} \left[1 - \frac{\gamma}{2} (\pi_t - \bar{\pi})^2\right].$$

Using this trigger, we can rewrite the first-order conditions for dividends as

$$\xi(a_{it}) = \begin{cases} 1 & \text{if } a_{it} \leq a_t^E; \\ 1/(1-\phi) & \text{if } a_{it} > a_t^E. \end{cases} \tag{22}$$

This condition simply states that the realized shadow value of internal funds jumps from 1 to $1/(1-\varphi) > 1$ because of costly external financing, when the realization of the idiosyncratic productivity shock is greater than the threshold value. Let z_t^E denote the standardized value of a_t^E; that is, $z_t^E = \sigma^{-1}(\log a_t^E + 0.5\sigma^2)$. Using equation (22), the expected shadow value of internal funds can be expressed as

$$\mathbb{E}_t^a[\xi_{it}] = \int_0^{a_t^E} 1 dF(a) + \int_{a_t^E}^{\infty} \frac{1}{1-\varphi} dF(a) = 1 + \frac{\varphi}{1-\varphi}[1 - \Phi(z_t^E)] \geq 1,$$

where $\Phi(\cdot)$ denotes the CDF of the standard normal distribution.

The expected shadow value is strictly greater than unity as long as equity issuance is costly ($\varphi > 0$) and the firm faces idiosyncratic liquidity risk ($\sigma > 0$). This makes the firm de facto risk averse when making its pricing decision. Setting the price too low and taking an imprudently large number of orders exposes the firm to the risk of incurring negative operating income, which must be financed through costly equity issuance. On the other hand, by raising the expected mark-up, $c_t/(w_t h_t) = c_t A_t/[w_t(c_t + \phi)^{1/\alpha}]$, the firm can lower the probability of external financing $1 - \Phi(z_t^E)$, and as a result, the expected shadow value of internal funds. Note that the equity financing trigger a_t^E—and hence the ex ante external financing cost $\mathbb{E}_t^a[\xi_{it}]$—are both directly affected by aggregate conditions. For instance, under reasonable parameter values, and holding wages constant, a contraction in demand that causes a reduction in c_t implies an increase in the expected cost of external finance because with lower production, fixed costs now account for a greater share of total costs.

We now consider how the value of internal funds affects the value of marginal sales in the

presence of financial market frictions. According to the first-order condition for c_{it} (equation 19), the value of marginal sales consists of two terms: current profits and the value of the customer base. From equation (19), after imposing the symmetric equilibrium condition, we have

$$\frac{\mathbb{E}_t^a[\nu_{it}]}{\mathbb{E}_t^a[\xi_{it}]} = \underbrace{1 - \frac{\mathbb{E}_t^a[\kappa_{it}]}{\mathbb{E}_t^a[\xi_{it}]}}_{\text{value of current profit}} + \underbrace{(1-\rho)\frac{\lambda_t}{\mathbb{E}_t^a[\xi_{it}]}}_{\text{value of market share}} . \tag{23}$$

To see that the first term corresponds to the value of marginal profits, we can substitute the first-order condition (18) in the second term of the above expression, which yield

$$\begin{aligned} 1 - \frac{\mathbb{E}_t^a[\kappa_{it}]}{\mathbb{E}_t^a[\xi_{it}]} &= 1 - \frac{\mathbb{E}_t^a[\xi_{it}a_{it}]}{\mathbb{E}_t^a[\xi_{it}]} \frac{w_t}{\alpha A_t} (c_t + \phi)^{\frac{1-\alpha}{\alpha}} \\ &\equiv 1 - \frac{\mathbb{E}_t^a[\xi_{it}a_{it}]}{\mathbb{E}_t^a[\xi_{it}]} \mu(A_t, c_t, w_t)^{-1}, \end{aligned}$$

where $\mu(A_t, c_t, w_t) \equiv \alpha(A_t/w_t)(c_t + \phi)^{\frac{\alpha-1}{\alpha}}$ denotes the aggregate (marginal) gross mark-up. With frictionless financial markets, the value of marginal profit is $1 - 1/\mu(A_t, c_t, w_t)$. The presence of financial distortions importantly tilts the way the firm assess the marginal revenue and cost through the terms $\mathbb{E}_t^a[\xi_{it}]$ and $\mathbb{E}_t^a[\xi_{it}a_{it}]$.

Using the property of a log-normal distribution (Johnson, Kotz, and Balakrishnan (1994)), the interaction term can be expressed as

$$\mathbb{E}_t^a[\xi_{it}a_{it}] = \int_0^{a_t^E} a dF(a) + \int_{a_t^E}^{\infty} a \frac{dF(a)}{1-\varphi} = 1 + \frac{\varphi}{1-\varphi}[1 - \Phi(z_t^E - \sigma)] \geq 1.$$

Note that $\mathbb{E}_t^a[\xi_{it}a_{it}] \geq \mathbb{E}_t^a[\xi_{it}] \geq 1$ and the inequalities are strict if and only if φ, $\sigma > 0$; note also that this difference measures the covariance between the shadow value of internal funds and the idiosyncratic productivity shock because $\mathbb{E}_t^a[\xi_{it}a_{it}] = \mathbb{E}_t^a[\xi_{it}]\mathbb{E}_t^a[a_{it}] + \text{Cov}_t^a[\xi_{it}, a_{it}] = \mathbb{E}_t^a[\xi_{it}] + \text{Cov}_t^a[\xi_{it}, a_{it}]$, where the last equality reflects the fact that $\mathbb{E}_t^a[a_{it}] = 1$. Algebraically, this covariance is given by

$$\text{Cov}_t^a[\xi_{it}, a_{it}] = \frac{\varphi}{1-\varphi}[\Phi(z_t^E) - \Phi(z_t^E - \sigma)] > 0. \tag{24}$$

With financial market frictions ($\varphi > 0$), this covariance term is strictly positive because the firm does not want to rely on costly external financing unless it is experiencing financial distress as a result of an unusually bad liquidity shocks (i.e., the realization of a_{it} if very high). Indeed, the positive covariance term can also be gleaned directly from equation (22): The presence of financial distortions simultaneously increases the value of marginal revenue ($\mathbb{E}_t^a[\xi_{it}]$) and the value of marginal cost ($\mathbb{E}_t^a[\xi_{it}a_{it}]$), though the latter effect dominates. As a result, an adverse productivity shock, or an increase in demand, makes the firm more conservative in its pricing decision in order to avoid potential losses.

To streamline the notation, we define the financially-adjusted mark-up

$$\tilde{\mu}(A_t, c_t, w_t) \equiv \frac{\mathbb{E}_t^a[\xi_{it}]}{\mathbb{E}_t^a[\xi_{it} a_{it}]} \mu(A_t, c_t, w_t) \leq \mu(A_t, c_t, w_t), \tag{25}$$

an expression that will be used to derive a closed-form solution for the value of the customer base.[13] First, however, let $g_t \equiv c_t / s_{t-1} = (s_t / s_{t-1} - \rho)/(1-\rho)$. By iterating equation (20) forward, one can then verify that the marginal value of an increase in the customer base satisfies:

$$\frac{\lambda_t}{\mathbb{E}_t^a[\xi_{it}]} = \theta(1-\eta)\mathbb{E}_t \left[\sum_{s=t}^{\infty} \tilde{\beta}_{t,s+1} \frac{\mathbb{E}_s^a[\xi_{is+1}]}{\mathbb{E}_t^a[\xi_{it}]} \left(\frac{\tilde{\mu}_{s+1} - 1}{\tilde{\mu}_{s+1}} \right) \right], \tag{26}$$

where $\tilde{\beta}_{t,s+1} \equiv m_{s,s+1} g_{s+1} \times \prod_{j=1}^{s-t} [\rho + \theta(1-\eta)(1-\rho) g_{t+j}] m_{t+j-1,t+j}$ denotes the growth-adjusted discount factor. The marginal value of the customer base is the expected present value of future marginal profits. Substituting the expression for the value of customer base into equation (19) and using the expression for the financially-adjusted mark-up then yields a closed-form solution for the value of marginal sales:

$$\frac{\mathbb{E}_t^a[\nu_{it}]}{\mathbb{E}_t^a[\xi_{it}]} = \frac{\tilde{\mu}_t - 1}{\tilde{\mu}_t} + \chi \mathbb{E}_t \left[\sum_{s=t+1}^{\infty} \tilde{\beta}_{t,s} \frac{\mathbb{E}_s^a[\xi_{is}]}{\mathbb{E}_t^a[\xi_{it}]} \left(\frac{\tilde{\mu}_s - 1}{\tilde{\mu}_s} \right) \right], \tag{27}$$

where $\chi \equiv (1-\rho)\theta(1-\eta) > 0$ if $\theta < 0$ and $\eta > 1$.

In this context, the liquidity condition of the firm—as summarized by the sequence of $\mathbb{E}_s^a[\xi_{is}]$, $s = t, \ldots, \infty$—determines the weight that the firm places on current versus future profits when determining the expected price trajectory. If today's liquidity premium outweighs the future liquidity premia, the firm will places a greater weight on current profits. In fact, using extensive simulations we show that when the current liquidity premium—as measured by $\mathbb{E}_t^a[\xi_{it}]$—sufficiently exceeds the next period's premium, the firm will value current profits more than future profits and, as a result, choose a higher price trajectory, resulting in higher inflation.

4.5 The Phillips Curve

In this section, we analyze how the presence of real and financial distortions affect aggregate inflation dynamics. Specifically, we study the local dynamics of inflation around the steady state, an approach that allows for an easy comparison with the standard literature.

Imposing the symmetric equilibrium ($p_{it} = 1$, $c_{it} = c_t$) and dividing equation (21) through by

[13] This also defines $\tilde{\mu}$ in real terms. Because $\mathbb{E}_t^a[\xi_{it}] / \mathbb{E}_t^a[\xi_{it} a_{it}] < 1$ due to the positive covariance term, the wedge makes the unadjusted mark-up μ go up to compensate for the financial wedge.

$\mathbb{E}_t^a[\xi_{it}]c_{it}$ yields the following Phillips curve:[14]

$$1 = \gamma\pi_t\left(\pi_t - \bar{\pi}\right) - \gamma\mathbb{E}_t\left[m_{t,t+1}\frac{\mathbb{E}_{t+1}^a[\xi_{it+1}]}{\mathbb{E}_t^a[\xi_{it}]}\pi_{t+1}\left(\pi_{t+1} - \bar{\pi}\right)\frac{c_{t+1}}{c_t}\right] + \eta\frac{\mathbb{E}_t^a[\nu_{it}]}{\mathbb{E}_t^a[\xi_{it}]}. \tag{28}$$

The local dynamics of inflation can be assessed by log-linearizing equation (28) as follows:

$$\hat{\pi}_t = \frac{1}{\gamma}(\hat{\xi}_t - \hat{\nu}_t) + \beta\mathbb{E}_t[\hat{\pi}_{t+1}], \tag{29}$$

where $\hat{\xi}_t$ and $\hat{\nu}_t$ denote the log-deviations of $\mathbb{E}_t^a[\xi_{it}]$ and $\mathbb{E}_t^a[\nu_{it}]$, respectively. Equation (29) clearly shows that given inflation expectations, the current inflation rate depends crucially on the relative importance of the value of internal funds ($\mathbb{E}_t^a[\xi_{it}]$) versus the value of marginal sales ($\mathbb{E}_t^a[\nu_{it}]$).

To highlight the relationship between the model's structural parameters and inflation dynamics, we can log-linearize equation (27) and substitute the result in equation (29). These steps yield the following Phillips curve

$$\begin{aligned}\hat{\pi}_t &= -\frac{\omega(\eta-1)}{\gamma}\left[\hat{\mu}_t + \mathbb{E}_t\sum_{s=t}^{\infty}\chi\tilde{\delta}^{s-t+1}\hat{\mu}_{s+1}\right] + \beta\mathbb{E}_t[\hat{\pi}_{t+1}] \\ &\quad + \frac{1}{\gamma}\left[\eta - \omega(\eta-1)\right]\mathbb{E}_t\sum_{s=t}^{\infty}\chi\tilde{\delta}^{s-t+1}\left[(\hat{\xi}_t - \hat{\xi}_{s+1}) - \hat{\beta}_{t,s+1}\right],\end{aligned} \tag{30}$$

where $\omega \equiv 1 - \beta\theta(1-\rho)/(1-\rho\beta)$, $\tilde{\delta} \equiv \beta[\rho + \theta(1-\eta)(1-\rho)]$, and $\hat{\beta}_{t,s+1}$ is the log-deviation of $\tilde{\beta}_{t,s+1}$. Note that this formulation of the Phillips curve encompasses a number of special cases:[15]

1. **New Keynesian** ($\theta = 0$, $\varphi = 0$): No internal habit ($\theta = 0$) implies $\omega = 1$ and $\chi = 0$. Furthermore, the absence of financial distortions ($\varphi = 0$) implies $\mathbb{E}_t^a[\xi_{it}] = \mathbb{E}_t^a[\xi_{it}a_{it}] = 1$ and hence $-\hat{\mu}_t = (\hat{w}_t - \hat{A}_t)$. In this case, equation (30) reduces to the traditional New Keynesian Phillips curve.

2. **Internal Habit Only** ($\theta < 0$, $\varphi = 0$): Without financial distortions, all terms involving $\hat{\xi}_t - \hat{\xi}_{s+1}$ in the second line of equation (30) disappear. However, becuase of the sticky customer base, the terms involving $\hat{\beta}_{t,s+1}$ remain. Recall that $\hat{\beta}_{t,s+1}$ captures the capitalized growth rate of customer base and thus measures the present value of the marginal benefit from expanding customer base today. According to equation (30), when the firm expects a greater benefit from the future customer base, it is more willing to lower its current price in order to build its customer base.

