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Trend inflation and an empirical test of real rigidities

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Abstract

Positive trend inflation resolves the observational equivalence of various sources of real rigidities which are first-order equivalent under zero trend inflation. This paper builds on this observation to assess the empirical performance of three widely used types of real rigidities — firm-specific capital, firm-specific wages and a kinked-demand curve — in matching the U.S. inflation dynamics. Firm-specific wages outperform the kinked-demand curve and firm-specific capital in terms of empirical fit. We document that positive trend inflation might reduce the ability of firm-specific factors to prolong the real affects of monetary disturbances.

Keywords: trend inflation, real rigidity, Calvo pricing, price dispersion, monetary policy, inflation persistence

JEL: E31, E52

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1 Introduction

Real rigidities inducing a strategic complementarity in price setting are generally viewed as key in propagating monetary shocks in New Keynesian models. Various sources of real rigidities used in the literature include sticky intermediate prices (Basu, 1995), a kinked-demand curve (Kimball, 1995), sticky real wages (Blanchard and Galí, 2007) or firm-specific factors (e.g. Woodford (2003), Sveen and Weinke (2005)).

Yet despite their common use in economic models, distinguishing between them with respect to their implications for economic dynamics and monetary policy has received only little attention in the economic literature. A potential explanation is, as put forth by Levin et al. (2008), that real rigidities are subject to the phenomenon of macroeconometric equivalence as real rigidities tend to have observationally equivalent implications for economic dynamics if the model is log-linearized around a zero steady-state inflation.

It is known, however, that different real rigidities might lead to different economic conclusions. Levin et al. (2008) and Levin et al. (2007) make a strong case by showing that accounting for the non-linearities implied by the different sources of real rigidity yields remarkably different implications for the welfare costs of inflation and thus optimal monetary policy.[1] Klenow and Willis (2016) document that different real rigidities significantly affect the ability of monetary models to be consistent with the newly available micro evidence on price setting.

While considering a non-linear model solution might be necessary for normative analysis of optimal monetary policy, for positive economic applications the macroeconometric equivalence in the case of a zero steady state inflation might be resolved by considering the first-order approximation around a generic trend inflation level which would imply preserving the model differences (Ascari and Sbordone, 2014). This argument is supported by the growing evidence in favor of incorporating non-zero steady inflation in monetary models

[1] The non-linear properties of real rigidities were emphasized also by Lindé and Trabandt (2018).

(see e.g. Amano et al. (2009), Ascari and Sbordone (2014), Ascari et al. (2018), Bauer and Rudebusch (2020)). As we show in this paper, considering a log-linearized model solution and imposing a positive trend inflation makes the model dynamics sufficiently rich to reveal the differences between the different sources of real rigidities which in turn can be used to distinguish between them on empirical grounds.

We use this observation to assess the empirical performance of three widely used types of real rigidity — a firm-specific capital allocation, firm-specific wages and kinked-demand curves — in matching the U.S. inflation dynamics. We analyze three variants of a textbook macroeconomic model (see Woodford (2003)) which differ solely in the source of real rigidity and compute the inflation rates implied by the Phillips curve for each model variant.[2] To this end we utilize the approach by Sbordone (2002), Dupor et al. (2010) and Woodford (1999) but reverse the line of argument: instead of fixing the parameters governing the degree of real rigidity and estimating the Calvo parameter, we fix the Calvo parameter based on the evidence on price setting from micro data and estimate the parameter governing the degree of real rigidity. The parameter values governing the degree of real rigidity for each model variant are estimated by minimizing the variance of the deviations of the model-implied inflation rate from the actual inflation rate.

We find that firm-specific wages caused by segmented, i.e. firm-specific, labor markets achieve the best empirical fit and significantly outperform the other two types of real rigidity. In other words, a version of the New-Keynesian model with Calvo pricing and firm-specific wages explains the U.S. inflation dynamics significantly better than versions of the model with firm-specific capital and the kinked-demand curve. This result points to the importance of constraints in labor mobility and the elasticity of labor supply in understanding the inflation dynamics.

[2] To assess the inflation fit a partial equilibrium approach focusing solely on the price-setting behavior would be sufficient. However, to assess the implications of the empirical estimates for overall economic dynamics in case of monetary disturbances we consider a general equilibrium approach from the beginning.

We further observe that trend inflation might mitigate the key property of real rigidities to amplify the real effects of monetary disturbances. More specifically, we document that positive trend inflation moderates the persistence effect for the model variants with firm-specific factors, whereas the impact of the kinked-demand curve is hardly affected. The basic intuition for this result is that positive trend inflation increases the effective discount factor and price setters care more about the future. Consider the case of a firm increasing its price when facing a real rigidity due to a firm-specific input. Lower demand decreases the production costs and thus the actual need for increasing the price in the first place. But because the production costs matter more under higher values of trend inflation, the channel through which firm-specific factors induce the strategic complementarity in price setting gets less important.[3] In contrast, the strategic complementarity channel of the kinked-demand curve is barely affected. Therefore, the trend inflation does not mitigate its effect on optimal price setting and thus its ability to prolong the real effects of monetary shocks. Our results have thus important implications for explaining and modelling the real effects of monetary policy. With trend inflation, even strong levels of firm-level real rigidities may not be strong enough to increase the effectiveness of monetary policy.[4]

Several papers have already focused on the interaction between trend inflation and real rigidities. Kurozumi and Zandweghe (2016) show that the kinked-demand curve can mitigate the effect of positive trend inflation in inducing equilibira indeterminacy in the New Keynesian model with a Taylor rule. Bakhshi et al. (2007) show that real rigidity due to firm-specific factors has the opposite effect and leads to larger regions of the parameter space resulting in equilibria indeterminacy. These opposite results underline the importance of distinguishing

[3]Several papers derive a generalized formulation of the New Keynesian Phillips curve with Calvo pricing under positive trend inflation (see Ascari (2004), Yun (2005), Cogley and Sbordone (2008) and Ascari and Sbordone (2014) for a comprehensive survey) and emphasize that the form of this curve is more forward-looking than its zero inflation counterpart. We find that it is exactly this implication of trend inflation which reduces the strategic complementarity property of some forms of real rigidity to prolong the persistence of responses to shocks.

[4]Burstein and Hellwig (2007) document a similar result considering a state-dependent pricing model.

between real rigidities on empirical grounds which is one of the main goals of this paper.[5]

The remainder of this paper is organized as follows. Section 2 presents the model variants. In Section 3 we derive the analytical results for the log-linearized versions of the three model variants with the different types of real rigidities. Our empirical analysis is described in Section 4 and our main findings are presented in Section 5. Section 6 studies the impact of monetary shocks on aggregate variables. Section 7 concludes.

2 Model economies

In this section we present our model framework based on a text book macroeconomic model (see Woodford (2003)) with positive trend inflation. We specify three model variants which differ solely in the source of real rigidity. The first model variant includes firm-specific wages due to segmented labor markets (henceforth: SLM) as modelled by Gertler and Leahy (2008). The second model variant features decreasing returns to labor inputs (henceforth: DRL), also referred to as fixed capital allocation at the firm level (see Sbordone (2002), Woodford (2003), Eichenbaum and Fisher (2007)). The third model variant exhibits real rigidity due to the kinked-demand curve (henceforth: KDC; see Kimball (1995), Levin et al. (2007), Kurozumi and Zandweghe (2016)).

2.1 SLM model

The model economy consists of a continuum of islands $z \in [0, 1]$. Time is discrete and denoted by $t = 0, 1, 2, ...$ Each island is populated by infinitely many households and infinitely many

[5] Klenow and Malin (2010) note that the overall empirical evidence on the presence of real rigidities is mixed. Gopinath and Itskhoki (2011) consider real rigidites as the main source of the incomplete pass-through of exchange rate changes to import prices. Eichenbaum and Fisher (2007) and Carvalho et al. (2015) find significant degrees of real rigidity in aggregate data. At the firm level Klenow and Willis (2016) and Kryvtsov and Midrigan (2013) find it difficult to reconcile some types of firm-level real rigidities with large idiosyncratic price changes and inventory-sales ratios, respectively. This mixed evidence might by explained by insufficiently taking into account that different sources of real rigidity can have different implications for economic dynamics.

monopolistically competitive firms. We provide details about each of these groups in turn.

Households On each island z, there is a continuum of households of mass unity. Households can supply labor only on this island. All households on all islands own identical shares of all firms and receive firms' profits as dividends. There is perfect consumption insurance across islands. Each household's instantaneous utility function in period t is

$$u(C_t, M_t/P_t, N_{z,t}) = \log\left[C_t\left(\frac{M_t}{P_t}\right)^{\nu}\right] - \frac{N_{z,t}^{1+\varphi}}{1+\varphi}, \tag{1}$$

where ν and φ are positive parameters, M_t denotes nominal money holdings, P_t is the aggregate price level, $N_{z,t}$ stands for the household's supply of labor, and C_t denotes a consumption basket, which consists of differentiated goods $C_{z,t}^j$. In particular, $C_{z,t}^j$ denotes the consumed quantity of an individual good j produced on island z in period t. The consumption basket is given by a Dixit-Stiglitz aggregator function

$$C_t = \left[\int_0^1 \int_0^1 (C_{z,t}^j)^{\frac{\varepsilon-1}{\varepsilon}} dj dz\right]^{\frac{\varepsilon}{\varepsilon-1}}, \tag{2}$$

where ε ($\varepsilon > 1$) stands for the elasticity of substitution between the differentiated goods. The aggregate price level P_t is given by

$$P_t = \left[\int_0^1 \int_0^1 (Q_{z,t}^j)^{1-\varepsilon} dj dz\right]^{\frac{1}{1-\varepsilon}}, \tag{3}$$

where $Q_{z,t}^j$ denotes the price set by an individual producer j from island z in period t.

Utility in future periods is discounted by the factor $\beta \in (0,1)$. In each period t, the real flow budget constraint is

$$\int_0^1 \int_0^1 \frac{Q_{z,t}^j}{P_t} C_{z,t}^j dj dz + \frac{M_t - M_{t-1}}{P_t} + \frac{\frac{1}{R_t^n} B_t - B_{t-1}}{P_t} = \frac{W_{z,t}}{P_t} N_{z,t} + T_{z,t} \tag{4}$$

where B_t stands for bond holdings, R_t^n the gross nominal bond yield, and $T_{z,t}$ is an island specific real transfer, which includes the profits of firms, the government's seigniorage revenues, and the transfers from consumption insurance. The island-specific nominal wage is denoted by $W_{z,t}$. Bonds, which are in zero net supply, are traded in an economy-wide market. The gross nominal bond yield, R_t^n, is therefore identical across islands.

Firms Each island $z \in [0,1]$ is populated by a continuum of firms of mass unity, which produce differentiated goods. The firms set their prices and sell their goods directly to consumers across all islands. Given the production function $Y_{z,t}^j = N_{z,t}^j$, where $N_{z,t}^j$ denotes the labor input of firm j on island z at time t, the profit of a goods producer j in period t is given by the difference between revenues and total labor costs

$$\Pi_{z,t}^j = \frac{Q_{z,t}^j}{P_t} Y_{z,t}^j - \frac{W_{z,t}}{P_t} N_{z,t}^j. \tag{5}$$

It is noteworthy that the nominal wage in the firm's instantaneous profit function given by equation (5) is only indexed by z and not by j, i.e. it is not firm-specific but only island specific. The segmented labor markets imply inelastic labor supply on each island and thus island specific wages.

The simple intuition for why SLM are a powerful source of real rigidity is the following. Consider a shock that raises a firm's cost. A firm that re-optimizes its price will respond by planning to increase its price. However, this price increase would reduce demand for this good, which would reduce output and thus labor demand on that island. Because wages are island specific, this leads to a fall in the firm's costs. This compensates for the initial increase in the firm's cost and the firm would raise its price by less than it would if labor markets were not segmented.

Goods producers are subject to price stickiness à la Calvo (1983) such that they can change their prices only with probability $1-\alpha$ in every period. This means that on an island either all prices change or no price changes. The optimization problem of a producer j on island z is thus given by

$$\max_{Q^j_{z,t}} \quad \mathbb{E}_t \quad \sum_{i=0}^{\infty} \Lambda_{t,t+i}\, \alpha^i \left[\left(\frac{Q^j_{z,t}}{P_{t+i}} \right)^{1-\varepsilon} Y_{t+i} - \frac{W_{z,t+i}}{P_{t+i}} \left(\frac{Q^j_{z,t}}{P_{t+i}} \right)^{-\frac{\varepsilon}{\gamma}} Y_{t+i}^{\frac{1}{\gamma}} \right], \tag{6}$$

where $\Lambda_{t,t+i} = \beta^i \frac{U'(C_{t+i})}{U'(C_t)} = \beta^i \frac{C_t}{C_{t+i}}$ denotes the stochastic discount factor between periods t and $t+i$ and where we have used the household's demand for good j given by $Y^j_{z,t+i} = \left(\frac{Q^j_{z,t}}{P_{t+i}} \right)^{-\varepsilon} Y_{t+i}$.

