DE GRUYTER The B.E. Journal of Macroeconomics. 2023; 23(2): 1037–1055

Contributions

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Idiosyncratic Shocks, Lumpy Investment and the Monetary Transmission Mechanism

https://doi.org/10.1515/bejm-2022-0129
Received August 8, 2022; accepted July 5, 2023

Abstract: Standard (S, s) models of lumpy investment allow us to match many aspects of the micro data, but it is well known that the implied interest rate sensitivity of investment is unrealistically large. In fact, the micro-level lumpiness in investment puts empirical discipline on the modeling of investment decisions, and this makes it hard to explain the monetary policy transmission mechanism.

Keywords: lumpy investment; monetary policy; sticky prices

JEL Classification: E22; E31; E32

1 Introduction

What explains the short-run effects of monetary policy on real variables of interest? This question takes center-stage in much of the literature in macroeconomics. Our motivation to reconsider this classical question originates in a well-known micro-macro puzzle in investment theory. In fact, (S,s)[1] models of lumpy investment

1 The nature of optimal microeconomic decisions implied by fixed adjustment costs is typically referred to as (S,s), this way highlighting the range of inaction, which is a general feature of those decisions (see, e.g., Dotsey, King, and Wolman 1999).

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allow us to match many aspects of the micro data,[2] but the implied interest rate sensitivity of investment is unrealistically large (see, e.g. Thomas 2002 and Khan and Thomas 2008). The monetary transmission mechanism is therefore a natural starting point to assess the macroeconomic relevance of any investment theory. For instance, Reiter, Sveen, and Weinke (2013) have shown that once an otherwise conventional NK model is augmented with a lumpy investment decision à la Thomas (2002), the implied monetary transmission mechanism becomes counterfactual. Specifically, the impact responses of investment and output to a change in the nominal interest rate become very large and the dynamic consequences of that shock are only short-lived.

A drawback of our work in Reiter, Sveen, and Weinke (2013) is, however, that the micro data on investment could not be fitted in a satisfactory way by just relying on a fixed adjustment cost for capital. Therefore, the present paper develops a HANK[3] model consistent with the cross-sectional distribution of establishment investment rates reported by Cooper and Haltiwanger (2006).

To this end, we combine the investment model by Khan and Thomas (2008) with a convex capital adjustment cost and integrate the resulting framework into an otherwise standard NK model.[4] The convex portion of the capital adjustment cost is used to make our model consistent with the observed small and positive serial correlation in investment rates. The model solution relies on the methods developed in Reiter (2009, 2010, 2023), and our main result shows that the implied interest rate sensitivity of investment is so large as to imply a counterfactual monetary transmission mechanism.

Let us now relate our results to the literature. NK models often abstract from capital accumulation,[5] and if capital accumulation is taken into account in the context of NK theory then it is common practice to postulate convex adjustment

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2 That lumpiness is reported by, e.g. Doms and Dunne (1998), and Cooper and Haltiwanger (2006). In the context of our theory there is no distinction between a plant and a firm and we therefore use those terms interchangeably.

3 HANK stands for Heterogeneous Agent New Keynesian. This term has been popularized by Kaplan, Moll, and Violante (2018).

4 In one of our robustness checks in Reiter, Sveen, and Weinke (2013) we had also considered a combination of fixed and convex capital adjustment costs, but without assuming idiosyncratic shocks to productivity, a key feature of the model in Khan and Thomas (2008). It was then shown that the resulting framework did not to have a better ability to fit micro data on investment, compared with the baseline model proposed in Reiter, Sveen, and Weinke (2013).

5 See, e.g. Galí (2015), among many others.

costs in the investment block of the framework.[6] But, in the absence of any other capital adjustment cost, a convex cost makes NK models inconsistent with the observed lumpiness in plant-level investment. An early attempt to make an NK model consistent with the lumpy nature of investment at the micro level is the work in Sveen and Weinke (2007). In this paper infrequent pricing and investment decisions are made in a Calvo (1983) fashion, and this framework is shown to be observationally equivalent in the aggregate to a model of convex capital adjustment costs at the firm-level, as in Woodford (2005). One drawback of our 2007 paper is, however, that the empirical performance of the Calvo model is relatively poor compared to the standard approach in modern investment theory. The theory of lumpy investment is an active field of research, and the work in Winberry (2021) is an interesting recent contribution to it.[7] He studies, however, the dynamic consequences of technological shocks in an RBC framework, whereas our paper is concerned with the monetary transmission mechanism. In the investment block of his model, Winberry (2021) extends the model in Khan and Thomas (2008) by combining it with convex capital adjustment costs. He also assumes habit formation in the preferences of the representative household.[8] The recently emerging HANK literature has mostly studied the aggregate consequences of heterogeneity at the household level. Two notable exceptions are the work in Ottonello and Winberry (2020) and Koby and Wolf (2020). In their footnote 1, Ottonello and Winberry (2020) write: "Reiter, Sveen, and Weinke (2013) showed that a model with firm heterogeneity and fixed capital adjustment costs generates a counterfactually large and short-lived response of investment to monetary policy because, conditional on adjusting, investment is extremely interest-sensitive in their model. We dampen the interest sensitivity of investment using financial frictions and convex adjustment costs to aggregate capital. Koby and Wolf (2020) dampened the interest-sensitivity using convex adjustment costs at the firm level and found that the fixed costs generate state-dependent responses to monetary policy." In fact, in the part of their paper that is most related to our work, Koby and Wolf (2020) embed a rich heterogeneous-firm block with lumpy firm investment into an otherwise standard medium-scale New Keynesian model, and indeed the resulting monetary transmission mechanism