3. **Financial Distortions Only** ($\theta = 0$, $\varphi > 0$): Without the sticky customer base, all present-

[14] This derivation of the Phillips curve exploits a steady-state relationship $\mathbb{E}^a[\xi_i]/\mathbb{E}^a[\nu_i] = 1/\eta$; see the model appendix for details.

[15] In deriving these special cases, we assume a constant returns-to-scale production technology.

value terms in equation (30) disappear. Reflecting the presence of financial friction, however, $-\hat{\mu}_t = \widehat{\xi a}_t - \hat{\xi}_t + \hat{w}_t - \hat{A}_t$, where $\widehat{\xi a}_t$ is the log-deviation of $\mathbb{E}_t^a[\xi_{it} a_{it}]$. As discussed above, $\mathbb{E}_t^a[\xi_{it} a_{it}] - \mathbb{E}_t^a[\xi_{it}]$ measures the covariance between the shadow value of internal funds and the idiosyncratic productivity shock. Hence, any disturbance that leads to an increase in that covariance may increase the inflation rate above the level that would have prevailed in the Modigliani–Miller paradigm of frictionless financial markets.[16]

4. **Internal Habit and Financial Distortions** ($\theta < 0$, $\varphi > 0$): With both a sticky customer base and financial market frictions, firms face a fundamental tradeoff between current profit maximization and the long-run maximization of their market share, which is reflected in the term $(\hat{\xi}_t - \hat{\xi}_{s+1}) - \hat{\beta}_{t,s+1}$. The maximization of their market share requires firms to lower current prices. However, firms may be forced to deviate from this dynamic optimization strategy, provided that their current liquidity position ($\hat{\xi}_t$) is sufficiently weak relative to future liquidity position ($\hat{\xi}_{s+1}$). In that case, firms may raise their current prices to avoid costly external financing, a policy that resembles a myopic optimization of current profits.

The fundamental tradeoff between the maximization of current cash flows and long-run maximization of market shares in our model hinges crucially upon a parameter restriction that $\eta - \omega(\eta - 1) > 0$. Otherwise, a seemingly pathological phenomenon may occur: Firms in strong financial condition may *increase* their current prices in order to *increase* their long-run market shares. This condition, however, is not particularly restrictive in our context because, as shown in the model appendix, $\eta - \omega(\eta - 1)$ is determined by the steady-state marginal profit:

$$\eta - \omega(\eta - 1) = \frac{\mathbb{E}^a[\xi_i]}{\mathbb{E}^a[\nu_i]} - \frac{\mathbb{E}^a[\kappa_i]}{\mathbb{E}^a[\nu_i]} = \frac{\mathbb{E}^a[\xi_i]}{\mathbb{E}^a[\nu_i]} \cdot \left[1 - \frac{\mathbb{E}^a[\kappa_i]}{\mathbb{E}^a[\xi_i]}\right] > 0$$

In other words, as long as θ, ρ and η are chosen such that the steady-state marginal profit is positive, we can exclude such pathological cases.

4.6 The Rest of the Model

The household faces a budget constraint

$$b_{t+1}^j + \int_0^1 p_{it} c_{it}^j di + \int_0^1 p_{it}^S s_{F,it+1}^j di = w_t h_t^j + (1 + r_{t-1}) b_t^j + \int_0^1 [\max\{d_{it}, 0\} + p_{it-1,t}^S] s_{F,it}^j di,$$

where b_t^j is the amount of government debt held by the household j, $s_{F,it}^j$ is the share of firm i directly owned by the household j, $p_{it-1,t}^S$ is the time-t value of shares outstanding at time $t-1$, and

[16] An interesting empirical implication of this model is that an econometrican who failed to include a proxy for financial frictions in the emprical specification of the Phillips curve may erroneously attribute positive forecast errors to markup shocks.

p^S_{it} is the ex-dividend value of equity at time t. The last two terms are related via the accounting identity $p^S_{it} = p^S_{it-1,t} + e_{it}$, where e_{it} is the value of new shares issued at time t.

The costly equity finance assumption implies that $e_{it} = -(1-\varphi) \times \min\{d_{it}, 0\}$. Using the equity accounting identity and the fact that $\int_0^1 p_{it} c^j_{it} di = \tilde{p}_t x^j_t$ (see equation (11)), we can rewrite the budget constraint as

$$\begin{aligned} b^j_{t+1} + \tilde{p}_t x^j_t + \int_0^1 p^S_{it} s^j_{F,it+1} di &= w_t h^j_t + (1+r_{t-1}) b^j_t \\ &\quad + \int_0^1 [\max\{d_{it}, 0\} + (1-\varphi)\min\{d_{it}, 0\} + p^S_{it}] s^j_{F,it} di. \end{aligned} \tag{31}$$

The above expression makes it clear that in general equilibrium, costly equity finance takes the form of sales of new shares at a discount. Because the owners of old and new shares are the same entity, there are no direct wealth effects associated with costly external finance—the losses borne by the old shareholders are offset exactly by the gains that accrue to the new shareholders.

Denoting the multiplier for the budget constraint by Λ^j_t and maximizing equation (8) subject to equation (31) yields the following first-order conditions:

$$x^j_t \;:\; \Lambda^j_t \tilde{p}_t = U_x(x^j_t - \delta_t, h^j_t) \tag{32}$$

$$h^j_t \;:\; \Lambda^j_t w_t = -U_h(x^j_t - \delta_t, h^j_t) \tag{33}$$

$$b^j_{t+1} \;:\; \Lambda^j_t = \beta \mathbb{E}_t[\Lambda^j_{t+1}(1+r_t)] \tag{34}$$

$$s^j_{F,it+1} \;:\; \Lambda^j_t = \beta \mathbb{E}_t \left[\Lambda^j_{t+1} \left(\frac{\tilde{d}_{t+1} + p^S_{t+1}}{p^S_t} \right) \right] \tag{35}$$

where $\tilde{d}_{t+1} \equiv \mathbb{E}^a_{t+1}[\max\{d_{it+1}, 0\}] + (1-\varphi)\mathbb{E}^a_{t+1}[\min\{d_{it+1}, 0\}]$, and we used the fact that $p^S_t = p^S_{it}$ in the symmetric equilibrium. From equation (32), it follows that $\Lambda^j_t = U_x(x^j_t, h^j_t)/\tilde{p}_t$. Because in the symmetric equilibrium, $\Lambda^j_t = \Lambda_t$, $p_{it} = 1$, and $s_{it-1} = s_{t-1}$, it follows that $\tilde{p}_t = s^\theta_{t-1}$. Hence $\Lambda_t = U_x(x_t, h_t)/s^\theta_{t-1}$ and

$$m_{t,t+1} = \beta \frac{U_x(x_{t+1} - \delta_{t+1}, h_{t+1})}{U_x(x_t - \delta_t, h_t)} \frac{s^\theta_{t-1}}{s^\theta_t}.$$

Equations (32) and (33) together imply the following efficiency condition:[17]

$$\frac{w_t}{\tilde{p}_t} = -\frac{U_h(x_t - \delta_t, h_t)}{U_x(x_t - \delta_t, h_t)}.$$

[17] In the numerical implementation of the model, we also assume an adjustment cost for the nominal wage by introducing market power associated with differentiated labor. For expositional purposes, we skipped those details; the complete derivation of the dynamic wage Phillips curve is contained in the model appendix.

4.7 Monetary Policy

Lastly, we assume that the monetary authority sets the nominal interest rate using a Taylor-type rule that responds to the inflation and output gaps:

$$r_t = \max\left\{0, (1+r_{t-1})^{\rho_r}\left[(1+\bar{r})\left(\frac{\pi_t}{\pi^*}\right)^{\rho_\pi}\left(\frac{y_t}{y_t^*}\right)^{\rho_y}\right]^{1-\rho_r} - 1\right\}. \tag{36}$$

The rule also allows for policy inertia, as reflected in letting $\rho_r \in (0,1)$. In our baseline specification, we set $\rho_y = 0$, so that only inflation enters the Taylor rule. We also allow the policy rate to be bounded below by zero, which allows us to explore the role of finacial distortions at the zero lower bound, a topic of particular relevance in the current environment.[18]

5 Model Simulations

5.1 Calibration

There are three sets of parameters in the model: (1) parameters related to preferences and technology; (2) parameters governing the strength of nominal rigidities and monetary policy response; and (3) parameters determining the strength of financial market friction.

We set the time discounting factor equal to 0.99. We set the deep habit parmeter θ equal to -0.8 following Ravn, Schmitt-Grohe, and Uribe (2006). We also choose a fairly persistent habit formation such that only 5 percent of the habit stock is depreciated in a quarter in order to highlight the firms' incentive to compete for market share. However, this is only marginally more persistent than in Ravn, Schmitt-Grohe, and Uribe (2006). The CRRA parameter is then set equal to 1, given that the deep habit specification provides a strong motive to smooth consumption. We set the elasticity of labor supply equal to 5. For the aggregate technology shock process, we assume $\rho_A = 0.90$, a somewhat lower value than that employed in the real business cycle literature; this choice reflects the fact our model has a number of elements that generate persistent dynamics of the endogenous quantities.

The elasticity of substitution is a key parameter in the customer-markets model—the greater the firm's market power, the greater is its incentive to invest in customer base. Broda and Weinstein (2006) provide a set of point estimates for the elasticity of substitution for the U.S. economy. Their estimates lie in the range between 2.1 and 4.8, depending on the characteristics of products

[18] When analyzing the dynamics of the economy when the policy rate is at the zero lower bound, we use the deterministic simulation routine of Adjemian, Bastani, Juillard, Mihoubi, Perendia, Ratto, and Villemot (2011) to allow for a fully nonlinear solution, after replacing the max operator in equation (36) with a smooth approximation, namely, $\max\{x,0\} \approx 0.5 \times (\sqrt{x^2+\epsilon^2}+x)$ (in our simulations, we set $\epsilon = 1e-4$). The use of a nonlinear solution method is important in this case because the shocks that push the policy rate to the zero lower bound are typically large and thus place the economy in the region where local dynamics in the neighborhood of a nonstochastic steady state may not adequately approximate the nonlinear response of the economy to such shocks.

(commodities vs. differentiated goods) and subsamples (before 1990 vs. after 1990). Using the post-1990 data, Broda and Weinstein (2006) estimate the median value of the elasticity of substitution for differentiated goods at 2.1, a product category that is most relevant for the deep habits model. Accordingly, we set $\eta = 2$; Ravn, Schmitt-Grohe, Uribe, and Uuskula (2010) also provides a point estimate of 2.48 using their structural estimation method.

Another important parameter is the fixed opearating cost, ϕ. This parameter is jointly determined with the returns to scale parameter α. We set α first, then choose ϕ so that the dividend payout ratio (relative to income) hits the post-WWII mean value of 2.5 percent. Decreasing returns-to-scale enhance the link between the financial market friction and the pricing decision. We choose $\alpha = 0.8$. While this degree of returns to scale parameter is not unusual in empirical investment literature based on Compustat data (see Hennessy and Whited (2007)), the model's dynamics are not substantially affected by varying the α between 0.8 and 1; in this sense, this is our "preferred" calibration. With the chosen α, ϕ and η, the average mark-up is equal to 1.19.

To calibrate the degree og financial distortions, we set the equity dilution cost $\varphi = 0.30$, the value used by Cooley and Quadrini (2001). When we consider the dilution cost as an exogenous shock process, we set the persistence of the financial shock at 0.90. However, in our crisis experiment—a simulation exercise that imposes an extreme degree of financial distortions—we let $\varphi = 0.50$. The volatility of the idiosyncratic shock is calibrated as 0.05 at a quarterly frequency, which implies a moderate amount of idiosyncratic uncertainty. With the fixed operating cost calibrated as described above, the combination of $\sigma = 0.05$ and $\varphi = 0.30$ yields $\mathbb{E}^a[\xi_i] = 1.127$.

For the parameters related to nominal rigidities, we set the adjustment costs of nominal prices $\gamma_p = 10.0$ and wages $\gamma_w = 30.0$. These values are close to the point estimates of 14.5 and 41.0 in Ravn, Schmitt-Grohe, and Uribe (2006), who show that deep habit model substantially enhances the persistence of inflation dynamics without the help of implausibly large amount of adjustment friction in nominal prices. Finally, we set the inertial Taylor coefficient at a conventional level of 0.75, and the coefficient of inflation gap as 1.5, which is in line with the New Keynesian literature.

5.2 Crisis and Inflation

Our main goal in developing the model is to gain insight as to why the massive slack in productive capacity observed in the last recession did not lead to a sizable drop in aggregate inflation, let alone an outright deflation spiral that was of much concern to both academics and policy makers. To study the dynamics of inflation and other endogenous variables in a financial crisis, we conduct two types of experiments. In this subsection, we consider an extreme calibration in which raising external finance is not impossible, but is tremendously costly, and the firms in the model finance themselves nearly entirely through internal cash flows. To implement such a scenario, we set $\varphi = 0.50$, which implies that the dilution effect of new equity is 50 percent. Admittedly, such an extreme situation can be considered only in the middle of financial crisis such as around the time

period of Lehman bankuptcy in 2008, where virtually no firms could contemplate raising outside equities to finance operating cost and investment. With this calibration, we study the impact of conventional supply and demand shocks and financial shocks on the pricing decisions of the firms.

Figure 6 shows the impact of one standard deviation technology shock both for the economy with the financial friction (solid blue) and for the economy without the financial friction (solid dot red). The negative technology shock leads a sizable drop in economic activity shown in panel (a) and a short burst of inflation in panel (b). These signs are as expected in the standard New Keynesian theory. In panel (a), we can see that the capital market friction implies a mild amplification in output, consistent with a financial accelerator mechanism at play.