Closing the model We close the model (and also the model variants which will follow) by assuming that the growth rate of the nominal money stock, which is denoted by g^m_t, follows an exogenously given stationary stochastic process. We allow for a positive unconditional mean of g^m_t, which enables us to model a positive inflation trend. The resulting seignorage revenues are used as lump-sum transfers to households.

2.2 DRL model

In this model version we abstract from the island structure of the economy since there is only one economy-wide labor market implying the same wages paid to all workers. Hence, the description of the households' side of the economy remains the same with the only modification that we consider only one island such that the integrals over the z's disappear.

Firms To introduce decreasing returns to labor inputs, we modify the production function of producer j in period t to $Y^j_t = \left(N^j_t\right)^{\gamma}$, where $\gamma \in (0,1)$ and N^j_t denotes the labor input of firm j at time t. With $\gamma \in (0,1)$, marginal costs of each firm are not constant and depend on the firm's output level. There are decreasing returns to scale, which could also be interpreted as the production function being of the Cobb-Douglas type but with fixed capital. DRL can be considered as a way of modeling that a firm's capital stock is fixed and cannot be reallocated after a shock.[6] The remaining description of the firms' side of the economy remains the same.

The basic intuition for why DRL are a source of real rigidity can be described as follows. With firm-specific capital, a firm's stock of capital is predetermined such that the firm's marginal cost is an increasing function of its output. In response to a positive shock in marginal costs, a firm that re-optimizes its price will respond by planning to raise its price. However, such a price increase would lower demand and thus output, which in turn leads to a fall in the firm's marginal cost. Therefore, the firm would raise its price by less than if capital were not predetermined.

2.3 KDC model

Households As in Kimball (1995), kinked-demand curves are approximated by concave demand functions for each differentiated good. This is achieved by abstracting from the Dixit-Stiglitz constant-elasticity-of-substitution aggregator. Following Levin et al. (2007) and Kurozumi and Zandweghe (2016), we assume that each household's function for aggregating the consumption basket is given by

$$\int_0^1 F\left(\frac{C_t^j}{C_t}\right) dj = 1, \tag{7}$$

where the function F is given by

$$F\left(\frac{C_t^j}{C_t}\right) = \frac{\rho}{(1+\epsilon)(\rho-1)}\left[(1+\epsilon)\frac{C_t^j}{C_t} - \epsilon\right]^{\frac{\rho-1}{\rho}} + 1 - \frac{\rho}{(1+\epsilon)(\rho-1)} \tag{8}$$

with $\rho = \varepsilon(1+\epsilon)$. The parameter ϵ governs the curvature of the demand curve for each differentiated good j. In the special case of $\epsilon = 0$, the aggregation technology in equation (7)

[6] See, e.g., Sbordone (2002) and Woodford (2003). Of course, the assumption of completely segmented capital markets might sound dramatic. However, Woodford (2003) and in particular Eichenbaum and Fisher (2007) document that assuming only partly flexible capital allocation yields similar results.

is reduced to the CES technology in equation (2).

As in the description of the other two model variants above, it is useful to sketch the basic intuition why KDC acts as a source of real rigidity. Consider again a rise in firm's cost, which induces a firm to increase its price. A concave downward sloping demand curve implies that for any given rise in its price, the demand curve for the firm's good will be more flat and thus more elastic. Therefore, the firm will raise its price by less than in the case of a CES aggregator with linear demand.

Our model variant with KDC is the same as the model in Kurozumi and Zandweghe (2016) with the only difference that they close the model with a Taylor rule. They provide a comprehensive exposition of the model description and solution which we abstract from in what follows and rather concentrate thoroughly on the implications of KDC for economic dynamics.

3 Solution

In this section we present the log-linearized equilibium conditions for all three model variants.

3.1 Equilibrium conditions for the SLM model

The equations describing the optimal behavior of households, which are stated in Appendix D.2, have well-known log-linear approximations around the steady state

$$w_{z,t} - p_t = \ln\left(\overline{\frac{W}{P}}\right) + \varphi \hat{N}_{z,t} + \hat{Y}_t, \tag{9}$$

$$\hat{Y}_t = -\left(\hat{R}_t^n - \mathbb{E}_t\left[\pi_{t+1}\right]\right) + \mathbb{E}_t\left[\hat{Y}_{t+1}\right], \tag{10}$$

$$m_t - p_t = \ln\left(\overline{\frac{M}{P}}\right) + \hat{Y}_t - \frac{1}{\bar{R}^n - 1}\hat{R}_t^n, \tag{11}$$

$$\hat{Y}_{z,t}^j = -\varepsilon\left(q_{z,t}^j - p_t\right) + \hat{Y}_t, \tag{12}$$

where small letters denote log levels, variables with a bar denote steady-state levels, and variables with a "hat" stand for relative deviations from the steady state. π_t is the relative deviation from the steady-state value of gross inflation P_t/P_{t-1}.[7]

The associated (generalized) New Keynesian Phillips curve with trend inflation and SLM (in terms of unit labor costs) is given by

$$\begin{aligned}\hat{\pi}_t = &\frac{1}{1+\varphi\varepsilon}\left[\frac{\left(1-\alpha\bar{\pi}^{\varepsilon-1}\right)\left(1-\alpha\beta\bar{\pi}^{\varepsilon(1+\varphi)}\right)}{\alpha\bar{\pi}^{\varepsilon-1}}\right]\left[\widehat{ulc}_t-(1+\varphi)\hat{s}_t\right] \\ &+\mathbb{E}_t\widehat{\pi}_{t+1}\beta\left[1+\frac{\varepsilon(1+\varphi)}{1+\varphi\varepsilon}\left(1-\alpha\bar{\pi}^{\varepsilon-1}\right)\left(\bar{\pi}^{1+\varphi\varepsilon}-1\right)\right] \\ &+\mathbb{E}_t\widehat{\psi}_{t+1}\frac{\beta}{1+\varphi\varepsilon}\omega\left(1-\alpha\bar{\pi}^{\varepsilon-1}\right)\left(\bar{\pi}^{1+\varphi\varepsilon}-1\right),\end{aligned} \tag{13}$$

where $\widehat{ulc}_t$ denotes the deviation of aggregate unit labor costs from their steady-state value, $\hat{s}_t$ is the relative price distortion due to inefficient dispersion of prices given by equation (14), $\bar{\pi}$ denotes the trend inflation rate and $\widehat{\psi}_t$ is an auxiliary variable given by equation (15):

$$\hat{s}_t = \alpha\varepsilon\frac{\bar{\pi}^{\varepsilon}-\bar{\pi}^{\varepsilon-1}}{1-\alpha\bar{\pi}^{\varepsilon-1}}\sum_{i=0}^{N}\left(\alpha\bar{\pi}^{\varepsilon}\right)^i\widehat{\pi}_{t-i}+\left(\alpha\bar{\pi}^{\varepsilon}\right)^{N+1}\hat{s}_{t-N-1} \tag{14}$$

$$\begin{aligned}\widehat{\psi}_t = &\left(1-\alpha\beta\bar{\pi}^{\varepsilon(1+\varphi)}\right)\sum_{i=0}^{N}\left(\alpha\beta\bar{\pi}^{\varepsilon(1+\varphi)}\right)^i\left[\widehat{ulc}_t-(1+\varphi)\hat{s}_t\right], \\ &+\varepsilon(1+\varphi)\sum_{i=1}^{N+1}\left(\alpha\beta\bar{\pi}^{\varepsilon(1+\varphi)}\right)^i\mathbb{E}_t\widehat{\pi}_{t+i}+\left(\alpha\beta\bar{\pi}^{\varepsilon(1+\varphi)}\right)^{N+1}\mathbb{E}_t\widehat{\psi}_{t+N+1}.\end{aligned} \tag{15}$$

Note that if steady state inflation equals zero, i.e. $\bar{\pi}-1=0$, the Phillips curve (13) reduces to the conventional NKPC with segmented labor markets (16), as $\hat{s}_t$ does not affect the first-order dynamics:

$$\hat{\pi}_t = \frac{(1-\alpha)(1-\alpha\beta)}{\alpha}\frac{1}{1+\varphi\varepsilon}\widehat{ulc}_t+\mathbb{E}_t\beta\hat{\pi}_{t+1}. \tag{16}$$

[7] We have used $\hat{Y}_t=\hat{C}_t$ for the derivation of (9)-(12).

The system of equilibrium conditions is given by equations (10), (11), (13) - (15) and is closed by the equation governing the evolution of the money stock.

3.2 Equilibrium conditions for the DRL model

The equations describing the optimal behavior of households are slightly different than in the SLM model since the island structure has been abolished. Therefore the New Keynesian IS curve, equation (10), and the money demand, equation (11), stay unchanged whereas the labor supply, equation (17), and the goods demand, equation (18), are not island specific:

$$w_t - p_t = \ln\left(\frac{\overline{W}}{P}\right) + \varphi \hat{N}_{z,t} + \hat{Y}_t. \tag{17}$$

$$\hat{Y}_t^j = -\varepsilon\left(q_t^j - p_t\right) + \hat{Y}_t. \tag{18}$$

The associated New Keynesian Phillips curve with trend inflation and DRL is given by

$$\begin{aligned}\hat{\pi}_t = \omega &\left[\frac{\left(1-\alpha\bar{\pi}^{\varepsilon-1}\right)\left(1-\alpha\beta\bar{\pi}^{\frac{\varepsilon}{\gamma}}\right)}{\alpha\bar{\pi}^{\varepsilon-1}}\right]\left[\widehat{ulc}_t - \hat{s}_t\right] \\ &+ \mathbb{E}_t\widehat{\pi}_{t+1}\beta\left[1+\frac{\varepsilon}{\gamma+\varepsilon(1-\gamma)}\left(1-\alpha\bar{\pi}^{\varepsilon-1}\right)\left(\bar{\pi}^{\frac{1}{\omega}}-1\right)\right] \\ &+ \mathbb{E}_t\widehat{\psi}_{t+1}\beta\omega\left(1-\alpha\bar{\pi}^{\varepsilon-1}\right)\left(\bar{\pi}^{\frac{1}{\omega}}-1\right),\end{aligned} \tag{19}$$

where $\omega = \frac{\gamma}{\gamma+\varepsilon(1-\gamma)}$, $\hat{s}_t$ denotes the relative price distortion due to inefficient dispersion of prices given by equation (20), $\bar{\pi}$ denotes the trend inflation rate, $\widehat{\psi}_t$ is an auxiliary variable given by equation (21):

$$
\begin{aligned}
\hat{s}_t &= \alpha \frac{\varepsilon}{\gamma} \frac{\bar{\pi}^{\frac{\varepsilon}{\gamma}} - \bar{\pi}^{\varepsilon-1}}{1-\alpha\bar{\pi}^{\varepsilon-1}} \sum_{i=0}^{N} \left(\alpha\bar{\pi}^{\frac{\varepsilon}{\gamma}}\right)^i \widehat{\pi}_{t-i} + \left(\alpha\bar{\pi}^{\frac{\varepsilon}{\gamma}}\right)^{N+1} \hat{s}_{t-N-1}, \qquad (20) \\
\widehat{\psi}_t &= \left(1-\alpha\beta\bar{\pi}^{\frac{\varepsilon}{\gamma}}\right) \sum_{i=0}^{N} \left(\alpha\beta\bar{\pi}^{\frac{\varepsilon}{\gamma}}\right)^i \left[\widehat{ulc}_t - \hat{s}_t\right] \\
&\quad + \frac{\varepsilon}{\gamma} \sum_{i=1}^{N+1} \left(\alpha\beta\bar{\pi}^{\frac{\varepsilon}{\gamma}}\right)^i \mathbb{E}_t \widehat{\pi}_{t+i} + \left(\alpha\beta\bar{\pi}^{\frac{\varepsilon}{\gamma}}\right)^{N+1} \mathbb{E}_t \widehat{\psi}_{t+N+1}. \qquad (21)
\end{aligned}
$$

With zero steady state inflation the Phillips curve (19) returns to the conventional form with decreasing returns to scale in labor inputs (22), as $\hat{s}_t$ again does not affect the first-order dynamics:

$$
\hat{\pi}_t = \frac{(1-\alpha)(1-\alpha\beta)}{\alpha} \, \omega \, \widehat{ulc}_t + \mathbb{E}_t \beta \hat{\pi}_{t+1}. \qquad (22)
$$

The system of equilibrium conditions is given by equations (10), (11), (19) - (21) and is closed by the equation governing the evolution of the money stock.