6 For instance, Christiano, Eichenbaum, and Evans (2005), or, more recently, Auclert, Rognlie, and Straub (2020), assume a convex investment adjustment cost, whereas Woodford (2005) postulates a convex capital adjustment cost.

7 Another interesting contribution is Baley and Blanco (2021). They apply a sufficient statistics approach to investigate the propagation of productivity shocks when firms make lumpy investments.

8 In Winberry (2021), the consumption habit is important in order to generate a plausible degree of volatility of the real interest rate. This is, of course, not an issue in the context of a New Keynesian model.

looks realistic. What does then explain the difference between the optimistic results in Koby and Wolf (2020) and Ottonello and Winberry (2020) on the one hand, and our negative result, on the other hand? There are two reasons. First, in contrast to Koby and Wolf (2020), we use the plant-level evidence on lumpy investment reported in Cooper and Haltiwanger (2006), rather than firm-level evidence from other sources, such as Zwick and Mahon (2017). This is because – in contrast to Zwick and Mahon (2017) – Cooper and Haltiwanger (2006) construct measures of retirement and sales of capital to measure negative investment. But the latter feature of the micro data puts empirical discipline on the convex adjustment cost parameter. That parameter can therefore not be used to dampen the interest sensitivity of investment sufficiently much. Second, Ottonello and Winberry (2020) analyze the monetary transmission mechanism in the presence of financial heterogeneity, but abstracting from the lumpy nature of investment at the micro level. For this simple reason, their model does not have the problem that we are pointing at in the present paper, even though Ottonello and Winberry (2020) use the data from Cooper and Haltiwanger (2006) for other aspects of their calibration. Taken together, we conclude that we are still a step away from a micro-founded theory of monetary policy. This is fair to say because all the way from Woodford (2005) to Ottonello and Winberry (2020) standard treatments of the monetary transmission mechanism have abstracted from the lumpy nature of investment (and its associated problems), and the optimistic results in Koby and Wolf (2020) depend crucially on a calibration which is based on a particular firm level data set which does not measure negative investment.

The remainder of the paper is organized as follows. Section 2 outlines the model. Section 3 presents the dynamic analysis. In the end of this section, we also discuss some ideas on how the problems that take center-stage in this paper could be addressed. In this regard, we pay in particular attention to the recent work by McKay and Wieland (2021). Section 4 concludes.

2 The Model

Our model integrates lumpy investment into an otherwise standard New Keynesian model of the monetary transmission mechanism. There are households, intermediate goods firms, retail firms and a central bank in charge of conducting monetary policy.

2.1 Households

Households are assumed to have access to a complete set of financial markets. The representative household has the following period utility function

$$U(C_t, L_t) = \ln C_t - \frac{\varphi}{1+1/\phi} L_t^{1+1/\phi}, \tag{1}$$

which is separable in its two arguments C_t and L_t. The former denotes a Dixit–Stiglitz consumption aggregate while the latter is meant to indicate hours worked. A household's time endowment is normalized to one per period, and throughout the analysis the subscript t denotes the time period. The steady state labor supply elasticity is given by ϕ, and parameter φ is used to make sure that the representative household spends one third of time working in the labor market. The consumption aggregate reads

$$C_t \equiv \left(\int_0^1 C_t(i)^{\frac{\epsilon-1}{\epsilon}} \mathrm{d}i \right)^{\frac{\epsilon}{\epsilon-1}}, \tag{2}$$

where ϵ is the elasticity of substitution between different varieties of goods $C_t(i)$. The associated price index is defined as follows

$$P_t \equiv \left(\int_0^1 P_t(i)^{1-\epsilon} \mathrm{d}i \right)^{\frac{1}{1-\epsilon}}, \tag{3}$$

where $P_t(i)$ is the price of good i. Requiring optimal allocation of any spending on the available goods implies that consumption expenditure can be written as P_tC_t. Households are assumed to maximize expected discounted utility

$$E_t \sum_{k=0}^{\infty} \beta^k U(C_{t+k}, L_{t+k}),$$

where β is the subjective discount factor. The maximization is subject to a sequence of budget constraints of the form

$$P_tC_t + E_t\{Q_{t,t+1}B_{t+1}\} \leq B_t + P_t w_t L_t + T_t, \tag{4}$$

where $Q_{t,t+1}$ denotes the stochastic discount factor for random nominal payments and B_{t+1} gives the nominal payoff associated with the portfolio held at the end of period t. We have also used the notation w_t for the real wage and T_t is nominal dividend income resulting from ownership of firms. The labor supply equation implied by this structure takes the standard form

$$\varphi\, C_t L_t^{1/\phi} = w_t, \tag{5}$$

and the consumer Euler equation is given by

$$Q^R_{t,t+1} = \beta \left(\frac{C_{t+1}}{C_t} \right)^{-1}, \tag{6}$$

where $Q^R_{t,t+1} \equiv Q_{t,t+1}\Pi_{t+1}$ is the real stochastic discount factor, and $\Pi_{t+1} \equiv \frac{P_{t+1}}{P_t}$ is the gross rate of inflation between periods t and $t+1$. We also note that $E_t\{Q_{t,t+1}\} = R_t^{-1}$, where R_t is the gross risk free nominal interest rate.