Although the output differential owing to the financial friction is modest, Figure 6 highlights that the differential responses of inflation rate is quite substantial – the inflation response is 40 percent greater with the financial friction. Panel (e)$\sim$(f) of the figure provide an explanation for the differential responses in inflation. In our environment, the news of negative technology shock becomes known before pricing decisions are made. Under the financial market friction, the news about the bad technology shock at the beginning of the period reduces the firms' expected internal cashflows and raises the probability that firms require costly external finance, which then leads to a 400 basis point increase in the shadow value of internal funds, shown in panel (f). In response, the firms seek to protect themselves against the idiosyncratic tail event that expost cash flows are negative and hence require external funds by choosing higher markups relative to the case where external finance is costless as shown in panel (e).

As discussed above, a severe financial market friction causes the value of internal cashflows and the value of marginal sales to move in tandem. Panel (f) and (g) displays this result: the financial market friction creates a direct link between the two valuations that does not exist for a frictionless economy. In fact, the value of marginal sales without the financial market friction moves in the opposite direction to that with the financial friction. Today's increase in price erodes the customer base both today and in the future. In the absence of financial frictions, firms are more concerned about the future customer base relative to current profits and the marginal value of sales falls.

In contrast, in the model with financial frictions, the substantial increase in the value of internal funds causes the marginal value of sales to rise. Finally, as shown by the closed-form solution for the marginal value of sales (equation 27), the benefits of future customer base is heavily discounted when liquidity conditions today are expected to be much worse than in the future. As a result, concern for current relative to future profits dominate the firms's pricing decision, a form of short-termism that is optimal from the firm's perspective, but that results in a significant rise in inflation which is subotimal from the perspective of a purely monopolistic firm that internalizes the effect of all pricing decisions on demand.

Figure 7 shows the case of demand shock which directly affects the marginal utility of consumption (see equation (8)), replicating a so called *autonomous* spending cut. The contractionary

demand shock implies a very similar output path across the model with versus without the financial friction but markedly divergent inflation paths. With no financial friction, prices fall substantially, leading to a persistent reduction in inflation. With the financial market friction, firms choose higher rather than lower prices to ensure against the need to issue external funds to meet liquidity requirements. As a result, the inflation rate exhibits a modest increase rather than a substantial decrease.

In both models, the negative demand shock leads to a sharp increase in the mark-up. The countercyclical mark-up in a demand-driven cycle arises naturally in the deep habit models. Our results highlight that this countercyclicality is substantially strengthened by the financial friction. According to panel (e), the model with financial friction exhibits an increase in the markup that is two time greater than the increase that would occur in the absence of financial distortions. Panel (f) and (g) show that the driving force behing the countercyclical mark-up is the sudden deterioration of liquidity conditions which causes firms to increase prices to maintain short term profit rates in the face of weak demand.

In Figure 8, we analyze how the cyclical pattern of markup interacts with nominal and financial frictions of the model, also with the sources of disturbances. In the left panel, in which we consider a negative technology shock, one can see that the countercyclicality of markup crucially depends on the strength of nominal rigidity. As can be seen in the panel, the markup in the internal habit model without nominal rigidity is strongly countercyclical regardless of the presence of financial friction (red, solid line for the case with financial friction, and blue, solid line for the case without). While financial friction helps create a stronger countercyclicality, the marginal contribution is realtively mild. The markup is weakly countercyclical when the nominal rigidity is present as the initial response of markup is negative in the first 2 to 3 periods. In this latter case, the presence of financial friction (red, dash-dotted line) substantially strengthens the countercyclicality of markup as the financial distress brought about by the adverse shock induces the firms to choose higher levels of prices than in a frictionless economy (blue, dash-dotted line).

The right panel shows the case of negative demand shock. In this case, the nominal rigidity plays an essential role to create the countercyclical pattern in markup as can be seen in the cases without financial friction (blue, solid line for the case without nominal rigidity, and blue, dash-dotted line with nominal rigidity). However, even with the nominal rigidity, the countercyclicality is weak as the markup response eventually turns negative. The introduction of financial friction in this case, as shown by red lines, dramatically strengthens the countercyclicality of markup.

It is notable that the markup response of the case with financial friction but without nominal rigidity is much greater than that with both financial and nominal friction. This implies that the firms want to increase their prices even more without nominal rigidity, suggesting that nominal rigidity is actually working as a stabilizing factor under financial friction. The bottom right panel shows that this is indeed the case. With greater increase in markup, output goes down much more

without sticky prices under financial friction. This is a remarkable feature that would not exist in conventional New Keynesian models.

5.3 Impact of a Financial Shock

An alternative way to characterize a period of financial turmoil is to view such a period as a time when the cost of external funds is temporarily elevated from its normal level. The model mechanism implies that liquidity conditions matter for pricing decision not because of their absolute level but because of the prospect that financing conditions will improve in the future. This suggests that the differential effects on markups and pricing policy between the frictionless model and the model with the financial friction will be magnified with a temporary increase in the cost of external financing.

To explore this possibility, we assume that the equity issuance cost parameter follows an AR(1) process,

$$\varphi_t = \bar{\varphi} f_t, \quad \log f_t = \rho_f \log f_{t-1} + \epsilon_{t,f} \tag{37}$$

We consider a shock $\epsilon_{t,f}$ that increases the level of dilution cost 25 percent from its normal level immediately, converging to the normal level thereafter. We reconsider the effects of supply and demand shocks we analyzed in the earlier section in this environment. Note that with the shock, the level of dilution cost is increased from 0.3 to 0.375, a much lower level than 0.5, the level chosen for φ as a 'parameter' in the ealier section.

Figure 9 displays the responses of the model economy to a one standard deviation demand shock: the solid blue line is the case with the demand shock when there is a simultaneous shock to the cost of external finance; solid-dot red line is the responses to the demand shock without the financial shock. The vertical differences between the solid blue and solid-dot red lines in these figures then measures the additional impact created by the shock to the financing cost.[19]

As we conjectured, the economy exhibits extreme sensitivity to the demand shock when the cost of external financing is temporarily elevated. For instance, in panel (a) and (b) of Figure 9, the additional effects on output and hours created by the temporarily increase in financing cost are tremendous: both the drops in output and hours are nearly doubled. The inflation response is not strongly positive with the financial shock, which makes an observational equialence to a case with technology shock. In our model, a tightened liquidity condition shrinks the financial capacity of the economy, which then directly shifts the Phillips curve upward.

In panel (e), (f) and (g), one can see that the responses of markup, the value of internal funds and the value of marginal sales shut up as much as ten times those without the temporary financial shock. Note that a substantial part of the increase in the shadow value of internal funds is endogenous in nature: As the economy deteriorates more than in the case without the financial shock, the probability of external financing gets even higher, which then increases the value of internal funds

[19]Since the normal level of dilution cost is 0.3 in this experiment, there exists a qualitative and quantitative difference between the solid blue lines in figure 7 and the solid-dot red lines in figure 9.

further. This within-period financial multiplier plays an important role in the greater propagation of the shocks in Figure 9.

It is useful to compare the responses of the economy when the cost of external finance is permanently elevated to 0.5 (the solid blue lines in Figure 7) and the situation when the external financing cost is temporarily elevated up 0.375 (the solid blue lines in Figure 9). The blue lines in Figure 7 represents a much harsher financial environment since the dilution cost is always equal to 0.5. However, the economic impact of the same sized technology shock is disproportionately greater for the case with the temporarily higher dilution cost. It is precisely in this sense that the prospect of improved financial condition makes matters worse since it maximizes economic agents' incentive to wait or postpone investment in market shares.

5.4 Role of the Zero Lower Bound

We close our simulation exercises by analyzing the role of financial market friction on pricing under the environment of a binding zero lower bound (ZLB for shorthand reference). To create a binding ZLB situation, we implement so called paradox of thrift scenario in which the time discounting factor of the agents is elevated exogenously for a certain number of periods exogenously before it returns to a normal level. In particular, we assume the following shock process,

$$\beta_t = \bar{\beta} v_t, \quad \log v_t = \rho_v \log v_{t-1} + \epsilon_{t,v},$$

and set $\epsilon_{t,v} = 0.009$ for $t = 1, \ldots, 4$ and $\epsilon_{t,v} = 0.0$ for $t = 5, \ldots, \infty$. The consecutive shocks make the discounting rate shock linearly go up to 1.016 ("hyper-patience") in the fourth quarter and return to the normal level thereafter.

Figure 10 displays the impact of such shocks for the baseline calibration. The figure shows how the economic impact of the binding ZLB is altered by the presence of financial distortions. The firms in the model economy with the financial friction are reluctant to cut their prices in order to maintain liquidity. However, the firms in the frictionless economy take a more aggressive stance: the prices are cut by 20 percent (a.r.) on the impact. In a ZLB environment, in panel (h), this translates into a massive increase in the real interest rate, which then leads to 10 percentage point drop in both output and hours. This suggests that once the ZLB is binding, firms incentives to cut price to maintain market share is a highly destabilizing force that is substantially moderated by firms need to maintain high cash flows owing to financial frictions.[20]

[20]While we do not report the results for the interest of space, we also performed a different experiment so that the economy gets the identical sequence of discounting rate shocks, but in an environment with 5 times greater nominal rigidity in terms of (nominal price and wage adjustment costs). In the model without financial frictions, the greater nominal rigidity makes it difficult for the firms to aggressively cut their nominal prices, and as a result, the deflationary force is much weaker than in the baseline calibration. This is consistent with the findings of Christiano et al. (2012) who document that increased price flexibility exacerbates a deflationary spiral. In contrast, in the model with financial frictions, it makes little difference whether firms face mild or severe nominal rigidities.

6 Equilibrium Dispersion of Firm-Specific Inflation Rates

For simplicity, we have exploited the notion of symmetric equilibrium where all firms in the economy choose the same inflation rates. We now extend the model such that a non-degenerate distribution of firm-specific inflation rates can exist. This also serves the purpose of illustrating how firms with strong balance sheet conditions try to drive out competitors by undercutting competitors prices during a financial stress episode.

6.1 Heterogeneous Operating Costs

We introduce the heterogeneity of operating costs: the production technology is modified into

$$y_{it} = \left(\frac{A_t}{a_{it}} h_{it}\right)^{\alpha} - \phi_i \tag{38}$$

where ϕ_i is fixed operating costs, which takes one of N-values from a set $\mathbf{\Phi} = \{\phi_1, \ldots, \phi_N\}$ with $0 \leq \phi_1 < \ldots < \phi_N$. We denote the measures of firms with each level of efficiency by $\omega_1, \ldots, \omega_N$ with $\sum_{k=1}^{N} \omega_k = 1$. With N finite, we can assume that each group has the same productivity distribution, $\log a_{it} \sim N(-0.5\sigma^2, \sigma^2)$.

With the introduction of heterogenous operating costs, the external financing trigger is now modified into

$$a_t^E(\phi_k) = \frac{c_{it}}{(c_{it} + \phi_k)^{1/\alpha}} \frac{A_t}{w_t} \left[p_{it} - \frac{\gamma}{2} \left(\pi_t \frac{p_{it}}{p_{it-1}} - \bar{\pi} \right)^2 \frac{c_t}{c_{it}} \right] \tag{39}$$

and the first-order condition for dividends (17) can now be written as

$$\xi(a_{it}; \phi_k) = \begin{cases} 1 & \text{if } a_{it} \leq a_t^E(\phi_k); \\ 1/(1-\phi) & \text{if } a_{it} > a_t^E(\phi_k). \end{cases} \tag{40}$$

From equation (40), the expected shadow value of internal funds is

$$\mathbb{E}_t^a[\xi_t | \phi_k] = \Phi(z_t^E(\phi_k)) + \frac{1}{1-\varphi}[1 - \Phi(z_t^E(\phi_k))] = 1 + \frac{\varphi}{1-\varphi}[1 - \Phi(z_t^E(\phi_k))] \geq 1$$

Note that $a_t^{E\prime}(\phi_k) < 0$, and hence, $d\mathbb{E}_t^a[\xi_t|\phi_k]/d\phi_k > 0$: with a lower operating efficiency, the firm is more likely to get in trouble in meeting its liquidity needs using only internally generated funds, and hence faces a higher expected external funds premium.