3.3 Equilibrium conditions for the KDC model

As mentioned above, the conditions for the model variant with kinked demand curves are not derived separately since they are provided in Kurozumi and Zandweghe (2016).

As shown by Kurozumi and Zandweghe (2016), log-linearized equilibrium conditions including the generalized New Keynesian Phillips curve with trend inflation and KDC in terms of unit labor costs are given by

$$\hat{\pi}_t = \beta E_t \hat{\pi}_{t+1} + \omega \frac{(1-\alpha\bar{\pi}^{\rho-1})(1-\alpha\beta\bar{\pi}^{\rho})}{\alpha\bar{\pi}^{\rho-1}} \left(\widehat{ulc}_t - \frac{\bar{s}}{\bar{s}+\epsilon}\hat{s}_t\right) \\ - \frac{1}{\alpha\bar{\pi}^{\rho-1}}\left(\hat{d}_t - \alpha\beta\bar{\pi}^{\rho-1}E_t\hat{d}_{t+1}\right) + \hat{d}_{t-1} - \alpha\beta\bar{\pi}^{\rho-1}\hat{d}_t \\ - \frac{\rho(1-\alpha\bar{\pi}^{\rho-1})\left[\alpha\beta\bar{\pi}^{\rho-1}(\bar{\pi}-1)(\rho-1) + \tilde{\epsilon}(1-\alpha\beta\bar{\pi}^{\rho})\right]}{\alpha\bar{\pi}^{\rho-1}\left[\rho-1-\tilde{\epsilon}(\rho+1)\right]}\hat{d}_t + \hat{\phi}_t + \hat{\psi}_t, \tag{23}$$

$$\hat{s}_t = \alpha\bar{\pi}^{\rho}\hat{s}_{t-1} + \frac{(\bar{\pi}-1)\alpha\rho\bar{\pi}^{\rho-1}}{1-\alpha\bar{\pi}^{\rho-1}}\left(\hat{\pi}_t + \hat{d}_t - \hat{d}_{t-1}\right), \tag{24}$$

$$\hat{d}_t = \frac{\alpha\bar{\pi}^{-1}\left[1-\alpha\beta\bar{\pi}^{\rho-1} + \tilde{\epsilon}\bar{\pi}^{\rho}(1-\alpha\beta\bar{\pi}^{-1})\right]}{1-\alpha\beta\bar{\pi}^{\rho-1} + \tilde{\epsilon}(1-\alpha\beta\bar{\pi}^{-1})}\hat{d}_{t-1} \\ - \frac{\tilde{\epsilon}\alpha\bar{\pi}^{-1}(\bar{\pi}^{\rho}-1)(1-\alpha\beta\bar{\pi}^{-1})}{(1-\alpha\bar{\pi}^{-1})\left[1-\alpha\beta\bar{\pi}^{\rho-1} + \tilde{\epsilon}(1-\alpha\beta\bar{\pi}^{-1})\right]}\hat{\pi}_t, \tag{25}$$

$$\hat{\phi}_t = \alpha\beta\bar{\pi}^{\rho}E_t\hat{\phi}_{t+1} \\ + \frac{\beta(\bar{\pi}-1)(1-\alpha\bar{\pi}^{\rho-1})}{1-\frac{\tilde{\epsilon}\rho}{\rho-1-\tilde{\epsilon}}}\left[\rho E_t\hat{\pi}_{t+1} + (1-\alpha\beta\bar{\pi}^{\rho})\left(E_t\widehat{ulc}_{t+1} - \frac{\bar{s}}{\bar{s}+\epsilon}E_t\hat{s}_{t+1} + \rho E_t\hat{d}_{t+1}\right)\right], \tag{26}$$

$$\hat{\psi}_t = \alpha\beta\bar{\pi}^{-1}E_t\hat{\psi}_{t+1} + \frac{\tilde{\epsilon}\beta(\bar{\pi}^{\rho}-1)(1-\alpha\bar{\pi}^{\rho-1})}{\bar{\pi}^{\rho}\left[\rho-1-\tilde{\epsilon}(\rho+1)\right]}\hat{\pi}_{t+1}, \tag{27}$$

where $\rho = \varepsilon(1+\epsilon)$, $\tilde{\epsilon} = \frac{\epsilon\left(1-\alpha\beta\bar{\pi}^{\rho-1}\right)}{1-\alpha\beta\bar{\pi}^{-1}}\left[\frac{1-\alpha\bar{\pi}^{\rho-1}}{1-\alpha}\right]^{-\frac{\rho}{\rho-1}}$, $\omega = \frac{1}{1-\frac{\tilde{\epsilon}\rho}{\rho-1-\tilde{\epsilon}}}$, and the dispersion in the steady state is $\bar{s} = \frac{1-\alpha}{1-\alpha\bar{\pi}^{\rho}}\left[\frac{1-\alpha}{1-\alpha\bar{\pi}^{\rho-1}}\right]^{-\frac{\rho}{\rho-1}}$.

When considering zero steady state inflation, the Phillips curve (23) again reduces to the conventional version with the kinked-demand curve (28), as price dispersion variables $\hat{s}_t$ and $\hat{d}_t$ become zero:

$$\hat{\pi}_t = \frac{(1-\alpha)(1-\alpha\beta)}{\alpha}\,\omega\,\widehat{ulc}_t + \mathbb{E}_t\beta\hat{\pi}_{t+1}. \tag{28}$$

The system of equilibrium conditions is given by equations (10), (11), (23) - (27) and is closed by the equation governing the evolution of the money stock.

4 Empirical implementation

After deriving the log-linearized equilibrium conditions in the previous section, we now turn to our estimation procedure. Note that for each model variant we only estimate one parameter which governs the corresponding degree of real rigidity. To this end, we rely on the two-step econometric approach used by Sbordone (2002), Woodford (2001) or Dupor et al. (2010). In the first step, since the Phillips curve contains expectations about future unit labor costs and inflation rates, we estimate a small, unrestricted, bivariate VAR model as a way to generate the corresponding forecasts. We employ a quarterly calibration because data on unit labor costs is available only on a quarterly basis. In the second step, we use the Phillips curve for each model variant to obtain a model-implied quarterly inflation series. In particular, as in Woodford (2001) and Dupor et al. (2010)[8], the corresponding Phillips curves are iterated forward.[9]

Finally, the parameters governing the degree of real rigidity in each model variant, i.e. the inverse of the Frisch elasticity of labor supply φ in the SLM model, the concavity parameter of the production function γ in the DRL model, and the concavity parameter of the demand curve ϵ in the KDC model are estimated from the data by minimizing the variance of a distance between the models' inflation rates and the actual inflation.

Our targeted period is 1965Q1 - 2004Q4, i.e. 160 quarters, which includes the Great Inflation period. We also report results for the period of Great Moderation 1988Q1 - 2004Q4, i.e. 68 quarters. To obtain the model-implied inflation rate we must compute the price dispersion measure s, which is a weighted sum of past inflation rates. Therefore, we use earlier data from 1960Q1. For the VAR model we also use data from the sample period 1960Q1 - 2004Q4. The annualized average quarter-on-quarter inflation rate in this period is 1.04% or 4.2%.

[8] Sbordone (2002) transforms the standard NKPC into a closed-form solution for the logarithm of the price-unit labor cost ratio, taking nominal marginal cost growth as given.

[9] We use the fact that the elements of the infinite sums exponentially decrease and cut the sums after 20 periods. Our results are robust to the cut off period.

We would like to emphasize that the estimation approach used in this paper was initially used to estimate the degrees of price and information stickiness (Sbordone, 2002; Dupor et al., 2010). We use this method to estimate the degrees of real rigidities while calibrating the value of the Calvo parameter α externally.[10] Hereby, we rely on the microeconomic evidence about price adjustment and calibrate the probability of price changes externally. In particular, we follow Klenow and Kryvtsov (2008) who find that the average duration of prices is 2.9 quarters.[11] Therefore, we calibrate α such that $2.9 = \frac{1}{1-\alpha}$, which yields $\alpha = 0.6552$. In Appendix D.3 we conduct a detailed robustness analysis of sensitivity of our results to the choice of α.

The remaining two parameters are set to standard values in the literature. We set the discount factor β to 0.99 since we consider quarterly data. The elasticity of substitution between differentiated goods in the CES aggregator case is $\varepsilon = 11$, following Gertler and Leahy (2008).

To make statistical inference, we compute the confidence intervals for parameter estimates using a bootstrap method. In particular, in order to maintain the time-series data structure, we generate 20 subsamples of 80 quarters which is the half of the overall sample length and perform the estimation in the bootstrapped time samples. For the shorter sample we also generate 20 subsamples with 34 observations (half of the sample length). We report the 5% and the 95% percentile of the final distribution of the estimates.[12]

[10] Alternatively, one could also use the GMM method as in Galí and Gertler (1999) or Eichenbaum and Fisher (2007). We rely on the approach highlighted in Sbordone (2002) mainly due to its tractability since the parameters governing the degree of real rigidties do not occur only in the slope of the Philips curve as with zero trend inflation. This complicates the functional form of the Philips curve to be estimated.

[11] Klenow and Kryvtsov (2008) report this frequency for the period 1988-2004. We use this statistic also for our baseline sample 1965-2004 but perform rigorous robustness analysis. Our main results remain qualitatively the same. Also there is a significant heterogeneity in the frequency of price adjustment across industries and sectors, yet we restrict our attention to a single-sector model.

[12] The method used to compute the confidence bounds generates overlapping estimation periods. For robustness we have also computed the confidence bounds by splitting the overall sample into subsequent, not overlapping subperiods of, however, much shorter length. For the long sample we have split the sample into five subperiods á 32 observations and for the shorter sample into four subperiods á 17 periods. We find that the confidence bounds do not change much and are qualitatively robust to this modification.

5 Findings

5.1 Results for the sample period 1965-2004

In this section we report and discuss our estimation results for our targeted period from 1965 to 2004 which includes the Great Inflation period. In the subsequent section we report results for a shorter sample period of the Great Moderation from 1988 to 2004. For the sake of completeness, we distinguish between the scenarios with and without trend inflation. As a measure of empirical fit we report the root mean squared error.

As can be seen from Table 1, with zero trend inflation, all three sources of strategic complementarity in price setting imply the same degree of real rigidity and therefore the same slope of the short-run Phillips curve, i.e. the parameter on $\widehat{ulc}_t$ in the corresponding Phillips curve, of 0.023. All three estimates are significantly different from values implying no real rigidity. The same functional form of the Phillips curve in the absence of positive trend inflation implies that the empirical fit of all three model variants is identical.

Including positive trend inflation changes the results remarkably. We find that the slope of the Phillips curve declines with trend inflation, a result emphasized by Ascari (2004), Bakhshi et al. (2007) and Cogley and Sbordone (2008). In particular, with no real rigidity, the slope of the NKPC is 0.18, whereas with the level of trend inflation in this period the slope decreases to 0.10.

The statistics in Table 1 show that the best empirical fit is achieved with real rigidity via segmented labor markets and a value of the inverse of Frisch elasticity of labor supply of 0.78. Notably, the presence of trend inflation improves the empirical fit by 20% compared to the case without trend inflation. The empirical fit deteriorates for the other two sources of real rigidity.

Interestingly, this exercise shows that to achieve the best empirical fit in the KDC model, the kink in the demand curve should be abolished. This result suggests a challenge for the

	Trend	Segmented labor markets (1)	Decreasing returns to labor (2)	Kink demand curve (3)
Empirical fit	no	1.84	1.84	1.84
φ		0.65 [0.50, 2.10]	0	0
γ		1	0.61 [0.32, 0.66]	1
ϵ		0	0	-6.52 [-20.98, -5.04]
PC slope		0.023	0.023	0.023
Empirical fit	yes	1.48	1.95	2.29
φ		0.78 [0.76, 1.17]	0	0
γ		1	0.82 [0.79, 0.85]	1
ϵ		0	0	0.00 [-0.03, 0.00]
PC slope		0.008	0.028	0.103

Table 1: Empirical fit: 1965Q1-2004Q4

Notes: As a measure of empirical fit we employ RMSE multiplied by 1000. PC slope denotes the slope of the short-run Phillips curve, i.e. the parameter on current unit labor costs $\widehat{ulc}_t$ in the Phillips curve. Numbers in parentheses show the 90% confidence intervals.

kinked-demand curve approach which has been widely used in recent literature.[13] Notably, the slope of the Phillips curve in the KDC model with trend inflation increases, compared to the scenario with zero inflation in steady-state, since the degree of real rigidity due to KDC is zero.