2.2 Intermediate Good Firms

There is a continuum of intermediate good firms indexed on the unit interval. They produce with capital and labor, and they face idiosyncratic shocks to their productivity. Let us note already that the relative intermediate good price is also the real marginal cost for retail firms. A key difference with respect to the model proposed in Khan and Thomas (2008) is that intermediate good firms are assumed to face not only a fixed cost but also a convex cost of adjusting the capital stock. Each period, an intermediate good firm therefore solves a problem of the form[9]

$$\max E_t \sum_{k=0}^{\infty} Q^R_{t,t+k} D_{t+k}$$

s.t.

$$D_t = q_t^M x_t z_0 \mathrm{e}^{\gamma t} \tilde{L}_t^{\nu} K_t^{\alpha} - w_t \tilde{L}_t - \Psi(K_t, K_{t+1}),$$

with

$$\Psi(K_t, K_{t+1}) = \begin{cases} i_t + \epsilon_\psi K_t \left(\dfrac{i_t}{K_t}\right)^2 & \text{if } i_t \in [aK_t, bK_t] \\ i_t + \epsilon_\psi K_t \left(\dfrac{i_t}{K_t}\right)^2 + f_t w_t & \text{if } i_t \notin [aK_t, bK_t] \end{cases} \tag{7}$$

and

$$i_t = \gamma K_{t+1} - (1-\delta)K_t. \tag{8}$$

All variables measured in units of output are defined as a Dixit–Stiglitz aggregate of the same form as the consumption aggregate. An intermediate good firm's capital stock, K_t, evolves according to (8), where i_t is its current investment, and $\delta \in (0,1)$ is the rate of capital depreciation. The growth rate of labor-augmenting technological progress is $\gamma - 1$, and all variables measured in units of output are deflated by the level of labor-augmenting technological progress. Equation (7) reflects the restrictions on an intermediate good firm's capital adjustment. Specifically, investments that are sufficiently minor relative to the existing capital are only subject to a convex adjustment cost. The latter is measured in terms of the aggregate good,

9 In order to lighten the notation in this place of the text, we omit a j-index to refer to the intermediate good firm being modeled, one among the continuum of intermediate good firms in our model.

and it is given by $\epsilon_\psi K_t \left(\frac{i_t}{K_t}\right)^2$, with parameter $\epsilon_\psi \geq 0$. The range of exemption is defined by parameters a and b, with $a \leq 0 \leq b$. Otherwise, an intermediate good firm also needs to pay a fixed adjustment cost, f_t, measured in units of labor and drawn from a time-invariant uniform distribution U: $[0, f] \to [0, 1]$. Adjustment cost shocks are iid across firms and over time. Labor used in the production of intermediate goods is denoted by $\tilde{L}_t$, and D_t is meant to indicate dividends, measured in terms of the aggregate good. Each intermediate good firm produces its output by combining labor, $\tilde{L}_t$, with its predetermined capital stock, K_t. The corresponding parameters in the production function are υ and α. Total factor productivity is common across intermediate good firms and evolves according to $z_0 e^{\gamma t}$.[10] Finally, x_t, is an intermediate good firm's idiosyncratic productivity, which is assumed to follow a Markov chain, and q_t^M is the relative intermediate good price.

2.3 Retail Firms

There is a continuum of retail firms indexed on the unit interval. Those firms introduce the New Keynesian (NK) elements into our model. Since the details of the NK model have been discussed elsewhere (see, e.g. Woodford 2003 or Galí 2015 for textbook treatments) we turn directly to the implied set of optimality conditions. A standard representation reads

$$\Pi_t = \left[\theta_p + (1 - \theta_p)(p_t^*)^{1-\epsilon}\right]^{\frac{1}{1-\epsilon}}, \tag{9}$$

$$q_t^M = \frac{1}{M_t}, \tag{10}$$

$$\Phi_t P_t^* = \mu_p \Upsilon_t P_t, \tag{11}$$

where θ_p is the Calvo parameter, i.e. the probability according to which a firm is not allowed to change price in a given period. We have also used the notation $p_t^* \equiv \frac{P_t^*}{P_{t-1}}$ for the optimal newly set price, P_t^*, that is chosen by all time t price-setters in our model, relative to the price of the consumption good one period earlier. The average price markup in period t is M_t, and $\mu_p \equiv \frac{\epsilon}{\epsilon - 1}$ denotes the desired frictionless markup. Finally, Φ_t and Υ_t are functions of the form

$$\Phi_t = Y_t + \theta_p E_t \left\{ \Pi_{t,t+1}^{\epsilon} Q_{t,t+1} \Phi_{t+1} \right\},$$

$$\Upsilon_t = Y_t + \theta_p E_t \left\{ \Pi_{t,t+1}^{\epsilon+1} Q_{t,t+1} \Upsilon_{t+1} \right\},$$