6.2 Aggregation

We now modify the symmetric equilibrium: All firms with an identical ϕ_k choose the same price level, i.e.,

$$P_{it}^{1-\eta} = \sum_{k=1}^{N} \mathbf{1}(\phi_i = \phi_k) \cdot P_{kt}^{1-\eta}. \tag{41}$$

Aggregate inflation dynamics is then determined by an weighted average of $N-$groups. Since $\pi_t \equiv P_t/P_{t-1} = 1/P_{t-1}\left(\int_0^1 P_{it}^{1-\eta} di\right)^{1/(1-\eta)}$, using equation (41), we can express the aggregate inflation rate as

$$\begin{aligned}
\pi_t &= \frac{1}{P_{t-1}}\left(\int_0^1 \sum_{k=1}^{N} \mathbf{1}(\phi_i = \phi_k) \cdot P_{kt}^{1-\eta} di\right)^{1/(1-\eta)} \\
&= \frac{1}{P_{t-1}}\left[\sum_{k=1}^{N} P_{kt}^{1-\eta} \int_0^1 \mathbf{1}(\phi_i = \phi_k) di\right]^{1/(1-\eta)} \\
&= \left[\sum_{k=1}^{N} \omega_k \left(\frac{P_{kt}}{P_{t-1}}\right)^{1-\eta}\right]^{1/(1-\eta)} \\
&= \left[\sum_{k=1}^{N} \omega_k \left(\frac{P_{kt}}{P_{kt-1}}\right)^{1-\eta} \left(\frac{P_{kt-1}}{P_{t-1}}\right)^{1-\eta}\right]^{1/(1-\eta)}.
\end{aligned}$$

Hence, the aggregate inflation rate is determined as a weighted average inflation rates of heterogeneous groups,

$$\pi_t = \left[\sum_{k=1}^{N} \omega_k p_{kt-1}^{1-\eta} \pi_{kt}^{1-\eta}\right]^{1/(1-\eta)} \tag{42}$$

where $\pi_{kt} \equiv P_{kt}/P_{kt-1}$, a type (sector) specific inflation rate and $p_{kt} \equiv P_{kt}/P_t$, a type (sector) specific relative price. Note that the relative price p_{kt} can no longer be equalized to 1 in the symmetric equilibrium. In equilibrium, there exists a non-degenerate dispersion of reltive prices. Hence the notion of symmetric equilibrium is restricted to 'within the type (sector)'. The following Phillips curve describes the inflation dynamics of $k-$type firms:

$$\begin{aligned}
0 &= p_{kt}\frac{c_{kt}}{c_t} - \eta \frac{\mathbb{E}_t^a[\nu_{it}|\phi_k]}{\mathbb{E}_t^a[\xi_{it}|\phi_k]}\frac{c_{kt}}{c_t} - \gamma \pi_{kt}\pi_t\left(\pi_{kt}\pi_t - \bar{\pi}\right) \\
&\quad + \gamma \mathbb{E}_t\left[m_{t,t+1}\frac{\mathbb{E}_{t+1}^a[\xi_{it+1}|\phi_k]}{\mathbb{E}_t^a[\xi_{it}|\phi_k]}\pi_{kt+1}\pi_{t+1}\left(\pi_{kt+1}\pi_{t+1} - \bar{\pi}\right)\frac{c_{t+1}}{c_t}\right]
\end{aligned} \tag{43}$$

The same notion of the modified symmetric equilibrium can be applied to equilibrium output,

i.e.,

$$c_{it}^{j} = \sum_{k=1}^{N} \mathbf{1}(\phi_i = \phi_k) \cdot c_{kt}^{j}.$$

Since the household sector is still characterized by a symmetric equilibrium, we can delete 'j' superscript. Using (11), we can express the individual demand for the products that are produced by firms with efficiency rank k as

$$c_{kt} = \left(\frac{p_{kt}}{\tilde{p}_t}\right)^{-\eta} s_{kt-1}^{\theta(1-\eta)} x_t \tag{44}$$

where

$$\tilde{p}_t = \left[\sum_{k=1}^{N} \omega_k p_{kt}^{1-\eta} s_{kt-1}^{\theta(1-\eta)}\right]^{1/(1-\eta)} \tag{45}$$

and

$$x_t = \left[\sum_{k=1}^{N} \omega_k \left(\frac{c_{kt}}{s_{kt-1}^{\theta}}\right)^{1-1/\eta}\right]^{1/(1-1/\eta)} \tag{46}$$

Both (45) and (46) are constructed applying the same steps used to derive (42) to (12) and (9). Aggregate demand should then satisfy

$$c_t = \left[\sum_{k=1}^{N} \omega_k [\exp(0.5\alpha(1+\alpha)\sigma^2) h_{kt}^{\alpha} - \phi_k]^{1-1/\eta}\right]^{1/(1-1/\eta)} \tag{47}$$

where the type-specific conditional labor demand should satisfy[21]

$$h_{kt} = \left[\frac{c_{kt} + \phi_k}{\exp(0.5\alpha(1+\alpha)\sigma^2)}\right]^{1/\alpha} \tag{48}$$

and

$$h_t = \sum_{k=1}^{N} h_{kt}. \tag{49}$$

6.3 Endogenous Countercyclicality of Dispersion of Inflation Rates

We now present the results of the extended model with heterogenous firms. For simplicity and maximum intuition, we consider only two different types of firms: one that is financially strong and the other that is weak. For financially weak firms, we set ϕ_2 equal to the baseline calibration used in earlier analyses. For financially strong firms, we set $\phi_1 = 0$. We assume that the two types of the

[21] The expression $\exp(0.5\alpha(1+\alpha)\sigma^2)$ is the expected value of $1/a_{it}$, which is strictly greater than 1 due to Jensen's inequality.

firms have an identical measure, i.e., $\omega_1 = \omega_2 = 0.5$. the The key question we ask in this exercise is the following: Do the financially strong firms slash their prices to drive out their competitors during a financial stress episode?

To answer this question, we analyze the impact of financial shock, an exogenous increase in the dilution cost. As in the case of Figure 9, we assume that the normal level of dilution cost is 0.3. The experiment then posits that the level of dilution cost jumps to 0.375, and slowly goes back to its normal level.[22]

Figure 11 confirms our prediction: in panel (a), which shows the impulse response functions of relative prices ($p_{kt} = P_{kt}/P_t$ for $k = 1, 2$), the financially strong firms (shown by blue, solid line) aggresively cut their prices while the financially weak firms cannot help but increase their prices substantially during an aggregate downturn to avoid external financing (shown by red, dash-dotted line). Panel (b) shows the responses of firm-specific inflation measures ($\pi_{kt} = P_{kt}/P_{kt-1}$ for $k = 1, 2$). One can see that our model generates countercyclical dispersion of inflation rates, thus replicating the pattern documented by Vavra (2011). What is different here is that in contrast to Vavra (2011), the countercyclicality is endogenously generated because of heterogeneity of financial conditions, rather than imposed by an exogenous shocks to uncertainty level that are calibrated countercyclically.

Panel (c) displays the differential output responses together with aggregate output response (black, dashed line). The financially strong firms enjoy a little boom during an aggregate downturn as a result of the victory during the price war. The outputs of financially weak firms undergo a severe hemorrhage as the prices of their products are undercutted by the financially strong firms. Again, the dispersion of output and employment at the micro-level is endogenously generated by the distortions in financial market.

Panel (e) depicts how the relative market shares of two groups of firms respond. Blue, solid line shows that the market share of the financially strong firms is strongly expanding during the downturn. This is also true for the 'habit' shares. Due to the deep habit in pereferences, the customer base of financially strong frims expands only gradually, but persistently. The switching customers form a royal group, a substantial part of which stay with the same products even after the relative prices of these products go back up to the normal level. For instance, one can see that the relative prices of the financially strong firms recover their normal levels after 20 quarters in panel (a). However, the relative habit shares of these firms are still at elevated levels even long after 20 quarters. This is the reason why undercutting competitors prices can be such a profitable investment.

In Figure 12, we consider a case that may be called the *paradox of financial strength*. The idea of the exercise is to see if some firms with disproportionately robust balance sheet condition can slash their own prices sufficiently low enough to drive out the financially vulnerable counterparts such

[22]Unlike in Figure 9, we do not intermingle the demand shock in this case for simplicity.

that the losses in aggregate output from the financially vulnerable firms dominate the gains from the financially robust firms. For this type of experiment, we increase the incentive of the financially robust firms to slash their prices so that investment of cutting price today will bring greater benefits in the future. There are several ways of achieving this: either making the contribution of the habit to the final demand more important and more persistent by choosing greater numbers for θ and ρ or reducing the price elasticity of demand by lowering η. In Figure 12, we illustrate the first case by setting $\theta = -0.850$ (baseline is -0.800) and $\rho = 0.985$ (baseline is 0.950).

In this experiment, we set $\phi_1 = 0.8\phi_2$ (denoted as case 1) instead of $\phi_1 = 0$ (denoted as case 2). Doing so substantially weakens the relative strength of the 'strong' firms. The paradox of financial strength can be seen in the fact that the case with more financially constrained firms ($\phi_1 = 0.8\phi_2$) is associated with a milder drop in the aggregate output (shown by thin, black-dashed line in panel (b)). In other words, when the gap between the financial strengths of heterogeneous firms is greater, the drop in the aggregate output is greater. This is because the first group of firms (strong firms) in case 2 cannot slash their prices as aggressively as in case 1. In panel (a), one can see that the price cut of the first group is 50 % greater in the case with $\phi_1 = 0$. This aggressive strategy drives down the output of financially vulnerable firms disproportionately more, and results in a greater downturn in aggregate output. This suggests that a stabilization policy can be more effective when focusing on providing financial supports to the firms at the margin.

7 Conclusion

In this paper, we have investigated the effect of financial conditions on price-setting behavior during the "Great Recession." We did so so through the lenses of customer-market theory, which emphasizes the idea that price-setting is a form of investment that builds the future customer base.

To motivate our analyis, we used confidential, individual producer prices from the BLS and Compustat to compare pricing behavior across firms with weak balance sheets relative to firms with strong balance sheets. We find strong evidence that at the peak of the crisis firms with relatively weak balance sheets increased prices, while firms with strong balance sheets lowered their prices. Similarly, firms with high investment into their customer base increased their prices during the financial crisis while firms with low investment into customers lowered their prices. Regression analysis shows that both the firm liquidity ratio and investment into customers matter for pricing decisions.

We explored the implications of our empirical findings within the context of a New Keynesian framework that allows for customer markets and departures from the Modigliani-Miller paradigm of frictionless financial markets. In our model, firms have an incentive to set a low price to invest in market share. When financial distortions are severe, firms forgo these investment opportunities and maintain high prices. The model implies a substantial attenuation of price dynamics relative to the baseline model without financial distortions in response to contractionary demand shocks. This

implies that in the context of the zero lower bound, financial frictions can paradoxically improve overall economic outcomes.

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Table 1: Summary Statistics, PPI and Matched Sample

		Full PPI	Matched PPI Sample
Monthly Inflation			
	Trimmed Mean	0.170%	0.147%
	Std. Dev.	0.147%	0.216%
	Median	0.180%	0.164%
Monthly Standard Deviation			
	Trimmed Mean	0.727%	1.053%
	Std. Dev.	0.084%	0.223%
	Median	0.707%	1.013%
Monthly Inflation, Weighted			
	Trimmed Mean	0.095%	0.120%
	Std. Dev.	0.517%	0.564%
	Median	0.158%	0.170%
Monthly Frequency of Price Changes			
	Trimmed Mean	13.80%	17.12%
	Std. Dev.	1.11%	1.55%
	Median	13.88%	17.28%
Monthly Frequency of Price Changes, Weighted			
	Trimmed Mean	41.28%	52.39%
	Std. Dev.	5.27%	9.00%
	Median	42.48%	52.11%
Number of Firms			
	Trimmed Mean	23628	769
	Std. Dev.	1515	109
	Median	23369	780

NOTE: We compute the above statistics using the micro price data underlying the PPI (full sample) and our sample matched to Compustat. The time period is from January 2005 through December 2012. First, we compute monthly inflation rates and the frequency of price changes at the level of the firm as the (weighted) means of log price changes and the price change indicators using within-firm importance weights. Second, we take (sales-weighted) means in each monthly cross section of firms. Finally, we report trimmed means, medians, and standard deviations of these means, as well as of the average monthly number of firms in the data.

Table 2: Summary Statistics, COMPUSTAT and Matched Sample

		Full Sample	Matched Sample
Liquidity Ratio			
	Trimmed Mean	0.217	0.149
	Std. Dev.	0.136	0.088
	Median	0.134	0.097
Operating Income Ratio			
	Trimmed Mean	0.005	0.030
	Std. Dev.	0.032	0.019
	Median	0.024	0.032
Interest Expense Ratio			
	Trimmed Mean	0.068	0.023
	Std. Dev.	0.021	0.011
	Median	0.017	0.013
SG&A Ratio			
	Trimmed Mean	0.495	0.272
	Std. Dev.	0.227	0.147
	Median	0.281	0.220
Sales Growth			
	Trimmed Mean	1.08%	0.52%
	Std. Dev.	3.91%	2.22%
	Median	1.03%	0.62%
Sales			
	Trimmed Mean	833.120	1538.576
	Std. Dev.	92.874	360.267
	Median	67.613	313.119
Number of Unique Firms			
		6326	584

NOTE: We compute the above statistics using the full Compustat database for 2005 through 2012 and our matched sample. First, we compute at the firm level and quarterly frequency the ratio of cash and other liquid assets to total assets, the ratio of operating income to total assets, the ratio of interest expenses to total assets, and the ratio of sales and administrative expenses to total assets. Second, we compute time-series averages for each firm of these ratios, sales growth, and total sales. Finally, we report trimmed means, medians, and standard deviations of these means, as well as the number of unique firms in the data.