Compared to the zero trend inflation case, with positive trend inflation only, the SLM model exhibits a flatter slope of the Phillips curve. Moreover, even though the empirical fit of the DRL model slightly deteriorates, it is still better than in the case with no real rigidities.[14]

[13] See e.g. Kurozumi and Zandweghe (2016) and (Lindé and Trabandt, 2018).

[14] This can be observed by comparing the KDC model results since due to the estimated zero kink in the demand curve the empirical fit of the KDC model corresponds to a model with positive trend inflation but no real rigidity.

Our estimates for parameters governing the particular types of real rigidity appear to be in line with values used in the literature. For the KDC approach, Kurozumi and Zandweghe (2016) use $\epsilon = -9$, Dotsey and King (2005) and Eichenbaum and Fisher (2007) employ $\epsilon = -10$ and $\epsilon = -33$. These values seem to be supported by our estimate for the case of zero trend inflation. In the DRL case, γ should be close to the labor share in aggregate income. Our estimates of $\gamma = 0.61$ for zero trend inflation and $\gamma = 0.82$ with positive trend inflation are consistent with this view. Finally, when considering the plausibility of our estimates for the degree of segmented labor markets, the crucial parameter φ is the inverse of the Frisch-elasticity of labor supply. Our estimates φ of 0.65 and 0.78 imply the Frisch-elasticities of 1.5 and 1.3, respectively. (Gertler and Leahy, 2008) argue that a Frisch-elasticity of 1 is a reasonable intermediate range value in the literature. Hence, our estimates are in line with values typically used in the literature.

Figure 1 visualizes the empirical fit of the considered sources of real rigidity.[15] The empirical fit of the SLM model markedly outperforms the other model variants at the time of the peak of the inflation rate in the late 70's and the beginning of the 80's. The KDC model appears to generate more upward deviations from the realized path of inflation than the other two models.

In the next section we focus on the period of the Great Moderation 1988-2004 which features a more stable path of quarterly inflation.

5.2 Results for the Great Moderation 1988 - 2004

In this section we provide the results for the period 1988Q1 - 2004Q4 (68 quarters). This period is also the main focus of Klenow and Kryvtsov (2008) who document that the frequency of price adjustment in this time span was on average 2.9 quarters. The VAR period begins five years earlier in 1983Q1.

[15] For visualization purposes Figure 1 shows smoothed time series using a centered moving average of four quarters. Underlying non-smoothed time series are plotted in Figure 6 in the appendix.

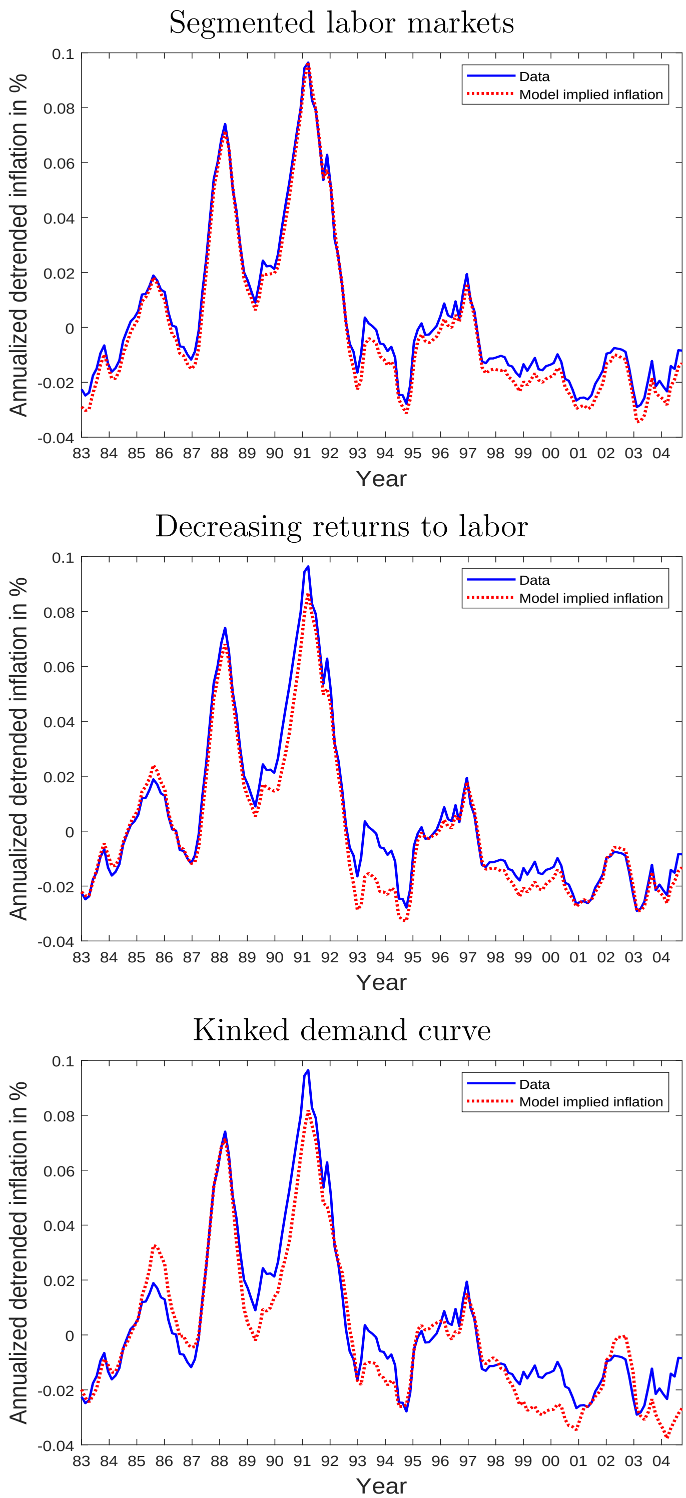

Figure 1: Realized and model-implied paths of inflation: 1965-2004

Notes: All time series are smoothed using a centered moving average of four quarters. The blue solid line represents the annualized de-trended inflation rate in the U.S. The red dotted line represents the inflation rate as implied by the GNKPC using the parameter governing the degree of real rigidity which minimizes the variance of deviations from the actual rate.

Table 2 shows that the result that SLM yield the best empirical fit is robust to the change of sample period. For the case without trend inflation, the degree of real rigidity which fits the data best is 0.04, i.e. three times as large as for the longer sample 1965-2004. Accordingly, the slope of the Phillips curve is further reduced from 0.02 to 0.008.

	Trend	Segmented labor markets (1)	Decreasing returns to labor (2)	Kink demand curve (3)
Empirical fit	no	2.09	2.09	2.09
φ		2.00 [0.49, 10]	0	0
γ		1	0.33 [0, 0.75]	1
ϵ		0	0	-20.00 [-35, -3.93]
PC slope		0.003	0.003	0.003
Empirical fit	yes	1.82	2.08	2.83
φ		3.31 [2.35, 3.71]	0	0
γ		1	0.58 [0.32, 0.61]	1
ϵ		0	0	-0.20 [-0.99, -0.33]
PC slope		0.001	0.012	0.110

Table 2: Empirical fit: 1988Q1-2004Q4

Notes: As a measure of empirical fit we employ RMSE multiplied by 1000. PC slope denotes the slope of the short-run Phillips curve, i.e. the parameter on current unit labor costs $\widehat{ulc}_t$ in the Phillips curve. Numbers in parentheses show the 90% confidence intervals.

Including trend inflation improves the empirical fit, not only of the SLM model variant but also of the DRL model. The fit worsens only in the KDC case. For the period of the Great Moderation we find evidence for a signficant kink in the demand curve, even though it is almost negligible. Our estimate of ϵ is -0.2, much smaller than the values assumed in the literature.[16] As for the longer sample including the Great Inflation period, the slope of the Phillips curve declines in comparison to the zero trend inflation case only in the SLM model. The DRL and the KDC model variants induce a rise of the slope. It is important to note that the slope in the DRL case is still far away from the slope without real rigidities (see again the KDC result).

Some thoughts concerning the plausibility of our estimates are in order. As discussed in the previous section, values of ϵ range up to -33, so our estimate in the zero trend inflation scenario of -20 is not an outlier. The estimate of γ of 0.33 with zero trend inflation appears to be rather low if thinking about it as a labor share of income. With positive trend inflation we estimate a more plausible value of 0.58. Finally, our estimates of φ are for the shorter sample larger than one. This implies values for the Frisch-elasticity of labor supply below one (0.5 and 0.3, respectively). These values appear to be more in line with microestimates of the Frisch-elasticity rather with values usually employed in macro studies (see Peterman (2014)). Yet by no means does our estimation procedure deliver values outside of the ranges seen in the literature.

Figure 2 visualizes the empirical fit of model-implied inflation rates to the realized path of inflation. The empirical fit is worse than for the longer sample, which follows from the performance of the VAR model for building expectations of unit labor costs and inflation.

[16] Note that the confidence interval reported in Table 2 does not include the estimate. This is because we use bootstrap confidence intervals which do not guarantee to include the actual estimate.

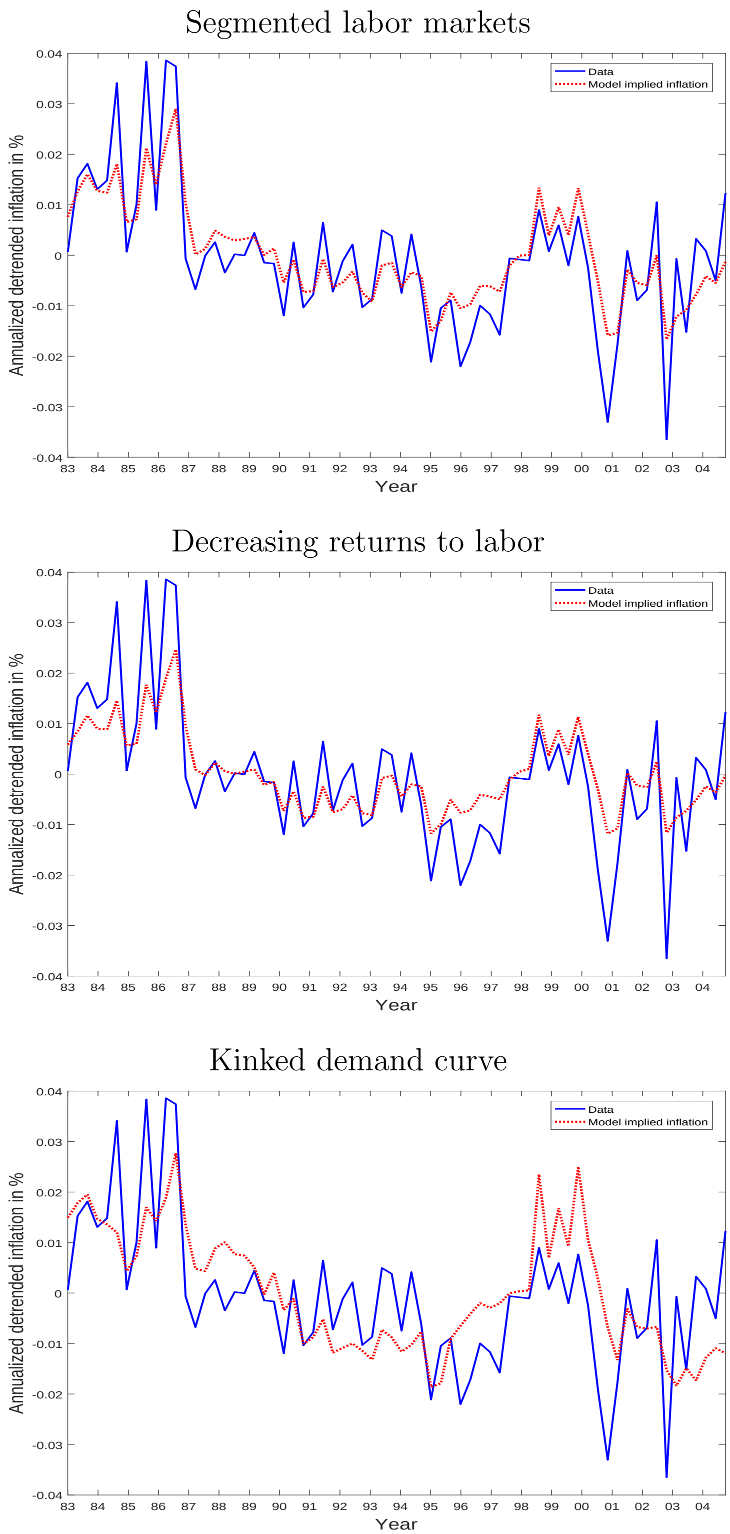

Figure 2: Realized and model-implied paths of inflation: 1988-2004

Notes: The blue solid line represents the annualized detrended inflation rate in the U.S. The red dotted line represents the inflation rate as implied by the GNKPC using the parameter governing the degree of real rigidity which minimizes the variance of deviations from the actual rate.