10 In Khan and Thomas (2008) total factor productivity is stochastic. This difference is explained by our research question. In fact, we restrict our attention to the monetary transmission mechanism.

where Y_t denotes aggregate output, defined as a Dixit–Stiglitz aggregate of the same form as the consumption aggregate.

2.4 To Close the Model

All markets are assumed to clear. Specifically, the aggregate goods market clearing condition reads

$$Y_t = C_t + \int_0^1 i_t(j) + \epsilon_\psi K_t \left(\frac{i_t(j)}{K_t(j)} \right)^2 \mathrm{d}j, \tag{12}$$

where the j-index is used to refer to one intermediate good firm among the continuum of intermediate good firms in our model. The labor market clearing condition is of the form

$$L_t = \int_0^1 \tilde{L}_t(j)\, \mathrm{d}j + \int_0^1 f_t(j) J\left(\frac{i_t(j)}{K_t(j)} \right) \mathrm{d}j,$$

where $J(x) = 0$, if $x \in [a, b]$, and $J(x) = 1$ otherwise. Finally, we follow Walsh (2005) in assuming a monetary policy rule of the form

$$R_t = (R_{t-1})^{\rho_r} \left[\frac{\Pi}{\beta} \left(\frac{\Pi_t}{\Pi} \right)^{\gamma_\pi} \left(\frac{Y_t}{Y} \right)^{\gamma_y} \right]^{1-\rho_r} \mathrm{e}^{e_{r,t}}. \tag{13}$$

Parameters γ_π and γ_y indicate the long-run responsiveness of the nominal interest rate to changes in current inflation and output,[11] respectively, and parameter ρ_r measures interest rate smoothing. We adopt the convention that a variable without time subscript indicates its steady state value. The shock, $e_{r,t}$, is iid with zero mean.

2.5 Baseline Calibration

The baseline calibration is summarized in Table 1. In particular, we consider a quarterly model, and we wish to make our New Keynesian model consistent with the micro facts on lumpy investment reported in Cooper and Haltiwanger (2006).

We use some of the values that have been proposed by Khan and Thomas (2008). This is clearly indicated by "KT (2008)" in Table 1. However, since the length of a period corresponds to one year in their model, we had to adjust some of the parameter values that are taken from Khan and Thomas (2008) in an appropriate way, as also indicated in Table 1. We set the rate of depreciation, δ, to a value that makes

11 Usually, the output gap, i.e. the ratio between equilibrium output and natural output (defined as the equilibrium output under flexible prices) enters the specification of monetary policy. Notice, however, that natural output does not change in response to a monetary disturbance.

Table 1: Parameter values.

Parameter	Description	Target/source
New Keynesian parameters		
$\epsilon = 7$	Elasticity of substitution	Standard
$\phi = 0.5$	Frisch labor supply elasticity	Standard
$\gamma_\pi = 1.5$	Monetary policy rule	Standard
$\gamma_y = 0.125$	Monetary policy rule	Standard
$\rho_r = 0.7$	Monetary policy rule	Standard
$\theta_p = 0.75$	Price stickiness	Standard
Preferences and technology		
$\gamma = 1.016^{\frac{1}{4}}$	Growth rate	KT (2008)
$\beta = 0.977^{\frac{1}{4}}$	Discount factor	KT (2008)
$\delta = 0.0187$	Rate of capital depreciation	KT (2008)
$\alpha = 0.256$	Production function parameter	KT (2008)
$\nu = 0.640$	Production function parameter	KT (2008)
$\rho_\epsilon = 0.859^{\frac{1}{4}}$	Idiosyncratic autocorrelation	KT (2008)
Baseline calibration		
$\sigma_\eta = 0.0422$	Idiosyncratic standard deviation	CH (2006)
$b = 0.010561$	Range of exemption	CH (2006)
$f = 0.055837$	Upper bound fixed cost	CH (2006)
$\epsilon_\psi = 0.017759$	Convex capital adjustment cost	CH (2006)

Our calibration follows studies in the literature, and in particular Khan and Thomas (2008). Some of their parameter values are adjusted to the quarterly frequency of our model, as indicated in Table 1. Taking this as a starting point, the parameter values that are called the “Baseline Calibration” can then be used to make our model consistent with the empirical targets in Cooper and Haltiwanger (2006), as illustrated in Table 2.

our model consistent with the conventional 10 % annual rate of investment in the stationary distribution. The Frisch labor supply elasticity ϕ is set to 0.5, and we had mentioned already that parameter φ is used to make sure that the representative household spends one third of time working in the labor market.