Table 3: Baseline Calibration

Description	Calibration
Preferences and production	
Time discounting factor, β	0.99
Constant relative risk aversion, γ_x	1.00
Deep habit, θ	-0.80
Persistence of deep habit, ρ	0.95
Elasticity of labor supply, $1/\gamma_h$	5.00
Elasticity of substitution, η	2.00
Persistence of technology shock, ρ_A	0.90
returns to scale, α	0.80
Fixed operation cost, ϕ	0.26
Nominal rigidity and monetary policy	
Price adjustment cost, γ_p	10.0
Wage adjustment cost, γ_w	30.0
Monetary policy inertia, ρ^r	0.75
Taylor rule coefficient for inflation gap, ρ^π	1.50
Financial Frictions	
Equity issuance cost, φ	0.30, 0.50
Idiosyncratic volatility (a.r.), σ	0.20
Persistence of financial shock, ρ_φ	0.90

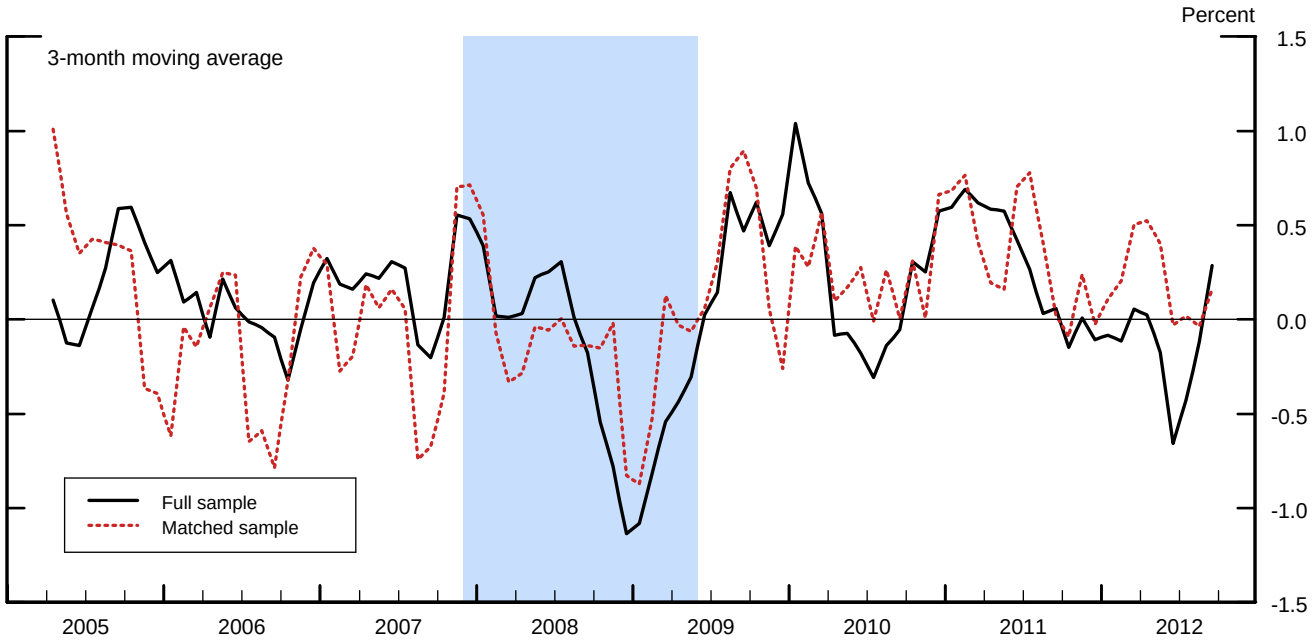
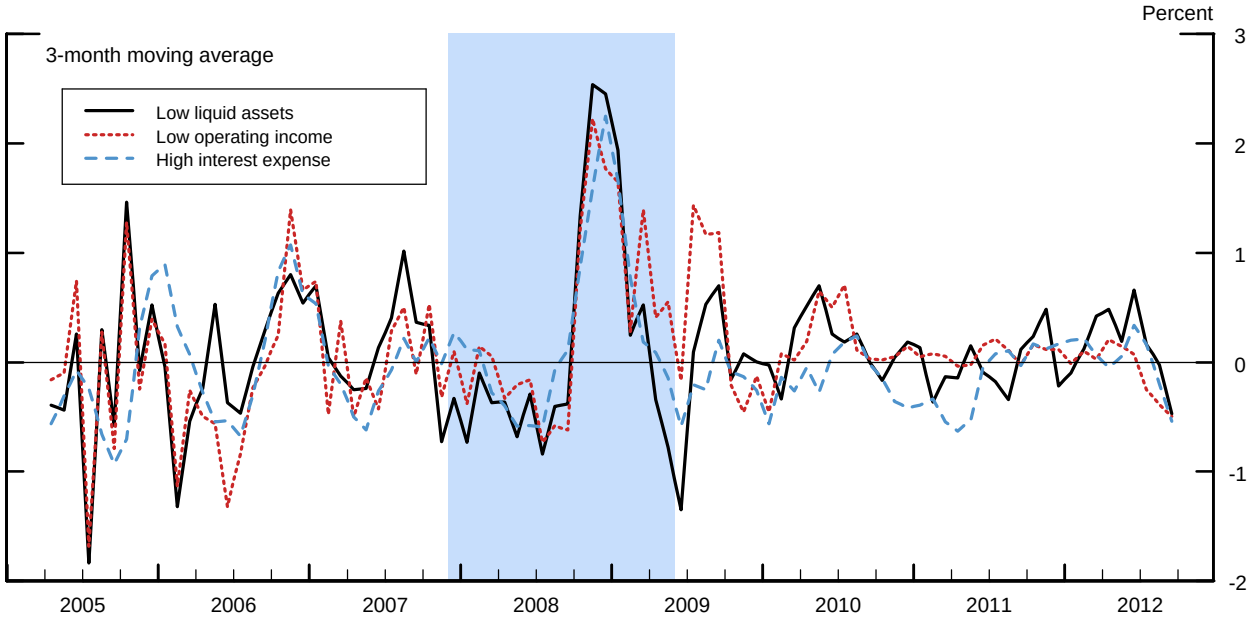
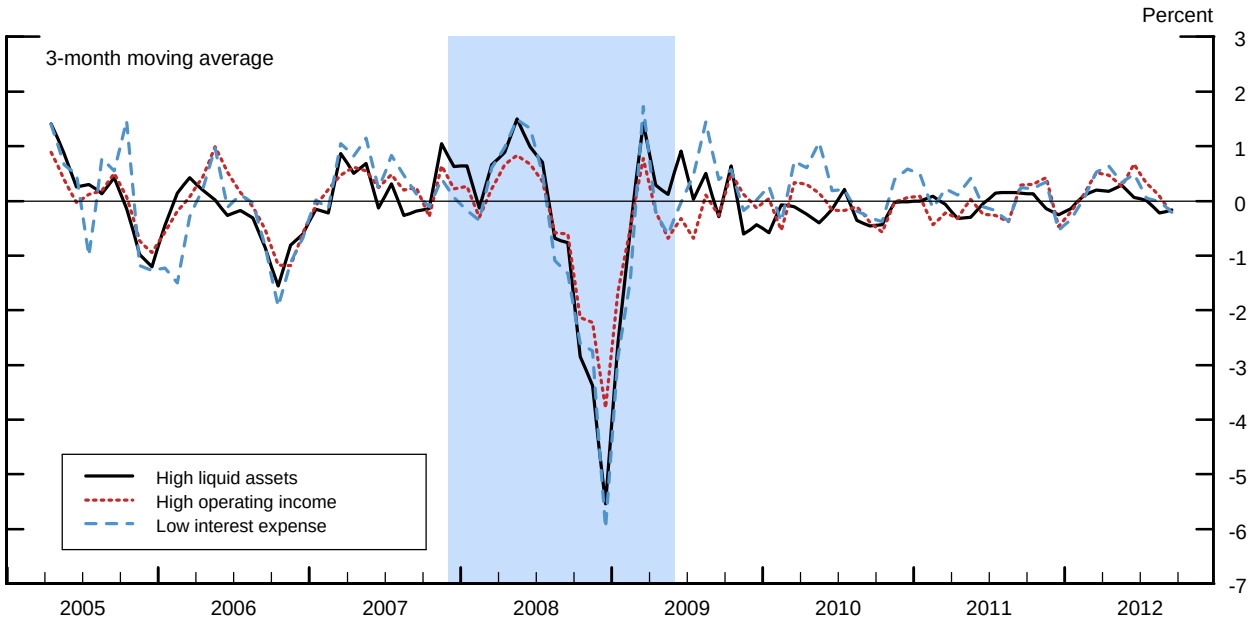


Figure 1: Producer Price Inflation, Full vs. Matched PPI Sample

NOTE: The solid line depicts the 3-month moving average of monthly inflation calculated using the full PPI sample, while the dotted line depicts the corresponding inflation calculated using the subsample of Compustat firms.



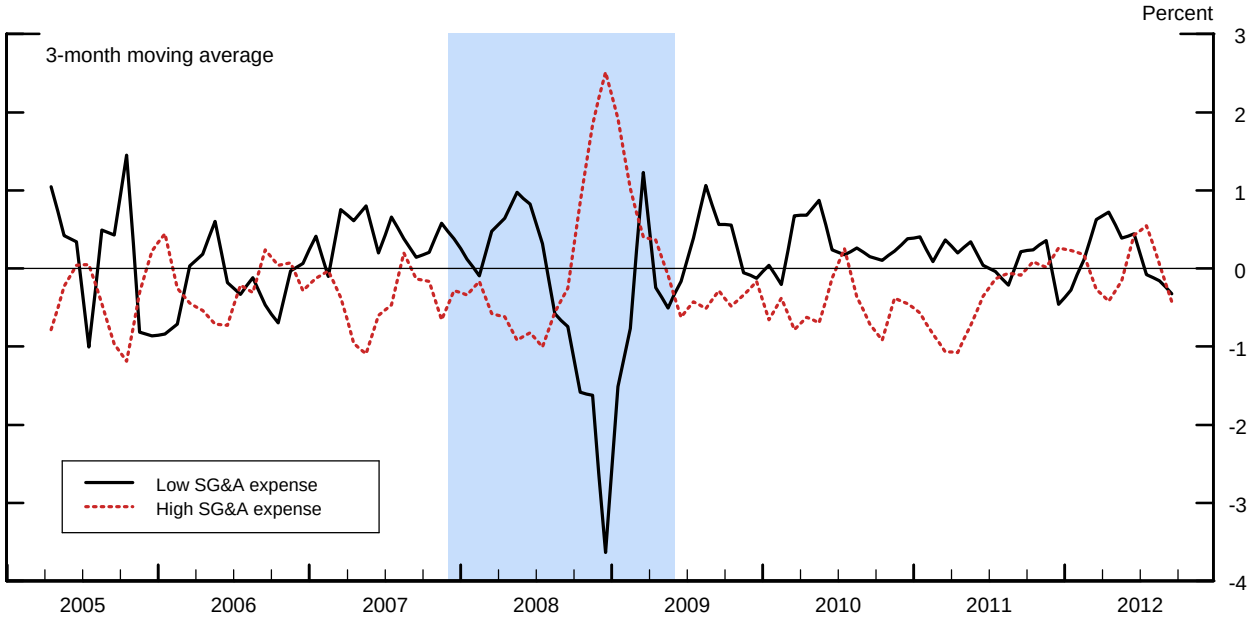
(a) Financially Weak Firms



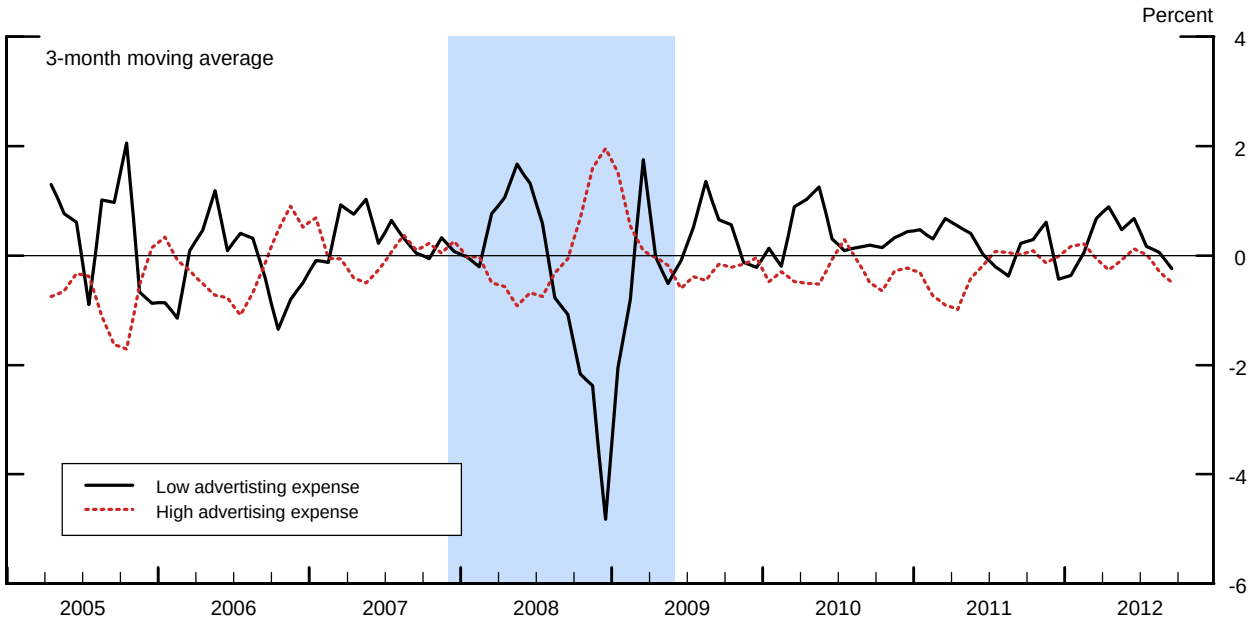
(b) Financially Strong Firms

Figure 2: Producer Price Inflation by Selected Financial Characteristics

NOTE: The top panel shows the industry-adjusted 3-month moving average of monthly inflation rates for financially weak firms, while the bottom panel shows the corresponding inflation rates for financially strong firms; see text for details.