6 Implications for the real effects of monetary policy

A major purpose of estimating the degree of real rigidities is to understand their importance for amplifying the real effects of monetary policy. Therefore, in this section we assess the aggregate implications of considered real rigidities by studying the impulse responses for each model variant with levels of real rigidity inferred from the data. We show impulse responses for both the long and the short sample.

6.1 Impulse responses in the long sample

As can be seen from Figure 3 for the estimates in the longer sample including the Great Inflation, segmented labor markets and decreasing returns to labor inputs imply more persistent effects of monetary disturbances than the kinked demand curve. This result can be traced back to the estimated zero kink in the demand curve.

Noticeably, even though the nature of impulse responses for the SLM and DRS variants are almost identical, the response of the relative price distortion from the labor market clearing condition varies considerably. The relative price distortion is the wedge between aggregate labor input and aggregate output and represents the main reason for a lower output in the presence of trend inflation in steady-state.

The intuition for this result comes from equation (71) in the Appendix. The parameter γ enters the equation for price dispersion and increases the response of distortion to changes in the inflation rate. Because price dispersion is the main source of welfare costs of inflation in New Keynesian models (see Nakamura et al. (2018)), the source of real rigidity can have important implications for optimal monetary policy.

If we observe a similar response of output in both the SLM and the DRS model but the distortion behaves differently, it must be labor supply which explains the difference. This follows from the aggregate labor supply equation. As we can see in the bottom left panel

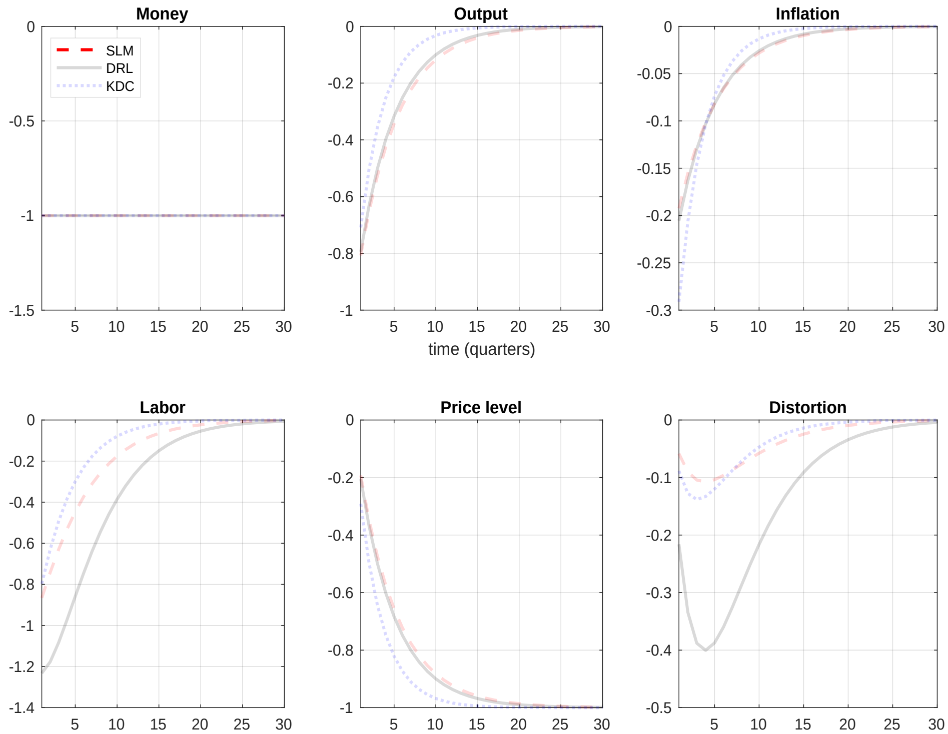

Figure 3: Impulse responses: 1965-2004

Notes: The shock is a permanent decrease of the nominal money stock by 1%. The vertical axis shows percentage points. Black solid line: fixed capital, i.e. decreasing returns to labor; red dashed line: segmented labor markets; blue dotted line: kinked demand curve. The panel at the right bottom shows the relative price distortion, i.e. the wedge between aggregate output and aggregate labor in the labor market clearing condition.

of Figure 3, the labor supply reacts much more strongly than in the other two models. This observation confirms the main motivation of this paper that distinguishing between sources of real rigidity matters. In addition, because the labor supply reacts so differently, it could be used as another criterion how to differentiate between real rigidities in the data by considering empirical impulse responses.

6.2 Impulse responses in the short sample

For the shorter sample 1988-2004, the results change considerably. Most importantly, as discussed in subsection 5.2, the estimated degrees of real rigidity increase compared to the longer sample period. In particular, while for the longer sample we estimate $\varphi = 0.78$, we obtain for the short sample $\varphi = 3.31$. However, as can be seen from subsection 6.2, the persistence of the response for the SLM case is as low as in the KDC model, while the estimate of the kink in the demand curve is only minor ($\epsilon = -0.2$ which is though significant but very low). The next section shows why the impulse responses to monetary shocks are not persistent despite strong degrees of rigidity inferred from the data.

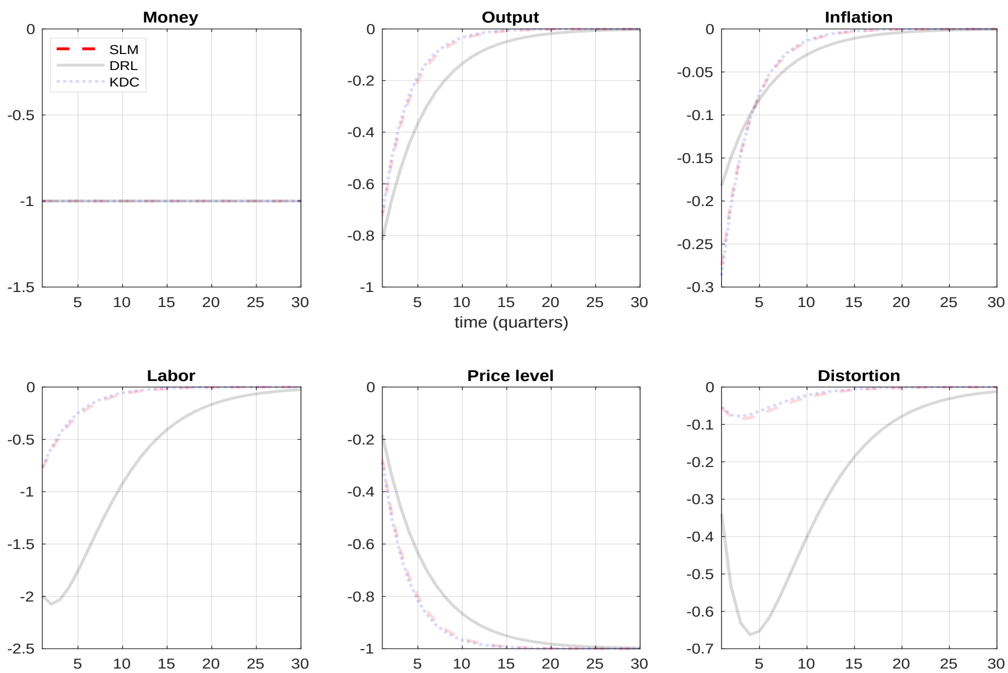

Figure 4: Impulse responses: 1988-2004

Notes: The shock is a permanent decrease of the nominal money stock by 1%. The vertical axis shows percentage points. The panel at the right bottom shows the relative price distortion, i.e. the wedge between aggregate output and aggregate labor in the labor market clearing condition.

6.3 Impact of positive trend inflation on the ability of real rigidities to prolong real effects of monetary policy

Despite strong firm-level real rigidities the impulse responses might not be more persistent than in a model without real rigidities. The intuition behind the result is based on the more pronounced forward-looking behavior of price-setters under positive trend inflation. We illustrate this observation in Figure 5 which shows the impulse responses of output (top line) and inflation (bottom line) for four cases: (1) no trend and no real rigidity, (2) no trend but real rigidity, (3) trend but no real rigidity and (4) trend and real rigidity.

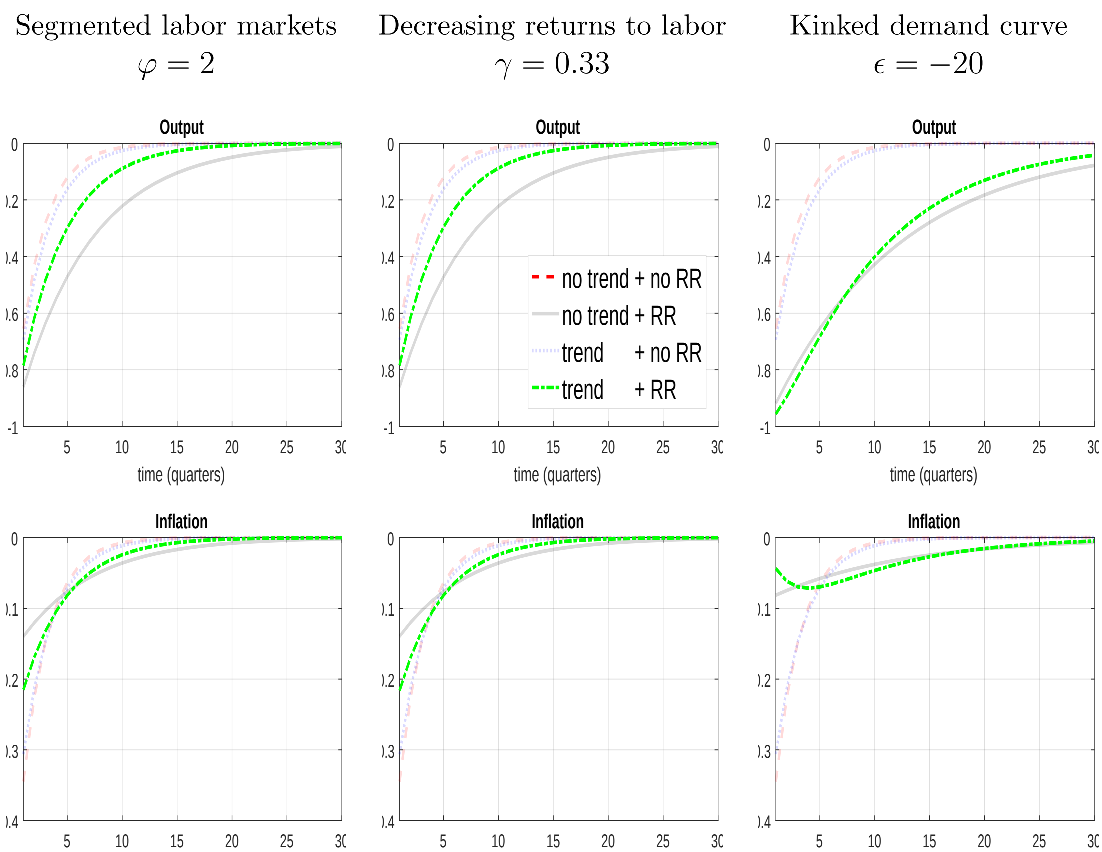

Figure 5: The effect of positive trend inflation on the persistence effect of real rigidities

Under SLM and DRS, positive trend inflation mitigates the long-lasting effect of the real rigidity, especially on the response of output. The reduction gets stronger the larger the real rigidity. However, the reponses in the KDC model are hardly affected. The intuition for this result is as follows. Firm-specific factors reduce the sensitivity of price setters to changes in the present value of future marginal costs. However, positive trend inflation increases the effective discount factor since price setters are more forward looking. This, in turn, increases the sensitivity of price setters to their cost structure and mutes the effect of real rigidities due to firm-specific input factors in prolonging the persistence of responses to shocks. This finding has important implications for modeling real effects of monetary policy since in the presence of trend inflation even strong levels of firm-level real rigidities can be too weak to generate much larger aggregate real effects from monetary shocks than a model without real rigidities.