As Khan and Thomas (2008) do, we model idiosyncratic productivity shocks and the Markov chain determining their evolution by discretizing a log-normal process

$$\log \epsilon_t = \rho_\epsilon \log \epsilon_{t-1} + \eta_t,$$

where η_t is iid with standard deviation σ_η. We also follow Khan and Thomas (2008) in assuming $|a| = b$. We then choose four parameter values in order to make our model consistent with the empirical targets that are shown in Table 2. Those parameters measure, respectively, the standard deviation of the idiosyncratic shock to

Table 2: Distribution of Plant investment rates.

	Inaction	Positive spike	Negative spike	Positive investment	Negative investment	Investment autocorr.
Data	0.081	0.186	0.018	0.815	0.104	0.058
Baseline	0.066	0.192	0.003	0.819	0.115	0.056
KW (2020)	0.137	0.171	0.000	0.863	0.000	0.059
KT (2008)	0.082	0.132	0.002	0.786	0.132	−0.015
Traditional	0.785	0.159	0.000	0.214	0.000	−0.121

Establishment data are from Cooper and Haltiwanger (2006). We also use their definitions: Inaction $|i/k| < 0.01$; positive spike, $i/k > 0.20$; negative spike, $i/k < -0.20$; positive investment, $i/k \geq 0.01$; negative investment, $i/k \leq -0.01$; serial correlation of i/k.

productivity (σ_n), the range of exemption from capital adjustment costs (b), the upper bound of the fixed cost distribution (f), as well as the convex portion of the capital adjustment cost (ϵ_ψ). Specifically, we choose the values for those parameters that are shown in the corresponding rows of Table 1.[12] This calibration, called our baseline, makes the model reasonably consistent with the empirical targets, as illustrated in the corresponding rows of Table 2.[13]

Let us also consider three additional calibrations. In our quantitative analysis, those calibrations will allow us to understand the economic mechanisms at work.[14] The term "KT (2008)" in Table 2 is meant to indicate a version of our model that sets the convex portion of the capital adjustment cost equal to zero.[15] This leaves us with three parameters (i.e. σ_η, b and f) that are now used in the calibration. The problematic aspect of the "KT (2008)" calibration is that it does not allow us to target the positive serial correlation in investment rates, which is one of the micro-facts that have been established by Cooper and Haltiwanger (2006).

12 Concretely, those values are chosen in such a way that the sum of squared deviations from the six empirical targets that are shown in table 2 is minimized.

13 Let us also note that "inaction" is redundant because its value is implied by the other targets. If we target "inaction" instead of "negative investment", then the results are very similar to our baseline calibration. We find this interesting because it shows that this change in targets does not imply a calibration featuring a substantial convex portion of the capital adjustment cost. Those results are available upon request.

14 Unless stated otherwise, the form of the criterion is the same as the one that we had explained for our baseline calibration, and also in the three additional calibrations the representative household spends one third of time working in the labor market.

15 In Table 1, "KT (2008)" is used to indicate that Khan and Thomas (2008) is the source of some of the parameter values, as explained in the text. This is a small abuse of notation, but in each case the context is clear, we believe.

We also consider a calibration, which is labeled "Traditional" model in Table 2. This one refers to a version of the "KT (2008)" model that does away with both the idiosyncratic productivity shocks and the range of exemption from the fixed capital adjustment cost. In other words, we are left with just one calibration parameter, namely the upper bound of the fixed cost, f. This parameter is set to 0.2106, a value that makes this model reasonably consistent with the observed number of positive spikes. The models in Thomas (2002) and Reiter, Sveen, and Weinke (2013) would also fall into this category. The (well known) problematic aspects of "Traditional" models are manifold. For instance, they imply that a very large portion of positive investment takes the form of an investment spike.

Finally, we consider a case in the spirit of Koby and Wolf (2020), labeled "KW (2020)" in Table 2. In this exercise we dampen the interest-sensitivity of investment using the convex adjustment cost parameter. The interest in this calibration is clear. In fact, we wish to analyze the monetary transmission mechanism, and the convex portion of the capital adjustment cost plays a crucial role for shaping the dynamics implied by our model, as we are going to see. Concretely, we set ϵ_{ψ} to 5. As shown in Table 2, this calibration gives rise to a plausible degree of positive lumpy investment, but its problematic aspect can be seen to be the absence of negative investment. Negative investment, and negative investment spikes, are, however, documented in the empirical work by Cooper and Haltiwanger (2006).

We solve the model by linearization around the stationary state without aggregate shocks (see Reiter 2009), using almost-exact state aggregation (see Reiter 2010). The non-convexity of the firm problem is handled based on the results in Reiter (2023).

3 The Monetary Transmission Mechanism

We wish to isolate the role of a realistic degree of lumpiness in plant-level investment for the monetary transmission mechanism.

3.1 Baseline vs. High Convex Capital Adjustment Cost

Figure 1 illustrates the dynamic consequences of a 100 basis point decrease in the annualized nominal interest rate. The rate of inflation is also annualized. All other variables are measured as the respective log deviation of the original variable from its steady state value.