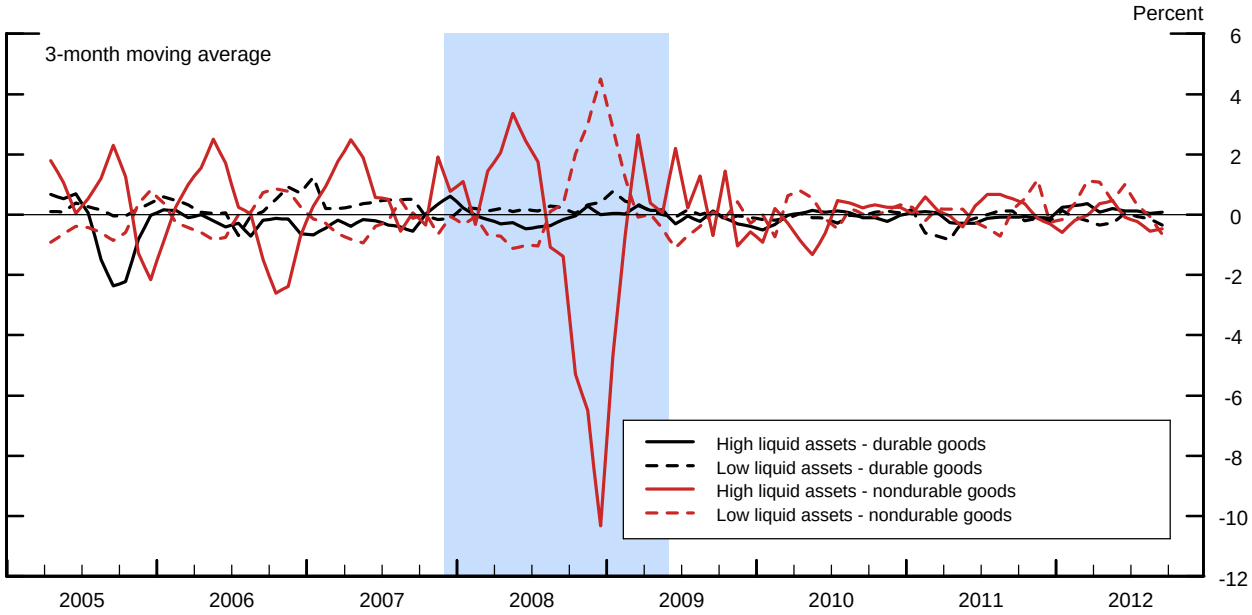
(a) By SG&A Expense Ratio



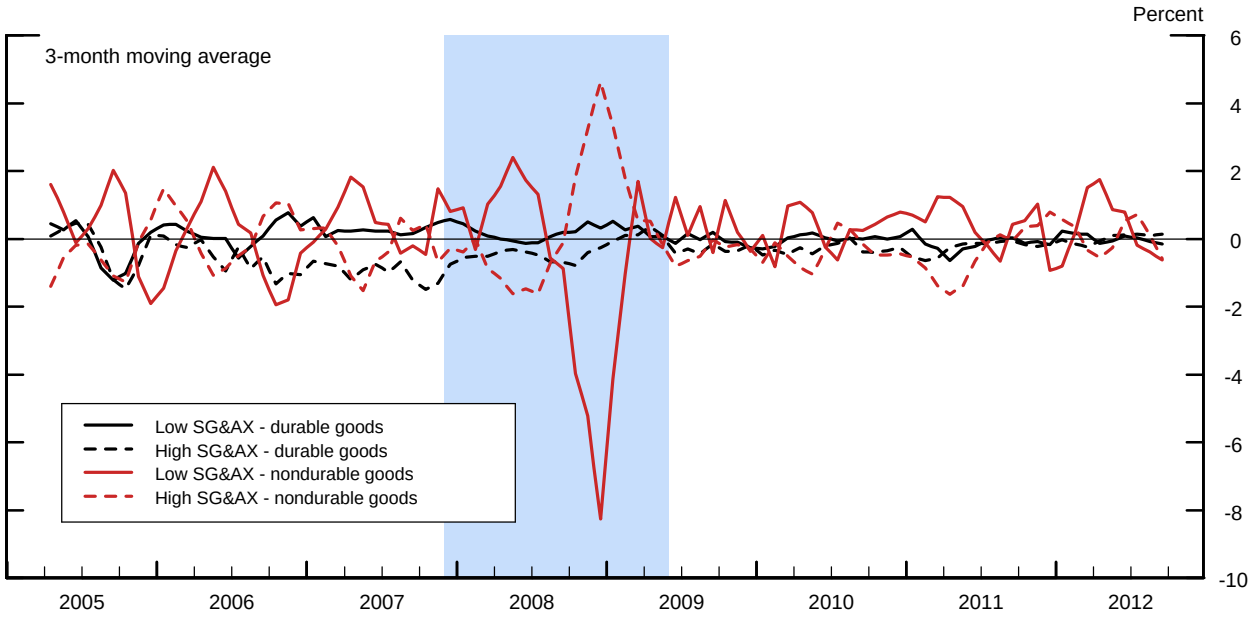
(b) By Advertising Expense Ratio

Figure 3: Producer Price Inflation by Selected Product-Market Characteristics

NOTE: The top panel shows the industry-adjusted 3-month moving average of monthly inflation rates for firms with different product-market characteristics; see text for details.



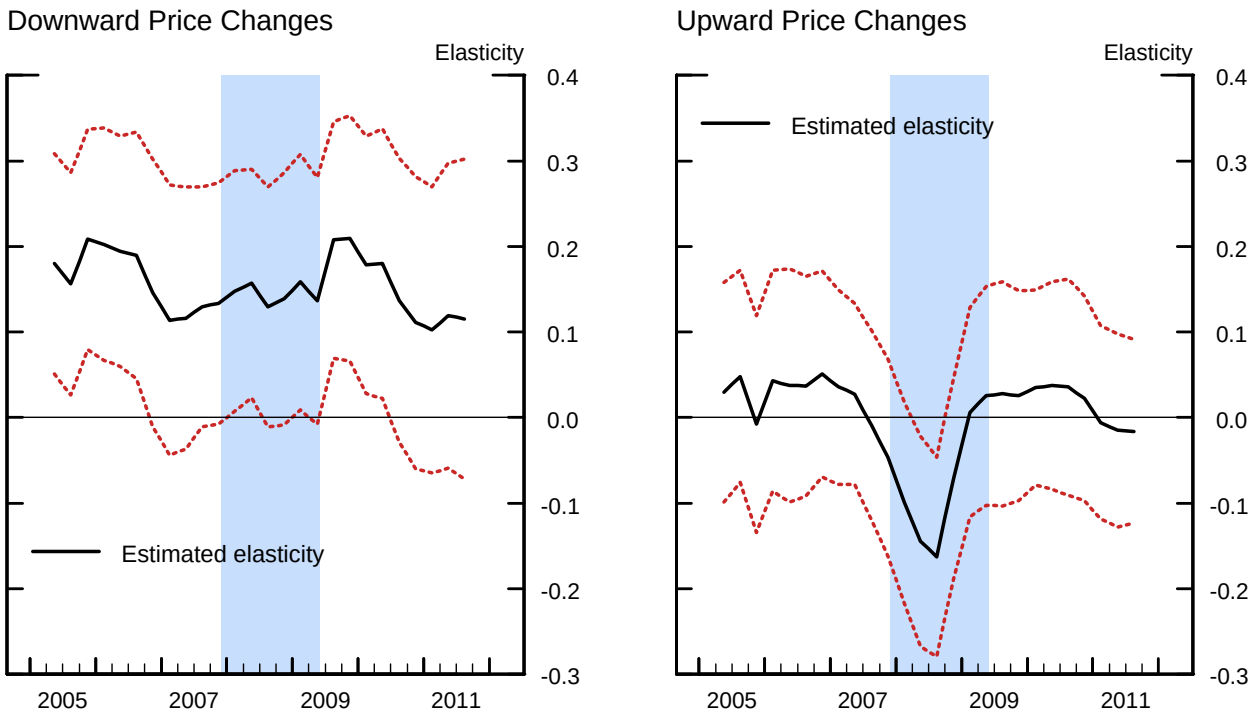
(a) By Durable vs. Nondurable Goods Sector and Liquidity Ratio



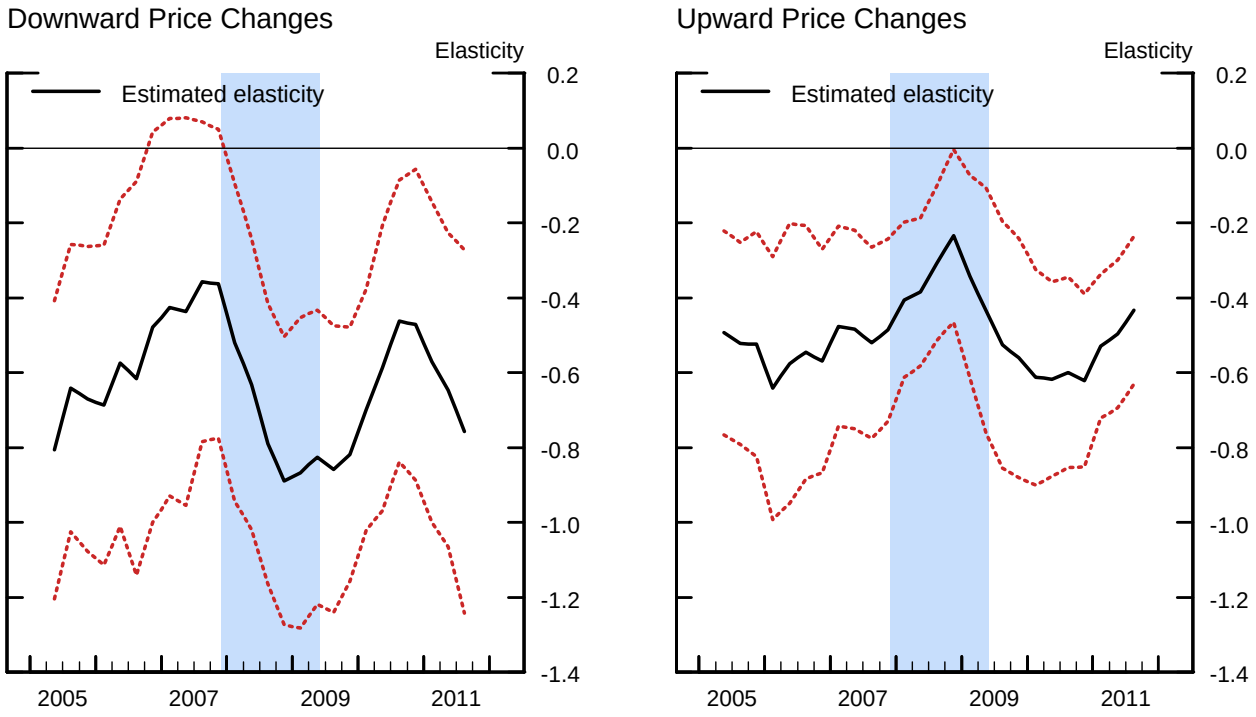
(b) By Durable vs. Nondurable Goods Sector and SG&A Ratio

Figure 4: Producer Price Inflation by Selected Firm Characteristics and Production Sector

NOTE: The top panel shows the 3-month moving average of monthly inflation rates for firms in different financial positions within the durable and nondurable goods sector. The bottom panel shows the 3-month moving average of monthly inflation rates for firms with different product-market characteristics within the durable and nondurable goods sectors; see text for details.



(a) With Respect to Liquidity Ratio



(b) With Respect to SG&A Ratio

Figure 5: Elasticities of Directional Price Changes

NOTE: The solid line in each panel depicts the estimated time-varying elasticity of the decision to adjust prices upwards or downwards—relative to a base category of no change—based on a multinomial logit specification; see text for details. Dotted lines denote robust 95% confidence intervals.

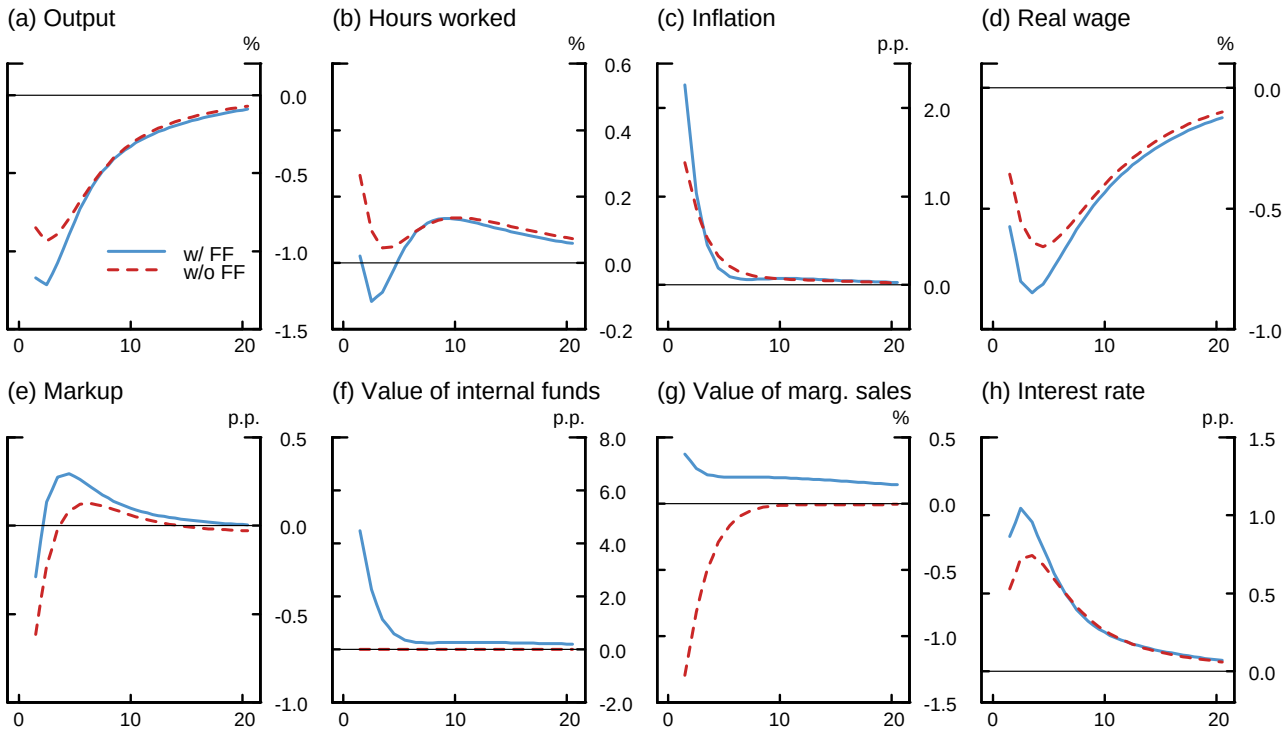


Figure 6: Impact of a Technology Shock

NOTE: Blue responses are from the model with financial distortions; red responses are from the model without financial distortions.