The key is equation (66). If $\varphi > 0$ or $\gamma < 1$, i.e. for the case of real rigidity in the SLM and DRS case, respectively, the impact of future inflation expectations on current inflation increases. If in this equation the parameters φ and γ are set to 0 and 1, respectively, the impulse responses of inflation and output are much more persistent. Equation (66) represents the log-linearized form of the numerator in the optimal price equation (44) which represents the discounted expected future costs. Hence, SLM and DRS are real rigidities which affect the cost structure of price setters. With positive trend inflation, which increases discounted costs, price setters are going to react more vigorously to changes in their cost structure despite strong real rigidities. In contrast, the KDC does not affect firms' cost structure but firms' revenues if adjusting prices. Therefore, trend inflation does not mitigate its effect on optimal price setting.

It would be interesting to assess the responses of real variables to other types of shocks, such as technology and preference shocks, under different types of real rigidity. Presumably, in scenarios in which trend inflation influences the present value of future expected revenues trend inflation would interact with the KDC too.

7 Conclusion

This paper proposes a method to empirically distinguish between different sources of real rigidity. This is achieved by exploiting the observation that positive trend inflation in the log-linearized New-Keynesian model implies different first-order effects of various types of real rigidities. To estimate the parameter values governing the degrees of real rigidity we use the approach from Sbordone (2002) and Dupor et al. (2010). However, unlike these papers, we fix the level of nominal rigidity based on the empirical evidence and estimate the degrees of various real rigidities. We document that in terms of empirical fit segmented labor markets outperform the other two types of real rigidity.

Moreover, we show that the presence of positive trend inflation might mitigate the effect of real rigidity in enhancing the persistence of responses to monetary shocks in the presence of segmented labor markets and decreasing returns to scale. This is due to the effect of positive trend inflation increasing the present value of future costs which offsets the impact of firm-specific inputs to react less strongly to changes in costs.

An interesting avenue for further research could be to consider non-linear versions of the Phillips curve, as e.g. emphasized recently by Lindé and Trabandt (2018) for the KDC approach. This modification would stress the importance of non-linearities in price setting. Moreover, to further examine robustness and plausibility of our results it would be interesting to include backward-looking components in the GNKPC as highlighted by Eichenbaum and Fisher (2007) or, as pointed out by Coibion (2010), a different way of building expectations such as out-of-sample forecasts and adaptive expectations or different measures of expectations such as expectations of professional forecasters. Furthermore, the analysis in this paper could be broadened to encompass additional types of real rigidities, especially sticky intermediate prices.[17] Another interesting question would be to analyze the impact of real rigidites on the responses to other types of shocks such as preference shocks or TFP shocks.

Exploring the sectoral heterogeneity of real rigidities such as in Carvalho and Nechio (2016) could also provide additional insights into how to calibrate the strategic complementarities in price setting. Finally, it would also be interesting to analyze the business cycle properties of real rigidities. It sounds plausible to assume that the degree of real rigidity due to the

[17] Ball and Romer (1990) and Klenow and Willis (2016) emphasize the distinction between so-called macro and micro rigidities. All three sources of real rigidity in this paper belong to the micro category since they make price-setters less willing to move their relative prices. Macro rigidities such sticky intermediate prices or sticky real wages introduce a sticky component to the cost of all firms and do not make firms less willing to change their relative prices.

elasticity of labor supply or capital adjustment costs as discussed in this paper can change over the business cycle. This would be useful for understanding the effectiveness of monetary policy in times of booms and busts.

D Appendix

D.1 Non-smoothed quarterly figure - long sample

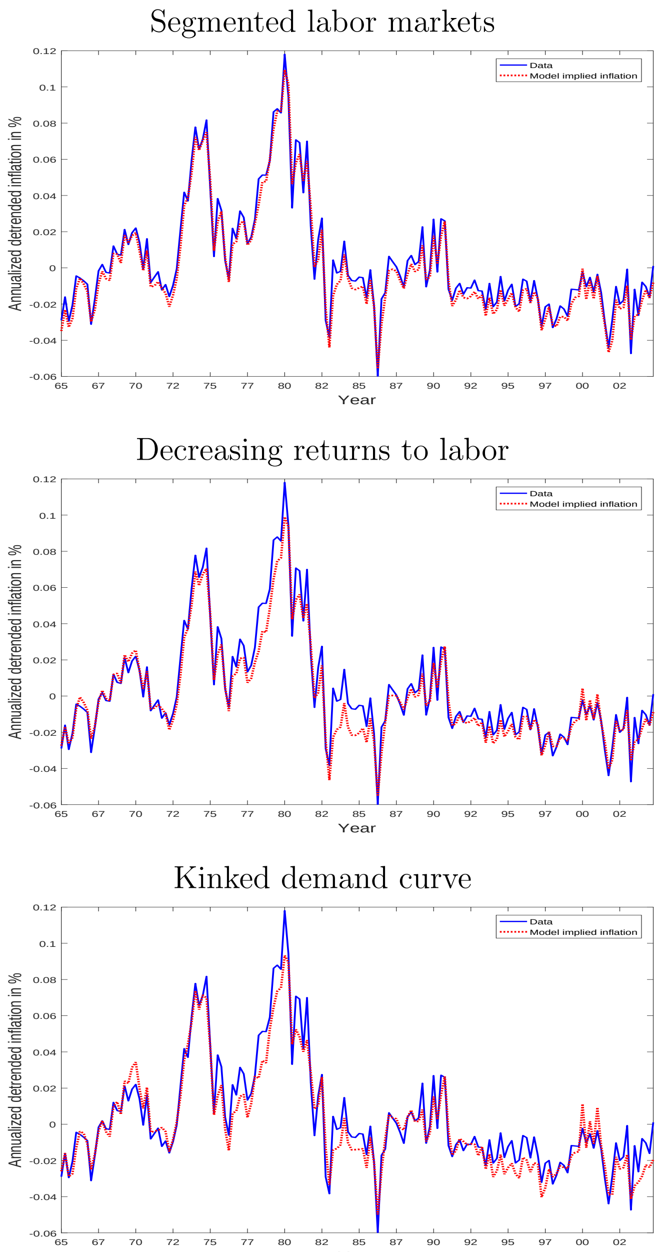

Figure 6: Non-smoothed realized and model-implied paths of inflation: 1965-2004

Notes: The blue solid line represents the annualized de-trended inflation rate in the U.S. The red dotted line represents the inflation rate as implied by the GNKPC using the parameter governing the degree of real rigidity which minimizes the variance of deviations from the actual rate.

D.2 Households' Optimality Conditions

In this section, we state the first-order conditions that describe the optimal behavior of households.

D.2.1 SLM model

Minimizing costs for a given size of the consumption basket C_t yields the demand function

$$C_{z,t}^j = \left(\frac{Q_{z,t}^j}{P_t} \right)^{-\varepsilon} C_t, \tag{29}$$

where the aggregate price level P_t is given by

$$P_t = \left[\int_0^1 (Q_{z,t}^j)^{1-\varepsilon} dz \right]^{\frac{1}{1-\varepsilon}}. \tag{30}$$

The household's utility maximization problem results in the following standard conditions:

$$\begin{aligned} \frac{W_{z,t}}{P_t} &= N_{z,t}^{\varphi} C_t, & (31) \\ \mathbb{E}_t \left[\beta \frac{C_t}{C_{t+1}} R_t^n \frac{P_t}{P_{t+1}} \right] &= 1, & (32) \\ \frac{M_t}{P_t} &= \nu C_t \frac{R_t^n}{R_t^n - 1}. & (33) \end{aligned}$$

□

D.2.2 DRL model

Minimizing costs for a given size of the consumption basket C_t yields the demand function

$$C_t^j = \left(\frac{Q_t^j}{P_t} \right)^{-\varepsilon} C_t, \tag{34}$$

where the aggregate price level P_t is given by

$$P_t = \left[\int_0^1 (Q_t^j)^{1-\varepsilon} dz\right]^{\frac{1}{1-\varepsilon}}. \tag{35}$$

The household's utility maximization problem results in the following standard conditions:

$$\frac{W_t}{P_t} = N_t^{\varphi} C_t, \tag{36}$$

$$\mathbb{E}_t \left[\beta \frac{C_t}{C_{t+1}} R_t^n \frac{P_t}{P_{t+1}}\right] = 1, \tag{37}$$

$$\frac{M_t}{P_t} = \nu C_t \frac{R_t^n}{R_t^n - 1}. \tag{38}$$

□

D.2.3 Deriving the Phillips curve

In this section we derive the New Keynesian Phillips curve under Calvo pricing with trend inflation and with two sources of real rigidity: decreasing returns to scale in labor inputs and segmented labor markets. Note that in the main article we have for exposition and clarity purposes strictly distinguished between these two sources of real rigidity. However, the way how we model them is not mutually exclusive such that these two sources of real rigidity can be easily nested in one model. Unfortunately this is not the case for the kinked-demand curve with trend inflation which cannot be easily introduced into the same model. The reason is that the model would not only lose its tractability but is not analytically solvable. To stay parsimonious, for notation details refer to the model description in the main article.

Profit optimization and price setting The production function of goods producers on island z is of the form

$$Y_{z,t}^j = \left(N_{z,t}^j\right)^{\gamma} \tag{39}$$

with $\gamma \in (0,1]$ and their real profit function $\forall\, t \geq 0$ is given by

$$\Pi^j_{z,t} = \frac{Q^j_{z,t}}{P_t} Y_{z,t} - \frac{W_{z,t}}{P_t} N^j_{z,t}. \tag{40}$$

Goods producers are subject to stickiness à la Calvo (1983), i.e. they can change their prices only with probability $1-\alpha$ in every period. Hence, the producer's optimization problem on island z is given by

$$\max_{Q^j_{z,t}} \quad \mathbb{E}_t \quad \sum_{i=0}^{\infty} \Lambda_{t,t+i} \alpha^i \left[\left(\frac{Q^j_{z,t}}{P_{t+i}} \right)^{1-\varepsilon} Y_{t+i} - \frac{W_{z,t+i}}{P_{t+i}} \left(\frac{Q^j_{z,t}}{P_{t+i}} \right)^{-\frac{\varepsilon}{\gamma}} Y_{t+i}^{\frac{1}{\gamma}} \right], \tag{41}$$

where $\Lambda_{t,t+i} = \beta^i \frac{U'(C_{t+i})}{U'(C_t)} = \beta^i \frac{C_t}{C_{t+i}}$ denotes the stochastic discount factor between periods t and $t+i$ and where we have used the household's demand for good j given by $Y_{z,t+i} = \left(\frac{Q_{z,tj}}{P_{t+i}} \right)^{-\varepsilon} Y_{t+i}$.

Computing the first order condition with respect to the individual price Q_{z,t^j}, using $C_{t+i} = Y_{t+i}\ \forall i \geq 0$, and simplifying, results in the following equation for the average optimal price on island z in period t, $Q^*_{z,t}$,

$$\left(Q^*_{z,t}\right)^{\frac{\gamma+\varepsilon(1-\gamma)}{\gamma}} = \frac{\varepsilon}{(\varepsilon-1)\gamma} \frac{\mathbb{E}_t \sum_{i=0}^{\infty} (\alpha\beta)^i \frac{W_{z,t+i}}{P_{t+i}} Y_{t+i}^{\frac{1-\gamma}{\gamma}} P_{t+i}^{\frac{\varepsilon}{\gamma}}}{\mathbb{E}_t \sum_{i=0}^{\infty} (\alpha\beta)^i P_{t+i}^{\varepsilon-1}}. \tag{42}$$

Note that $Q^*_{z,t}$ depends on the island specific wage $W_{z,t}$. For aggregation purposes we would like to replace the island specific wage by an aggregate variable to be able to use the aggregate data on unit labor costs. To this end we combine the household's labor supply condition, the production function equation (39) and the households' demand equation

$$\frac{W_{z,t}}{P_t} = N^{\varphi}_{z,t} Y_t = Y_{z,t}^{\frac{\varphi}{\gamma}} Y_t = \left[\left(\frac{Q_{z,t}}{P_t} \right)^{-\varepsilon} Y_t \right]^{\frac{\varphi}{\gamma}} Y_t = \left(\frac{Q_{z,t}}{P_t} \right)^{-\frac{\varepsilon\varphi}{\gamma}} Y_t^{1+\frac{\varphi}{\gamma}}. \tag{43}$$

We plug this expression into equation (42) and receive

$$\left(Q_{z,t}^{*}\right)^{\frac{1}{\omega}} = \frac{\varepsilon}{(\varepsilon-1)\gamma}\frac{\mathbb{E}_t \sum_{i=0}^{\infty} (\alpha\beta)^i Y_{t+i}^{\frac{1+\varphi}{\gamma}} P_{t+i}^{\frac{\varepsilon(1+\varphi)}{\gamma}}}{\mathbb{E}_t \sum_{i=0}^{\infty} (\alpha\beta)^i P_{t+i}^{\varepsilon-1}}, \tag{44}$$

where $\omega = \frac{\gamma}{\gamma+\varepsilon(1+\varphi-\gamma)}$.