Let us compare those results with the empirical evidence that has been obtained using structural vector autoregressive (SVAR) methods. A classical reference is Christiano, Eichenbaum, and Evans (2005). They document that monetary policy shocks have strong and persistent consequences for real variables. For

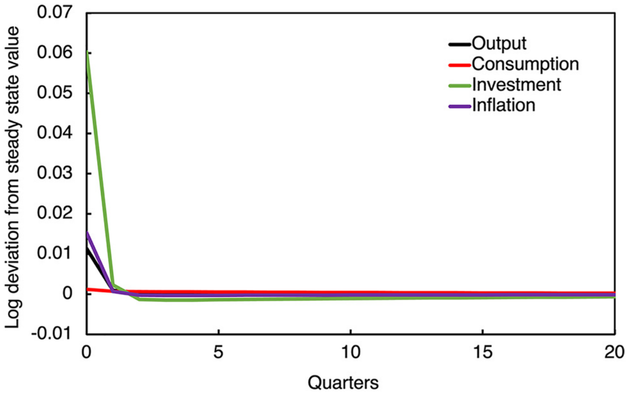

Figure 1: Baseline. Figure illustrates the dynamic consequences of a 100 basis point decrease in the annualized nominal interest rate under our baseline calibration. The rate of inflation is also annualized. All other variables are measured as the respective log deviation of the original variable from its steady state value.

instance, the estimates reported by Christiano, Eichenbaum, and Evans (2005) indicate that the maximum output response to an identified monetary policy shock is about 0.5 percent (with 95 percent confidence interval around this point estimate of about ±0.2).[16] After that, output is estimated to take about one and a half years to revert to its original level which is in line with the model's prediction. Christiano, Eichenbaum, and Evans (2005) also estimate a maximum investment response of about one percent (with 95 percent confidence interval around this point estimate of about ±0.5). The estimated maximum consumption response is roughly 0.2 percent (with 95 percent confidence interval around this point estimate of about ±0.1). Finally, Christiano, Eichenbaum, and Evans (2005) estimate a maximum inflation response of roughly 0.2 percent (with 95 percent confidence interval around this point estimate of about ±0.15).[17]

Figure 1 shows that the monetary transmission mechanism under our baseline calibration is out of line with the empirical SVAR counterpart. In fact, the impact responses of investment and output to a change in the nominal interest rate become very large and the dynamic consequences of that shock are only short-lived. For instance, in the period when the monetary shock hits the economy investment deviates by about six percent from its steady state value. In other words, the impact

16 The maximum response is estimated to occur about six quarters after the shock. This is one reason why additional real and nominal frictions are typically added to New Keynesian models in order to increase their empirical realism. See, e.g. Christiano, Eichenbaum, and Evans (2005).
17 The estimated maximum inflation response occurs about two years after the shock.

investment response is about six times larger than the size of the response that appears to be plausible based on the above mentioned SVAR evidence. In this context, the (S, s) nature of investment decisions is crucial. To understand this, one simply needs to follow well-trodden paths. In response to an expansionary monetary policy shock firms choose to undertake some of the investment activity that they would have otherwise done later. This is crucially different in the presence of capital adjustment costs of a size that allows us to entertain a plausible monetary transmission mechanism, as we are going to see next.

Figure 2 shows the monetary transmission mechanism for the case that is called "KW (2020)" in Table 2. Interestingly, the implied dynamics are (at least qualitatively) similar to the above mentioned SVAR evidence. The only notable exception is the inflation response, which is much larger than its SVAR counterpart. The reason is, of course, that price-setting and investment decisions take place in two different sectors of our model. Price-setters therefore do not internalize the consequences of their price-setting decisions for the marginal costs that they are expecting to face over the life-time of a newly chosen price. Assuming firm-specific capital would allow us to deal out of this problem, as analyzed in (Sveen and Weinke 2005).[18] The "KW (2020)" calibration is consistent with both a plausible number of investment spikes and a realistic persistence in annual investment rates at the firm level, as we had seen in Table 2. However, those choices also imply that there is no negative investment in the stationary distribution of our model, as we had also seen in Table 2. Intuitively, negative investment is unattractive to firms in the presence of substantial costs of adjusting the capital stock. Summing up, our results therefore show that if the convex portion of the capital adjustment cost is used to dampen the interest rate elasticity of investment sufficiently much to generate a realistic monetary transmission mechanism, then the resulting calibration looses its ability to match the micro facts on negative investment that are documented in Cooper and Haltiwanger (2006).

3.2 Inspecting the Mechanism

Let us further inspect the economic mechanisms at work. To this end, we compare the monetary transmission mechanism for three versions of our model: (i) Baseline, (ii) the case that is called "KT (2008)" in Table 2, i.e. a version of our model where

18 The basic intuition has been developed in Galí, Gertler, and López-Salido (2001) and Sbordone (2002) in the context of models featuring decreasing returns to labor resulting from a fixed capital stock at the firm level. Sveen and Weinke (2005) have shown that this simple intuition also helps understand the large degree of endogenous price stickiness that is implied by the assumption of firm-specific capital.