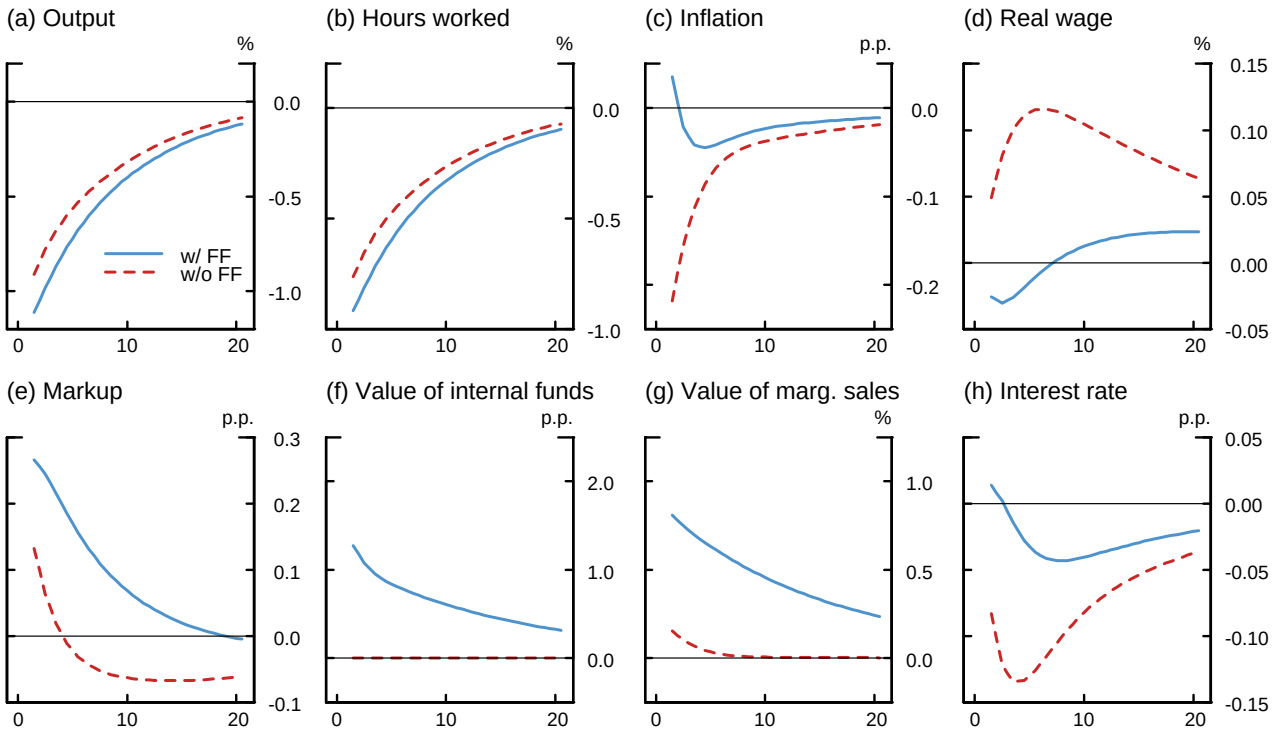


Figure 7: Impact of a Demand Shock

NOTE: Blue responses are from the model with financial distortions; red responses are from the model without financial distortions.

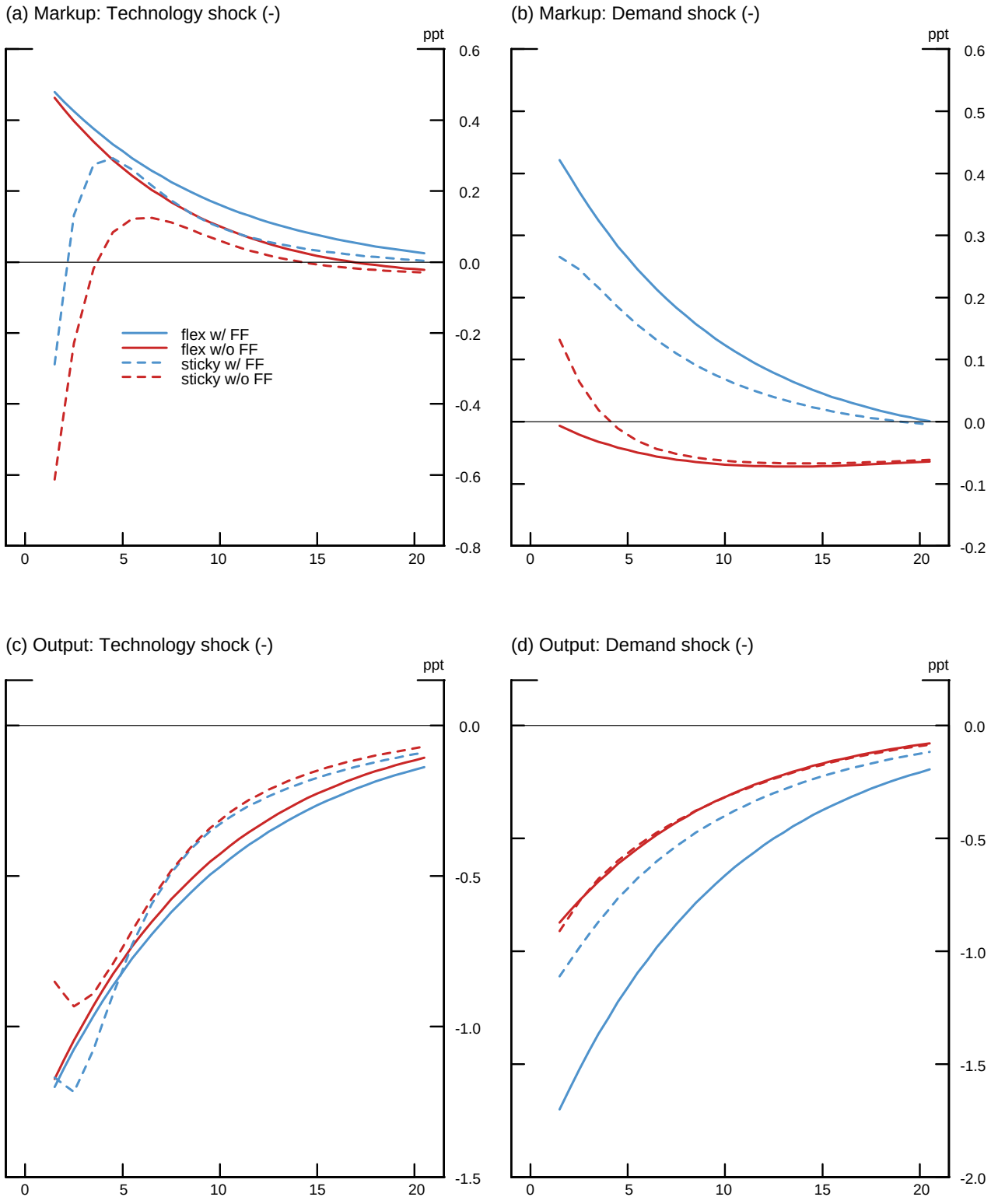


Figure 8: Nominal Rigidities, Financial Distortions, and the Dynamics of Markups

NOTE: Blue responses are from the model with financial distortions; red responses are from the model without financial distortions.

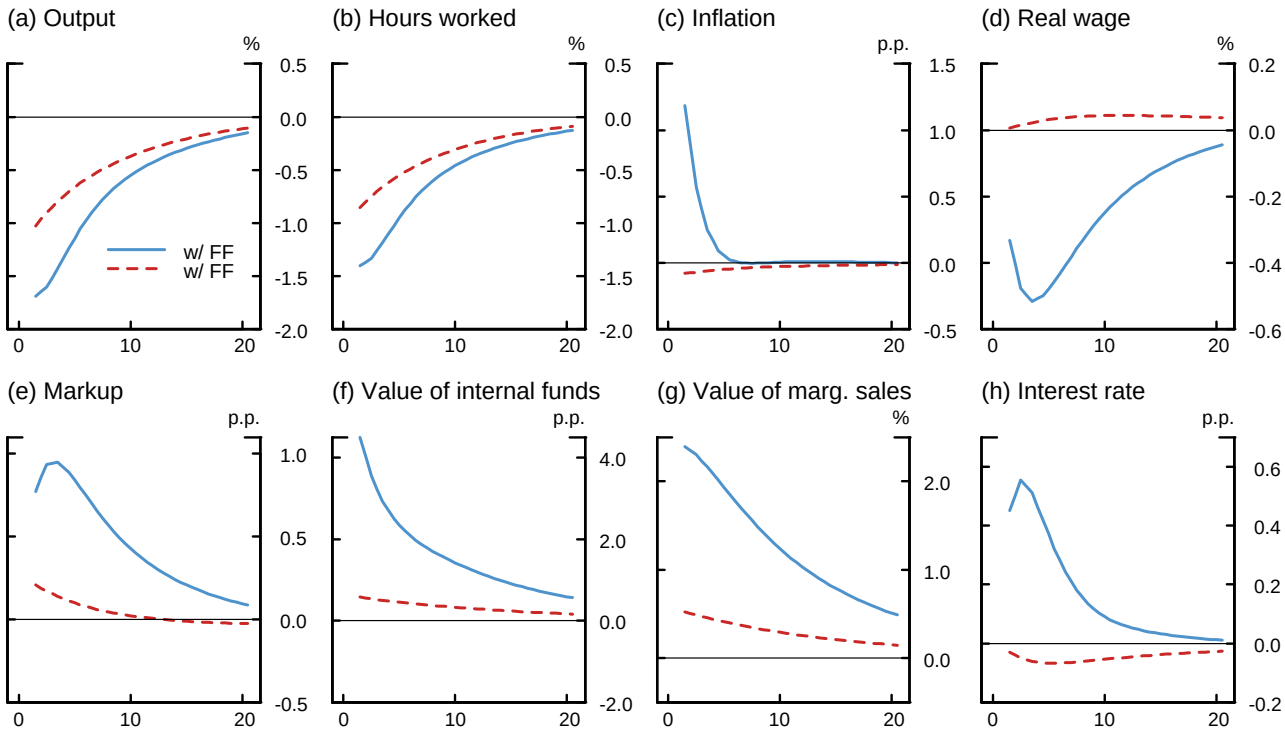


Figure 9: Impact of a Demand Shock with Higher External Financing Costs

NOTE: Both models contain financial distortions. Blue responses are from the model with temporarily elevated external financing costs; red responses are from the model without a temporary increase in external financing costs.

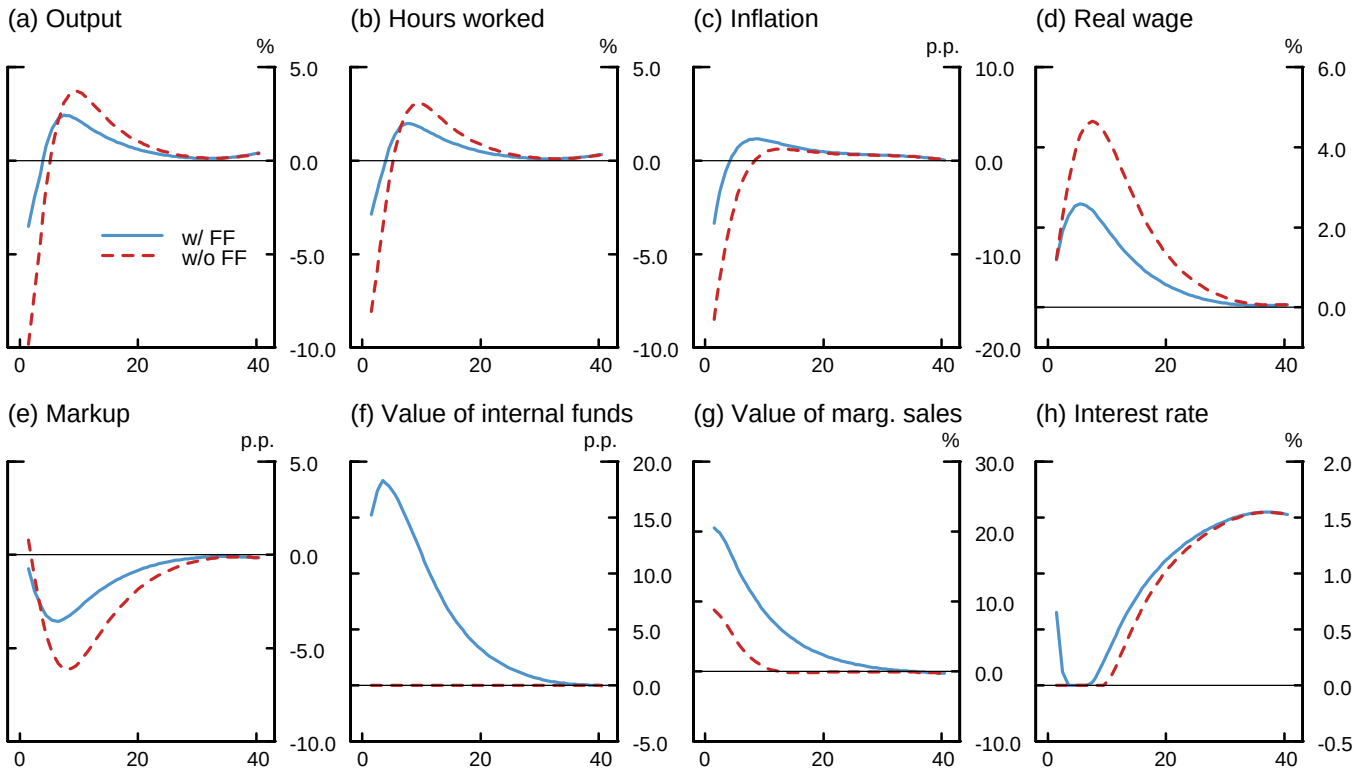


Figure 10: Impact of a Discount Rate Shock

NOTE: Blue responses are from the model with financial distortions; red responses are from the model without financial distortions.