We divide equation (42) by $P_t^{\frac{1}{\omega}}$ and simplify to get

$$\kappa_{z,t}^{\frac{1}{\omega}} := \left(\frac{Q_{z,t}^{*}}{P_t}\right)^{\frac{1}{\omega}} = \frac{\varepsilon}{(\varepsilon-1)\gamma}\frac{\psi_t}{\phi_t}, \tag{45}$$

where

$$\psi_t \equiv \mathbb{E}_t \sum_{i=0}^{\infty} (\alpha\beta)^i Y_{t+i}^{\frac{1+\varphi}{\gamma}} \pi_{t,t+i}^{\frac{\varepsilon(1+\varphi)}{\gamma}}, \tag{46}$$

$$\phi_t \equiv \mathbb{E}_t \sum_{i=0}^{\infty} (\alpha\beta)^i \pi_{t,t+i}^{\varepsilon-1}. \tag{47}$$

In the equations above $\pi_{t,t+i}$ denotes the inflation between periods t and $t+i$. Note that equation (46) and equation (47) can be rewritten recursively as

$$\psi_t = Y_t^{\frac{1+\varphi}{\gamma}} + \alpha\beta\mathbb{E}_t\left[\pi_{t+1}^{\frac{\varepsilon(1+\varphi)}{\gamma}}\psi_{t+1}\right], \tag{48}$$

$$\phi_t = 1 + \alpha\beta\mathbb{E}_t\left[\pi_{t+1}^{\epsilon-1}\phi_{t+1}\right]. \tag{49}$$

Price level, aggregation and price dispersion Upon Calvo pricing, the price level given by equation (35) evolves according to

$$P_t = \left[\alpha P_{t-1}^{1-\varepsilon} + (1-\alpha)\left(Q_{z,t}^{*}\right)^{1-\varepsilon}\right]^{\frac{1}{1-\varepsilon}} \tag{50}$$

where we use the fact that the average price on an island will be the same on all islands which have been hit by a Calvo shock.

Dividing equation (50) by P_t and defining $\pi_t = P_t/P_{t-1}$ yields

$$1 = \left[\left(\alpha P_{t-1}^{1-\varepsilon} + (1-\alpha)\left(Q_{z,t}^{*}\right)^{1-\varepsilon}\right) P_t^{-(1-\varepsilon)}\right]^{\frac{1}{1-\varepsilon}}, \tag{51}$$

$$1 = \alpha \pi_t^{\varepsilon-1} + (1-\alpha)\left(\frac{Q_{z,t}^{*}}{P_t}\right)^{1-\varepsilon}, \tag{52}$$

$$\kappa_{z,t} = \frac{Q_{z,t}^{*}}{P_t} = \left[\frac{1-\alpha\pi_t^{\varepsilon-1}}{(1-\alpha)}\right]^{\frac{1}{1-\varepsilon}}. \tag{53}$$

Price dispersion Labor demand of firm on island z in period t is derived from its production function and is given by

$$N_{z,t} = \left(Y_{z,t}\right)^{\frac{1}{\gamma}}. \tag{54}$$

The aggregate labor demand is then given by

$$N_t = \int_0^1 N_{z,t} dz = \int_0^1 Y_{z,t}^{\frac{1}{\gamma}} dz = Y_t^{\frac{1}{\gamma}} \underbrace{\int_0^1 \left(\frac{Q_{z,t}}{P_t}\right)^{-\frac{\varepsilon}{\gamma}} dz}_{s_t}, \tag{55}$$

where s_t denotes the resource costs due to inefficient price dispersion in the economy.

Under the assumption of Calvo pricing, we can rewrite s_t as follows:

$$\begin{aligned} s_t =& (1-\alpha)\left(\frac{Q_{z,t}}{P_t}\right)^{-\frac{\varepsilon}{\gamma}} + \alpha(1-\alpha)\left(\frac{Q_{z,t-1}}{P_t}\right)^{-\frac{\varepsilon}{\gamma}} \\ & + \alpha^2(1-\alpha)\left(\frac{Q_{z,t-2}}{P_t}\right)^{-\frac{\varepsilon}{\gamma}} + \ldots \end{aligned} \tag{56}$$

Now by expanding all terms by $(P_{t-1}/P_{t-1})^{\frac{\varepsilon}{\gamma}}$ and by collecting the terms, we end up with a recursive formulation of s_t:

$$s_t = (1-\alpha)\left(\frac{Q_{z,t}}{P_t}\right)^{-\frac{\varepsilon}{\gamma}} + \alpha\pi_t^{\frac{\varepsilon}{\gamma}}\left[(1-\alpha)\left(\frac{Q_{z,t-1}}{P_{t-1}}\right)^{-\frac{\varepsilon}{\gamma}} + \alpha(1-\alpha)\left(\frac{Q_{z,t-2}}{P_{t-1}}\right)^{-\frac{\varepsilon}{\gamma}} + \dots\right], \tag{57}$$

$$= (1-\alpha)\left(\frac{Q_{z,t}}{P_t}\right)^{-\frac{\varepsilon}{\gamma}} + \alpha\pi_t^{\frac{\varepsilon}{\gamma}} s_{t-1}. \tag{58}$$

Unit labor costs Economy-wide unit labor costs are given by

$$ulc_t = \frac{W_t N_t}{P_t Y_t} = \frac{W_t}{P_t} Y_t^{\frac{1-\gamma}{\gamma}} s_t, \tag{59}$$

where we have used equation (55).

D.2.4 Log-linearization

In what follows, lowercase letters represent the log levels of variables and variables with a "hat" stand for relative deviations from their steady state values.

Log-linearizing equation (45) yields

$$\frac{1}{\omega}\hat{\kappa}_{z,t} = \hat{\psi}_t - \hat{\phi}_t. \tag{60}$$

Log-linearizing equation (48) yields

$$\hat{\psi}_t = \left(1 - \alpha\beta\bar{\pi}^{\frac{\varepsilon(1+\varphi)}{\gamma}}\right)\frac{1+\varphi}{\gamma}\hat{Y}_t + \alpha\beta\bar{\pi}^{\frac{\varepsilon(1+\varphi)}{\gamma}}\left(\frac{\varepsilon(1+\varphi)}{\gamma}\mathbb{E}_t\hat{\pi}_{t+1} + \mathbb{E}_t\hat{\psi}_{t+1}\right). \tag{61}$$

Log-linearizing equation (59) and yields

$$\widehat{ulc}_t = \widehat{\left(\frac{W_t}{P_t}\right)} + \frac{1-\gamma}{\gamma}\hat{Y}_t + \hat{s}_t. \tag{62}$$

Next, taking the labor supply equation (43), aggregating and taking difference yields

$$\widehat{\left(\frac{W_{z,t}}{P_t}\right)} - \widehat{\left(\frac{W_t}{P_t}\right)} = -\frac{\varepsilon\varphi}{\gamma}\hat{\kappa}_{z,t} - \varphi\hat{s}_t. \tag{63}$$

Note that the labor supply equation can be rewritten to

$$\widehat{\left(\frac{W_{z,t}}{P_t}\right)} + \frac{\varepsilon\varphi}{\gamma}\hat{\kappa}_{z,t} = \left(1 + \frac{\varphi}{\gamma}\right)\hat{Y}_t. \tag{64}$$

Using equation (63) and equation (64) to simplify equation (62) yields

$$\widehat{ulc}_t = \frac{1+\varphi}{\gamma}\hat{Y}_t + (1+\varphi)\hat{s}_t. \tag{65}$$

This expression can be used to rewrite equation (61) as

$$\begin{aligned}\hat{\psi}_t = &\left(1 - \alpha\beta\bar{\pi}^{\frac{\varepsilon(1+\varphi)}{\gamma}}\right)\left[\widehat{ulc}_t - (1+\varphi)\hat{s}_t\right] \\ &+ \alpha\beta\bar{\pi}^{\frac{\varepsilon(1+\varphi)}{\gamma}}\left[\frac{\varepsilon(1+\varphi)}{\gamma}\mathbb{E}_t\hat{\pi}_{t+1} + \mathbb{E}_t\hat{\psi}_{t+1}\right].\end{aligned} \tag{66}$$

Log-linearizing equation (49) yields

$$\hat{\phi}_t = \alpha\beta\bar{\pi}^{\varepsilon-1}\left(\mathbb{E}_t\hat{\phi}_{t+1} + (\varepsilon-1)\mathbb{E}_t\hat{\pi}_{t+1}\right). \tag{67}$$

Log-linearizing equation (53) yields

$$\hat{\kappa}_{z,t} = \frac{\alpha\pi^{\varepsilon-1}}{1-\alpha\pi^{\varepsilon-1}}\hat{\pi}_t. \tag{68}$$

Substituting equation (68) into equation (60) and solving for $\hat{\phi}_t$ yields

$$\hat{\phi}_t = \hat{\psi}_t - \frac{1}{\omega}\frac{\alpha\bar{\pi}^{\varepsilon-1}}{1-\alpha\bar{\pi}^{\varepsilon-1}}\hat{\pi}_t. \tag{69}$$

Using this equation to replace $\hat{\phi}_t$ and $\hat{\phi}_{t+1}$ in equation (67) leads to

$$\begin{aligned}\hat{\psi}_t = &\frac{1}{\omega}\frac{\alpha\bar{\pi}^{\varepsilon-1}}{1-\alpha\bar{\pi}^{\varepsilon-1}}\hat{\pi}_t + \alpha\beta\bar{\pi}^{\varepsilon-1}(\varepsilon-1)\mathbb{E}_t\hat{\pi}_{t+1} \\ &+ \alpha\beta\bar{\pi}^{\varepsilon-1}\left[\mathbb{E}_t\hat{\psi}_{t+1} - \frac{1}{\omega}\frac{\alpha\bar{\pi}^{\varepsilon-1}}{1-\alpha\bar{\pi}^{\varepsilon-1}}\mathbb{E}_t\hat{\pi}_{t+1}\right].\end{aligned} \tag{70}$$

Price dispersion Log-linearizing equation (58) yields:

$$\hat{s}_t = \alpha\frac{\varepsilon}{\gamma}\frac{\bar{\pi}^{\frac{\varepsilon}{\gamma}} - \bar{\pi}^{\varepsilon-1}}{1-\alpha\bar{\pi}^{\varepsilon-1}}\hat{\pi}_t + \alpha\bar{\pi}^{\frac{\varepsilon}{\gamma}}\hat{s}_{t-1}, \tag{71}$$

where we have used equation (68).

GNKPC Equation (66) and equation (70) can be combined to derive the generalized New Keynesian Phillips curve with trend inflation in terms of unit labor costs

$$\begin{aligned}\hat{\pi}_t = &\,\omega\left[\frac{\left(1-\alpha\bar{\pi}^{\varepsilon-1}\right)\left(1-\alpha\beta\bar{\pi}^{\frac{\varepsilon(1+\varphi)}{\gamma}}\right)}{\alpha\bar{\pi}^{\varepsilon-1}}\right]\left[\widehat{ulc}_t - (1+\varphi)\hat{s}_t\right] \\ &+ \mathbb{E}_t\widehat{\pi}_{t+1}\beta\left[1 + \frac{\varepsilon(1+\varphi)}{\gamma+\varepsilon(1+\varphi-\gamma)}\left(1-\alpha\bar{\pi}^{\varepsilon-1}\right)\left(\bar{\pi}^{\frac{1}{\omega}}-1\right)\right] \\ &+ \mathbb{E}_t\widehat{\psi}_{t+1}\beta\omega\left(1-\alpha\bar{\pi}^{\varepsilon-1}\right)\left(\bar{\pi}^{\frac{1}{\omega}}-1\right),\end{aligned} \tag{72}$$

where $\widehat{\psi}_t$ is given by equation (66).