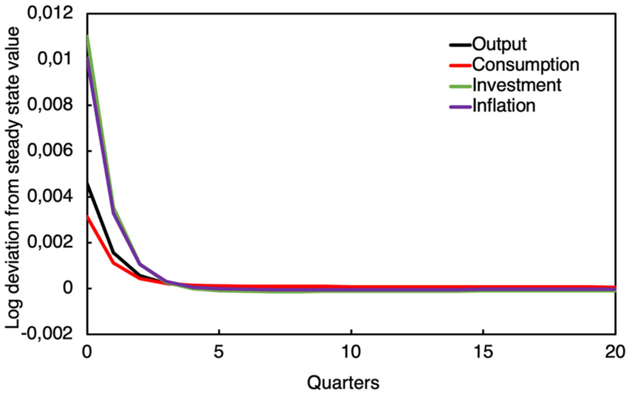

Figure 2: KW (2020). Figure illustrates the dynamic consequences of a 100 basis point decrease in the annualized nominal interest rate under the KW (2020) calibration. The rate of inflation is also annualized. All other variables are measured as the respective log deviation of the original variable from its steady state value.

the convex portion of the capital adjustment cost is set to zero in our calibration, (iii) the case that is called "Traditional" in Table 2, i.e. a version of our model where the upper bound of the fixed cost distribution is the only parameter that is used in the calibration. As it turns out, in each case the results are very similar. This is illustrated in Figures 1, 3 and 4.

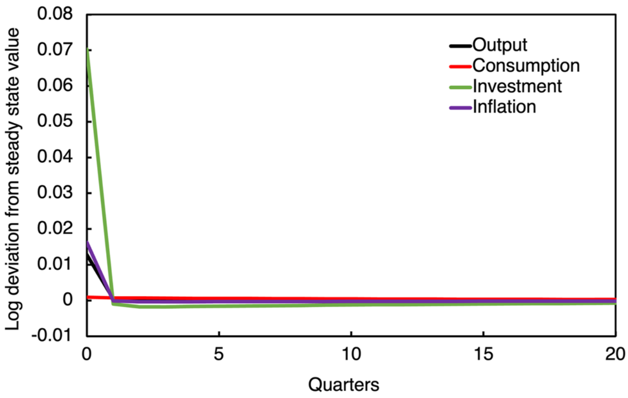

Figure 3: KT (2008). Figure illustrates the dynamic consequences of a 100 basis point decrease in the annualized nominal interest rate under the KT (2008) calibration. The rate of inflation is also annualized. All other variables are measured as the respective log deviation of the original variable from its steady state value.

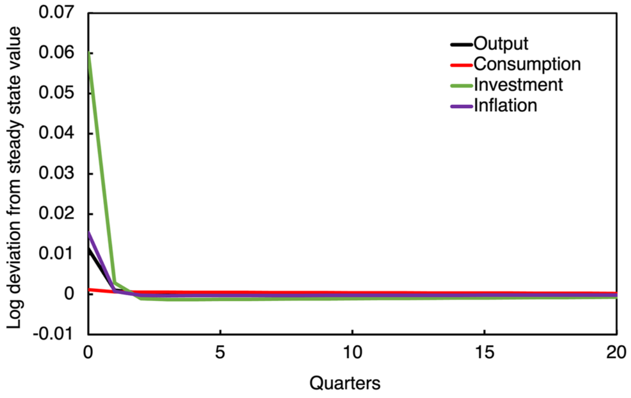

Figure 4: Traditional. Figure illustrates the dynamic consequences of a 100 basis point decrease in the annualized nominal interest rate under the traditional calibration. The rate of inflation is also annualized. All other variables are measured as the respective log deviation of the original variable from its steady state value.

We saw in Table 2 that the small convex portion of the capital adjustment cost plays an important role for our baseline calibration. In fact, as discussed there, without that portion we are unable to match the positive serial correlation in investment rates that is reported by Cooper and Haltiwanger (2006). As far as the dynamics are concerned, the “KT (2008)” case implies, however, a monetary transmission mechanism that is very similar to its counterpart under the baseline calibration. This is shown in Figure 3. The reason is, of course, that the positive serial correlation in investment rates reported by Cooper and Haltiwanger (2006) is relatively small. This puts empirical discipline on the convex adjustment cost parameter. We also saw in Table 2 that the idiosyncratic productivity shocks combined with a range of exemption from the fixed capital adjustment cost play an important role for the baseline calibration. In fact, as documented there, without those features we are unable to match many aspects of the micro data on investment. As far as the dynamics are concerned, also the “Traditional” case implies, however, a monetary transmission mechanism that is very similar to its counterpart under the baseline calibration. This is shown in Figure 4. The reason why we find this interesting is as follows. If idiosyncratic factors are relevant for investment decisions at the micro level, firms will respond differently to aggregate shocks. In fact, in our model there are always firms just at the margin between investing and not investing, which will then change behavior in response to a change in the interest rate. With idiosyncratic shocks, the distribution is more spread out, and the density at those margins is smaller. This limits the extent to which firms choose to undertake some of the investment activity that they would have otherwise done later. Our analysis shows, however, that the quantitative relevance of this effect is very small for the implied monetary transmission mechanism. We also find it interesting to compare our baseline results to a flexible capital case.[19] The latter is obtained by doing away with the fixed capital adjustment cost in the context of the "Traditional" model of the monetary transmission mechanism. Also in this case, the results are very similar to their counterpart under the baseline calibration. This finding is reminiscent of the irrelevance results in Thomas (2002) and Khan and Thomas (2008).