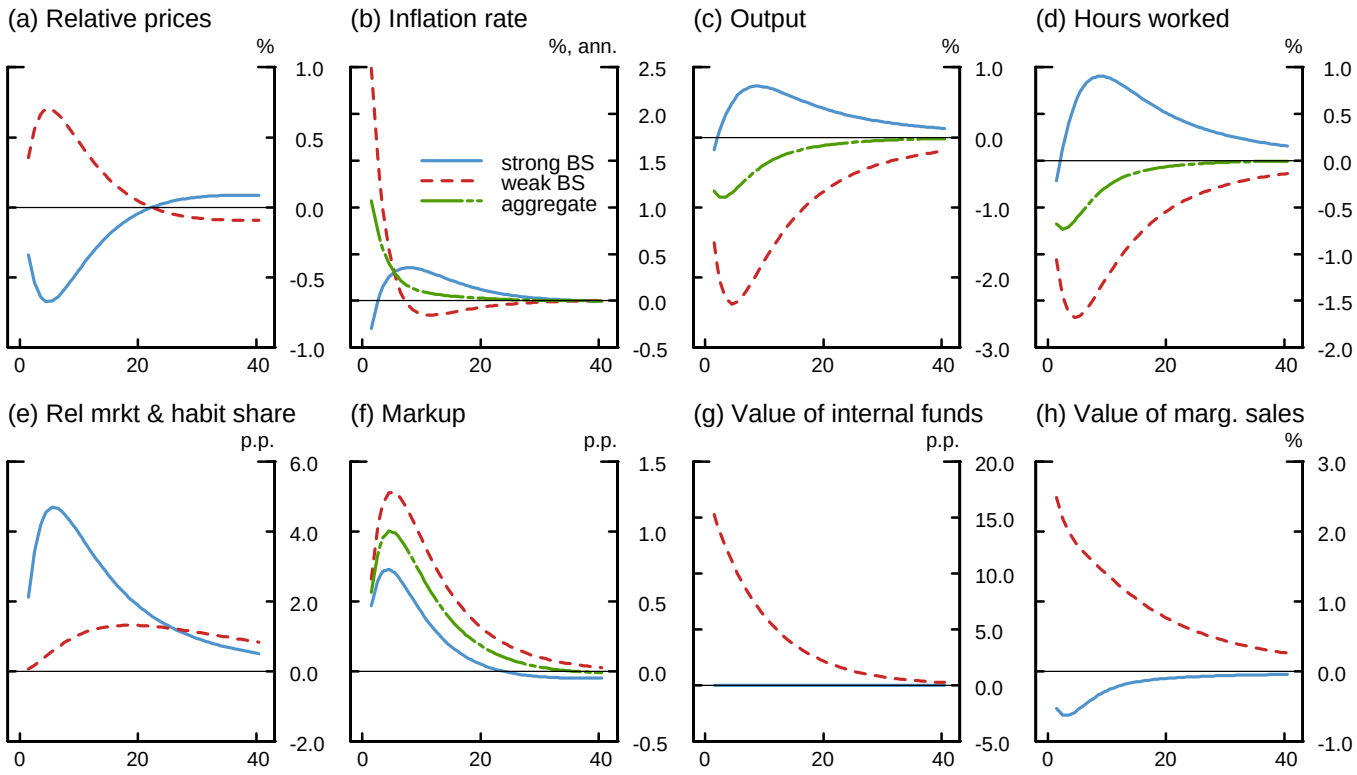


Figure 11: Impact of a Financial Shock with Firm Heterogeneity

NOTE: Blue responses are those of firms with strong balance sheets; red responses are those of firms with weak balance sheets; and green responses are those of the aggregate economy.

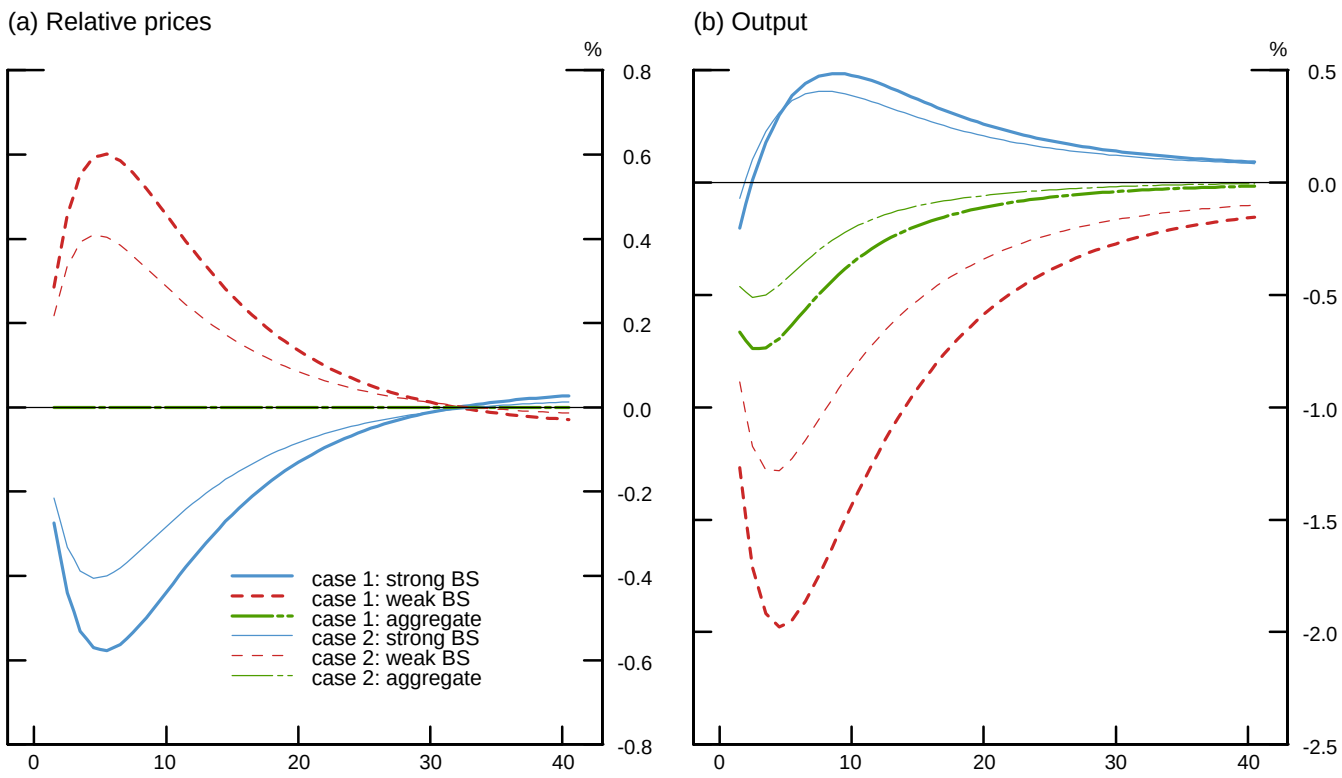


Figure 12: Paradox of Financial Strength

NOTE: Cases 1 and 2 correspond to $\phi_1 = 0$ and $\phi_1 = 0.8\phi_2$, respectively.

Appendices

A Log-linearization of Phillips Curve

From (28), we derive the steady state relationship between the value of internal funds and the value of marginal sales as

$$\frac{\mathbb{E}^a[\nu_i]}{\mathbb{E}^a[\xi_i]} = \eta. \tag{A-1}$$

(19) in the steady state implies

$$\mathbb{E}^a[\nu_i] = \mathbb{E}^a[\xi_i] - \mathbb{E}^a_t[\kappa_i] + (1-\rho)\lambda$$

Dividing this expression through by $\mathbb{E}^a[\nu_i]$ yields

$$1 = 1/\eta - \frac{\mathbb{E}^a_t[\kappa_i]}{\mathbb{E}^a[\nu_i]} + (1-\rho)\frac{\lambda}{\mathbb{E}^a[\nu_i]} \tag{A-2}$$

Since the ratio between the marginal value of customer base and the marginal value of sales is determined by (20) as

$$\frac{\lambda}{\mathbb{E}^a[\nu_i]} = \frac{\beta\theta(1-\eta)}{(1-\rho\beta)}, \tag{A-3}$$

combining (A-2) and (A-3) yields

$$\frac{\mathbb{E}^a_t[\kappa_i]}{\mathbb{E}^a[\nu_i]} = 1/\eta - 1 - (\eta-1)\frac{\beta\theta(1-\rho)}{(1-\rho\beta)}$$

Sunstracting the above expression from the inverse of (A-1) yields

$$\begin{aligned}\frac{\mathbb{E}^a[\xi_i]}{\mathbb{E}^a[\nu_i]} - \frac{\mathbb{E}^a[\kappa_i]}{\mathbb{E}^a[\nu_i]} &= \frac{\mathbb{E}^a[\xi_i]}{\mathbb{E}^a[\nu_i]} \cdot \left[1 - \frac{\mathbb{E}^a[\kappa_i]}{\mathbb{E}^a[\xi_i]}\right] \\ &= 1 + (\eta-1)\frac{\beta\theta(1-\rho)}{(1-\rho\beta)} = \eta - \omega(\eta-1)\end{aligned}$$

where $\omega \equiv 1 - \dfrac{\beta\theta(1-\rho)}{1-\rho\beta}$. Hence, requiring $\eta - \omega(\eta-1) > 0$ is equivalent to a strictly positive marginal profit in the steady state.

B Equilibrium Dispersion of Prices in the Steady State

In the steady state, the Phillips curve implies

$$p_k = \eta\frac{\mathbb{E}^a[\nu_i|\phi_k]}{\mathbb{E}^a[\xi_i|\phi_k]}. \tag{B-1}$$

From the FOC for s, we have

$$\frac{\lambda_k}{\mathbb{E}^a[\xi_i|\phi_k]} = \frac{\theta(1-\eta)\beta}{1-\rho\beta}\frac{\mathbb{E}^a\left[\nu_i|\phi_k\right]}{\mathbb{E}^a[\xi_i|\phi_k]}. \tag{B-2}$$

Combining the two yields

$$\frac{\lambda_k}{\mathbb{E}^a[\xi_i|\phi_k]} = p_k \frac{\theta(1-\eta)\beta}{\eta(1-\rho\beta)}. \tag{B-3}$$

The FOC for c and h in the steady state imply

$$\frac{\mathbb{E}^a[\nu_i|\phi_k]}{\mathbb{E}^a[\xi_i|\phi_k]} = -\frac{\mathbb{E}^a[\xi_i a_i|\phi_k]}{\mathbb{E}^a[\xi_i|\phi_k]} \frac{w}{\alpha A} (c_k + \phi_k)^{\frac{1-\alpha}{\alpha}} + p_k + (1-\rho)\frac{\lambda_k}{\mathbb{E}^a[\xi_i|\phi_k]}. \tag{B-4}$$

Substituting (B-1) and (B-3) in (B-4) yields

$$p_k = \frac{\eta(1-\rho\beta)}{(\eta-1)[(1-\rho\beta) - \theta\beta(1-\rho)]} \frac{\mathbb{E}^a[\xi_i a_i|\phi_k]}{\mathbb{E}^a[\xi_i|\phi_k]} \frac{w}{\alpha A} (c_k + \phi_k)^{\frac{1-\alpha}{\alpha}}. \tag{B-5}$$

The external financing triggers in the steady state are given by

$$a_k^E = \frac{p_k c_k}{(c_k + \phi_k)^{1/\alpha}} \frac{A}{w}. \tag{B-6}$$

The consumption aggregators in the steady state imply

$$\frac{c_k}{c_l} = \left(\frac{p_k}{p_l}\right)^{-\eta} \frac{s_k^{\theta(1-\eta)}}{s_l^{\theta(1-\eta)}} \tag{B-7}$$

and

$$x = \left[\sum_{m=1}^{N} \omega_m \left(c_m^{1-\theta}\right)^{1-1/\eta}\right]^{1/(1-1/\eta)}. \tag{B-8}$$

Equilibrium consistency requires

$$1 = \left[\sum_{m=1}^{N} \omega_m p_m^{1-\eta}\right]^{1/(1-\eta)}, \tag{B-9}$$

which is the steady state version of (42) with $\pi = \pi_k = 1$. Finally labor market and goods market clearing conditions imply

$$\frac{w}{\tilde{p}} x^{-\gamma_x} = \zeta h^{\gamma_h} \tag{B-10}$$

and

$$c = \left[\sum_{m=1}^{N} \omega_m [\exp(0.5\alpha(1+\alpha)\sigma^2) h_m^{\alpha} - \phi_m]^{1-1/\eta}\right]^{1/(1-1/\eta)} \tag{B-11}$$

where the type conditional labor demand satisfies

$$h_k = \left[\frac{c_k + \phi_k}{\exp(0.5\alpha(1+\alpha)\sigma^2)}\right]^{1/\alpha} \tag{B-12}$$

and

$$h = \sum_{m=1}^{N} h_m \tag{B-13}$$

Deep-habit adjusted price index in the steady state satisfies

$$\tilde{p} = \left[\sum_{m=1}^{N} \omega_m p_m^{1-\eta} c_m^{\theta(1-\eta)} \right]^{1/(1-\eta)} . \tag{B-14}$$

which is the steady state version of (45). (B-5)∼(B-14) can then be solved for $4N + 5$ variables: p_k, c_k, a_k^E, h_k for $k = 1, \ldots, N$ and x, w, $\tilde{p}$, h and c.