If the steady state inflation equals zero, i.e. $\bar{\pi} - 1 = 0$, the Phillips curve (72) reduces to the conventional NKPC with segmented labor markets and decreasing returns to scale in labor inputs, as $\hat{s}_t$ does not affect the first order dynamics

$$\hat{\pi}_t = \frac{(1-\alpha)(1-\alpha\beta)}{\alpha}\,\omega\,\widehat{ulc}_t + \mathbb{E}_t\beta\hat{\pi}_{t+1}. \tag{73}$$

Forward and backward iterations for estimation purposes Iterating forward equation (66) yields

$$\begin{aligned}\widehat{\psi}_t = & \left(1-\alpha\beta\bar{\pi}^{\frac{\varepsilon(1+\varphi)}{\gamma}}\right)\sum_{i=0}^{N}\left(\alpha\beta\bar{\pi}^{\frac{\varepsilon(1+\varphi)}{\gamma}}\right)^i\left[\widehat{ulc}_t-(1+\varphi)\hat{s}_t\right] \\ & +\frac{\varepsilon}{\gamma}\sum_{i=1}^{N+1}\left(\alpha\beta\bar{\pi}^{\frac{\varepsilon(1+\varphi)}{\gamma}}\right)^i\mathbb{E}_t\widehat{\pi}_{t+i} \\ & +\left(\alpha\beta\bar{\pi}^{\frac{\varepsilon(1+\varphi)}{\gamma}}\right)^{N+1}\mathbb{E}_t\widehat{\psi}_{t+N+1}. \end{aligned} \tag{74}$$

Iterating forward equation (67) yields

$$\widehat{\phi}_t = (\varepsilon-1)\sum_{i=1}^{N}\left(\alpha\beta\bar{\pi}^{\varepsilon-1}\right)^i\,\mathbb{E}_t\widehat{\pi}_{t+i}+\left(\alpha\beta\bar{\pi}^{\varepsilon-1}\right)^N\mathbb{E}_t\widehat{\psi}_{t+N}. \tag{75}$$

Iterating forward equation (71) yields

$$\hat{s}_t = \alpha\frac{\varepsilon}{\gamma}\frac{\bar{\pi}^{\frac{\varepsilon}{\gamma}}-\bar{\pi}^{\varepsilon-1}}{1-\alpha\bar{\pi}^{\varepsilon-1}}\sum_{i=0}^{N}\left(\alpha\bar{\pi}^{\frac{\varepsilon}{\gamma}}\right)^i\widehat{\pi}_{t-i}+\left(\alpha\bar{\pi}^{\frac{\varepsilon}{\gamma}}\right)^{N+1}\hat{s}_{t-N-1}. \tag{76}$$

D.3 Sensitivity to the value of the Calvo parameter

One of the main goals of this paper is to estimate the degree of different types of real rigidity, using the aggregate inflation dynamics. We rely on the approach in Sbordone (2002) and Dupor et al. (2010). However, unlike these papers, we do not fix the degree of real rigidity and estimate the level of nominal rigidity. We rather keep the level of nominal rigidity constant and estimate the degree of real rigidity. In this section we discuss the implications of imposing the degree of nominal rigidity for our results.

D.3.1 No trend inflation

First, we estimate the degree of real rigidity for different levels of nominal rigidity when the trend inflation is zero. Parameter estimates and confidence bounds are shown in Figure 7.[18] We denote the degree of real rigidity by λ. Figure 7 shows that the estimated degrees of real rigidity vary markedly with the imposed levels of nominal rigidity in a non-linear way.

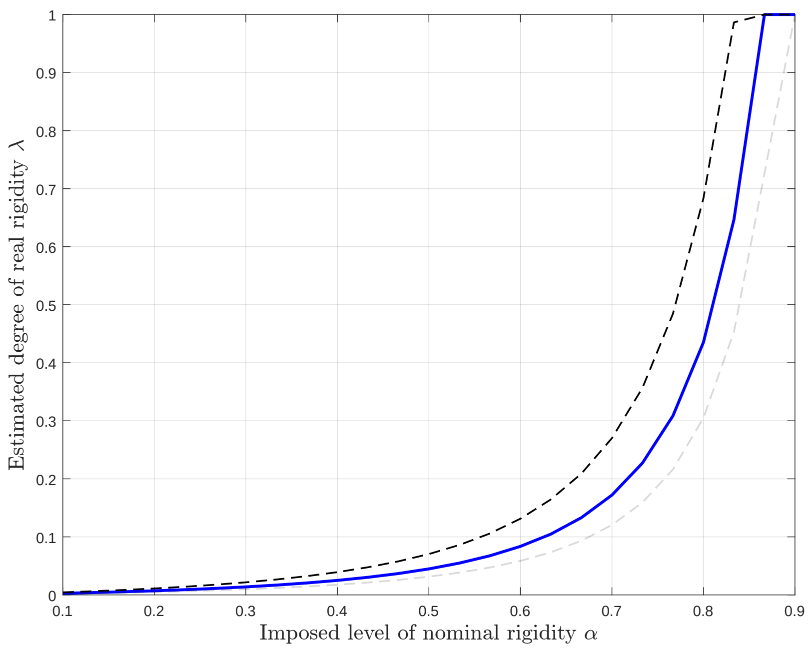

Figure 7: Estimated degrees of real rigidity, conditional on the level of nominal rigidity

Notes: Recall that λ is defined as the inverse of the degree of real rigidity meaning that smaller values of λ imply stronger degrees of real rigidity.

The intuition for these results is straightforward. The data imply a small and positive link between inflation and the output gap. This can be seen in Table 1 and Table 2 which show the empirical slopes of the Phillips curve. For high degrees of nominal rigidity it is not necessary to assume high degrees of real rigidity to generate a flat Phillips curve. However, when the imposed level of nominal rigidity is low, which implies more flexible prices, the empirical evidence on the persistence of real effects of monetary policy requires high degrees

[18] Similar figure can be found in Coibion (2010) who is however considering the sticky information parameter.

of real rigidity, i.e. low values of λ.

For our baseline value of $\alpha \approx 0.66$, we obtained a degree of real rigidity of 0.12 and a slope of Phillips curve of 0.023. Woodford (2003) argues that plausible values of λ are between 0.10 and 0.15 (see also (Coibion, 2010)). According to our estimates, a value of λ of 0.1 implies $\alpha = 0.63$ and a λ of 0.15 implies $\alpha = 0.67$ which is close to our baseline calibration.

D.3.2 Trend inflation

For the case of positive trend inflation we report the degrees of real rigidity for the SLM scenario since this model variant implies the best empirical fit. In the SLM model $\lambda = \frac{1}{1+\varphi\varepsilon}$. As can be seen from Figure 8, the relationship between the degree of nominal and real rigidity changes with positive trend inflation. In particular, the previously found negative monotonic relationship, which implies lower degrees of real rigidity if the level of nominal rigidity increases, now partly breaks down.

For a high level of nominal rigidity, i.e. α close to 1, the required values of λ do not approach 1 as in the case of zero trend inflation. It follows that the substitutability between nominal and real rigidities in keeping the slope of the NKPC low breaks down. The empirical fit is much better than with zero trend inflation even if, in the case of high degrees of nominal rigidity, the parameter λ remains low.

D.4 Magnitude of idiosyncratic shocks

Klenow and Willis (2016) argue that micro rigidities (KDC) necessitate implausible large idiosyncratic productivity shocks in comparison to macro rigidities (sticky intermediate prices) to match individual price dynamics from the U.S. CPI.

In our analysis we examine three types of micro rigidities but in the following we show, that the argument of Klenow and Willis (2016) holds also within the category of micro rigidities. In particular, we show that the estimated results imply that the magnitude of idiosyncratic

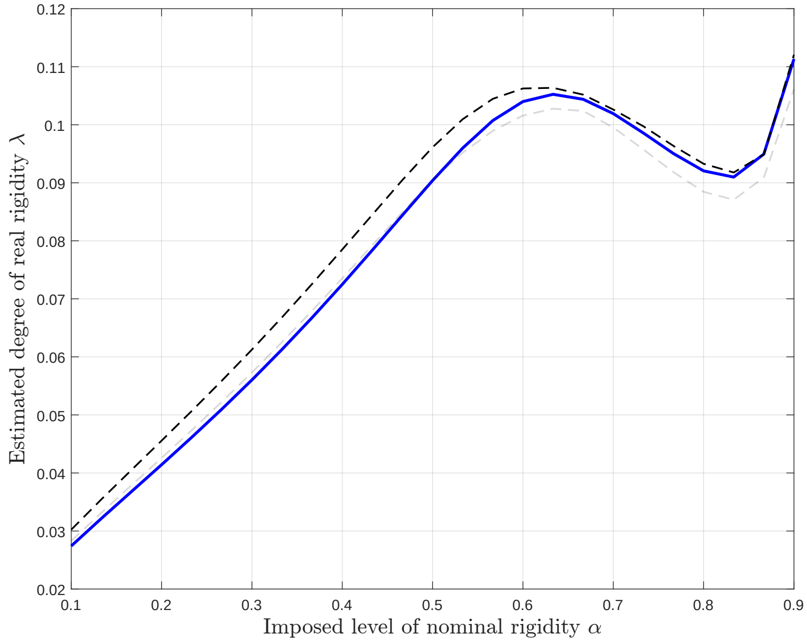

Figure 8: Estimated degrees of real rigidity with positive trend inflation, conditional on the level of nominal rigidity

Notes: Recall that λ is defined as the inverse of the degree of real rigidity meaning that smaller values of λ imply stronger degrees of real rigidity.

productivity shocks must be five times larger in the variant with decreasing returns to scale than in the model variant with segmented labor markets.

To this end we introduce idiosyncratic productivity shocks as in Gertler and Leahy (2008). The economy is populated by a continuum of monopolistically competitive goods producers, indexed by $j \in [0, 1]$. Each firm j produces the individual good j and sells it directly to consumers. The production function is of the form

$$Y_{j,t} = X_{j,t} N_{j,t}^{\gamma}, \tag{77}$$

with $\gamma \in (0, 1]$ and where $X_{j,t}$ is an idiosyncratic productivity level and $N_{j,t}$ is the labor input of firm j at time t. For $\gamma < 1$, there are decreasing returns to scale, which could also be interpreted as the production function being of the Cobb-Douglas type but with fixed capital.

In every period, each firm j is hit by a productivity disturbance with probability $1 - \alpha$. When this happens, the firm survives with probability τ. For surviving firms, productivity changes according to $X_{j,t} = X_{j,t-1}e^{\xi_{j,t}}$, where $\xi_{j,t}$ is an i.i.d. firm-specific shock that is uniformly distributed over the support $\left[-\frac{\chi}{2}, +\frac{\chi}{2}\right]$. If a firm does not survive, which happens with probability $1 - \tau$, conditional on a shock, it is immediately replaced by a new firm with productivity one, i.e. $X_{j,t} = 1$. This can be interpreted as product substitutions. We note that the main purpose of the assumption that firms may die with probability $1 - \tau$ is to guarantee a stationary distribution of productivities across firms as in Gertler and Leahy (2008) on each island.

It can be shown that the log-linearized price-setting equation is given by

$$q^j_{z,t} = \frac{\gamma}{\gamma + \varepsilon(1 + \varphi - \gamma)}\left(\hat{\psi}_t - \hat{\phi}_t\right) \boldsymbol{-} \frac{\mathbf{1}}{\boldsymbol{\gamma + \varepsilon(1 - \gamma)}} \boldsymbol{x^j_{z,t}} + p_t + \ln\left(\frac{\overline{Q}}{P}\right), \tag{78}$$

$$\hat{\psi}_t = \left(1 - \alpha\beta\bar{\pi}^{\frac{\varepsilon(1+\varphi)}{\gamma}}\right)\left[\widehat{ulc}_t - (1 + \varphi)\hat{s}_t\right] + \alpha\beta\bar{\pi}^{\frac{\varepsilon(1+\varphi)}{\gamma}}\left[\frac{\varepsilon(1 + \varphi)}{\gamma}\mathbb{E}_t\hat{\pi}_{t+1} + \mathbb{E}_t\hat{\psi}_{t+1}\right], \tag{79}$$

$$\hat{\phi}_t = \alpha\beta\bar{\pi}^{\varepsilon-1}\left[\mathbb{E}_t\hat{\phi}_{t+1} + (\varepsilon - 1)\mathbb{E}_t\hat{\pi}_{t+1}\right]. \tag{80}$$

Since the parameter in front of $x^j_{z,t}$ depends positively on γ but not at all on φ, it is straightforward that in the DRS scenario the magnitude of real rigidites must be larger to achieve the same magnitude of price changes due to idiosyncratic productivity shocks. Hence, therefore even different micro real rigidities can have different implications for the size of idiosyncratic shocks and this conclusion is not limited to the comparison of micro and macro rigidites as highlighted by Klenow and Willis (2016). Given our estimates for the shorter sample, DRS necessitate five times as large shocks as SLM.

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