3.3 The Road Ahead

Our main result confirms the existence of the puzzle in Reiter, Sveen, and Weinke (2013) under more general circumstances. In fact, we show that it is hard to entertain a reasonable monetary transmission mechnanism in the context of a standard New Keynesian model while, at the same time, remaining disciplined by the microevidence on lumpy investment reported by Cooper and Haltiwanger (2006). How to deal out of this problem? In this regard, we would like to point at some recent work by McKay and Wieland (2021). They show in the context of a fixed-cost model of durable consumption demand that the implied interest rate sensitivity of demand can be so large as to imply a counterfactual monetary transmission mechanism. They also notice that this problem is similar to the one discussed in Reiter, Sveen, and Weinke (2013). Most importantly, however, they offer an interesting way of fixing this problem. First, they assume operating costs as a component of the user cost of capital that is not sensitive to interest rates. Second, they also assume shocks to the quality of the match between a household and its durable stock. These match-quality shocks are a source of inframarginal adjustments, and their estimates imply that 75 % of adjustments in steady state are due to the match-quality process. Let us make three observations in this context. First, our main motivation for assuming idiosyncratic productivity shocks in the present paper has been their potential to generate inframarginal adjustments so as to limit the interest rate sensitivity of investment. As it turns out, however, this effect is not quantitatively relevant under our baseline calibration, as we had shown before. It is therefore fair to say, we believe, that the details of the modelling and of the calibration strategy matter for the results obtained in this class of models. Second, let us observe that the Calvo modelling of lumpy investment decisions that has been analyzed in Sveen and Weinke (2007) can also be interpreted as an (extreme) example of a situation in which idiosyncratic shocks (here the outcomes of lotteries) affect aggregate dynamics in quantitatively important ways. Our baseline calibration in the present paper

19 Available upon request.

is, however, very different from a Calvo-case because the latter assumption would only allow us to make the average expected frequency of investment decisions consistent with their counterpart in the data. Finally, we like the idea of assuming shocks that limit the extent to which the user cost of capital is sensitive to interest rates. In our context, it might therefore be interesting to look at shocks to the rate of depreciation, and analyzing those aspects in more detail is high on our agenda.

4 Conclusions

We introduce lumpy investment into an otherwise standard New Keynesian framework. In the investment block, we extend the (S, s) model in Khan and Thomas (2008) by allowing for a combination of convex and non-convex capital adjustment costs. On the one hand, our HANK model is shown to be consistent with the cross-sectional distribution of establishment investment rates reported by Cooper and Haltiwanger (2006). On the other hand, the impact responses of investment and output to a change in the nominal interest rate become very large and the dynamic consequences of that shock are only short-lived. Ottonello and Winberry (2020) and Koby and Wolf (2020) dampened the interest sensitivity of investment using substantial convex capital adjustment costs. Our results show, however, that this is problematic. In fact, Ottonello and Winberry (2020) (and many other standard treatments of the monetary transmission mechanism) have abstracted from the lumpy nature of investment (and its associated problems), and the optimistic results in Koby and Wolf (2020) depend crucially on a calibration which is based on a particular firm level data set which does not measure negative investment.

The number of caveats that applies to any calibration strategy in a DSGE context is never small, and this is of course also true for our work. It is therefore important to stress the limited point that we are making in this paper: We notice that all the way from Khan and Thomas (2008) to Ottonello and Winberry (2020) micro data from Cooper and Haltiwanger (2006) have been used by business-cycle economists to discipline macroeconomic models. Taking this as a starting point, our results then show that this makes it hard to explain the monetary transmission mechanism.

Estimated impulse responses to identified monetary policy shocks have many other properties that are left out of the focus of this paper, and we have noted that this is one reason why additional real and nominal frictions are typically added to New Keynesian models (see, e.g. Christiano, Eichenbaum, and Evans 2005). It seems to us that also the modelling of those additional frictions should be disciplined by the micro data. In this context, it would also be interesting to take up a question raised by Eberly, Rebelo, and Vincent (2012): How does the right model of investment vary with the level of aggregation?

Acknowledgement: Thanks to Jordi Galí, Adrian Ochs, Christian Wolf, and to seminar participants at several venues. Patrick Brock, Natascha Ellis, Clara Hoffmann, Dennis Zander and Lara Zarges provided excellent research assistance.
Research funding: This research was funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) – 402884221, and the Fonds zur Förderung der wissenschaftlichen Forschung (FWF Austrian Science Fund) – I3840-G27. Their financial support is gratefully acknowledged. The usual disclaimer applies.

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