Delayed Adjustment and Persistence in Macroeconomic Models

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Abstract

Estimated impulse responses of investment and hiring typically peak well after the impact of a shock. Standard models with adjustment costs in capital and labor do not exhibit such delayed adjustment, but we argue that it arises naturally when we relax the assumption that the production technology is separable over time. This result holds for both non-convex and convex cost functions, and for reasonable parameter values the effect is strong enough to match the persistence observed in the data. We discuss some evidence for our explanation and ways to test the model.

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1 Introduction

A typical impulse response function for investment estimated from aggregate data (e.g. Altig, Christiano, Eichenbaum, and Linde (2011)) to a technology or monetary policy shock, has a hump shape. Investment jumps up in response to the shock, and then continues to increase before gradually falling back to zero. Most macroeconomic models since the first contributions to real business cycle theory correctly predict the sign and size of this response (King and Rebelo (1999a)), but have trouble explaining why there is a lag before investment peaks after a shock.

A similar puzzle arises for investments in labor input. In frictional labor market models as in Diamond (1982), Mortensen (1982) and Pissarides (1985), employment is a state variable, in which firms may invest through costly hiring. Estimates show a clear hump shape not only in the response of employment (Christiano, Eichenbaum, and Evans (1999)), but also in that of the job finding rate (as a measure of hiring), to technology (Canova, Lopez-Salido, and Michelacci (2010), Canova, Lopez-Salido, and Michelacci (2013)) and monetary policy shocks (White (2018)).[1]

In this paper, we propose a small and plausible modification to standard models that generates the type of hump-shaped impulse responses for investment and hiring observed in the data. We relax the assumption, implicit in almost all macroeconomic models, that the production technology is intertemporally separable. In combination with standard adjustment costs in capital and labor, a non-separable production technology gives rise to delayed adjustment: the peak of hiring and investment takes place a while after a shock has hit the economy. We show that delayed adjustment arises for both non-convex and convex adjustment cost functions, and that for reasonable parameter values the effect is strong enough to match the persistence observed in the data.

Modern theories of investment are micro-founded versions of Lucas (1967)'s "flexible accelerator" model: investment is increasing in the distance between the actual and the desired stock of capital or labor. Depending on the specifics of the model, capital adjusts gradually (with convex adjustment costs) or instantaneously (with fixed adjustment costs or irreversible investments) to its target. While intuitively attractive, these models have the counterfactual implication that investment is highest immediately after a change in demand or productivity, when the capital stock is furthest away from its target. In reality, firms slowly increase their investments, with most investment happening as much as 18 months after a shock.

We are not the first to notice that macroeconomic models do not seem to match the persistence in macroeconomic aggregates. The lack of propagation in these models is a long standing puzzle (Cogley and Nason (1995); Rotemberg and Woodford (1996)), although the literature seems to have focused more on the lack of amplification, perhaps

[1] In fact, the puzzle is even starker for hiring than it is for investment. While the autocorrelation of capital is quite a bit higher than that of investment, the same is not true for employment compared to hiring, and almost all of the persistence in employment seems to be driven by persistence in hiring. A time series for the steady state unemployment rate corresponding to the current job finding rate looks almost indistinguishable from the actual unemployment rate (Shimer (2012)).

because adjustment costs provide a straightforward way to increase the autocorrelation in the model. As opposed to the early contributions on propagation, we draw a sharp distinction between the persistence in stock and flow variables, arguing that adjustment costs may explain persistence and hump-shaped responses in the stocks (capital and employment), but they cannot by themselves account for persistence in the flows (investment and hiring). Many researchers are aware of this problem (Christiano, Eichenbaum, and Trabandt (2018), Fiori (2012)), and often resort to cost-of-change adjustment costs, as in Christiano, Eichenbaum, and Evans (2005)). We show that the dynamics of our model with a non-separable production function are very similar to the dynamics of models with cost-of-change adjustment costs, even though we use standard adjustment costs in the levels of investment and hiring.

We model non-separabilities in the production technology by introducing an additional state variable, which we label organizational capital, that acts as a storage technology for capital and labor input. This is the simplest way to relax the extreme assumption that all current capital and labor input immediately contributes to production, and that current capital and labor are the only inputs in production. Organizational capital is the accumulation of organizational investment, infrequent activities that are crucial to the firm in the long run, but do not immediately benefit production in the short run. The infrequent nature of these activities generates a margin of adjustment for production. When faced with higher demand or productivity, firms can temporarily expand production without investing in more capital or hiring more workers. Eventually, further depleting the stock of organizational capital becomes costly, and investment and hiring increase slowly, as they do in the data.

A good example of an organizational investment from our own production technology as academics is giving a research seminar. Giving a seminar does not immediately contribute to the production of research papers. In fact, it takes time away from directly productive activities like analyzing data or writing text. However, the comments we receive from colleagues and potential referees at the seminar do affect the quality of our paper, and may influence the direction of our work for many months or even years afterwards. More generic examples of organizational investments are machine maintenance, employee training and staff meetings to coordinate team work.

Probably the most direct evidence for the mechanism we have in mind comes from a, now somewhat dated, survey of plant managers by Fay and Medoff (1985). In this survey, managers recalled how many workers they let go in the last recession, and were then asked how many they could have let go while still meeting demand. The difference, which on average amounted to 6% less workers fired than would have been feasible, was interpreted as labor hoarding. More importantly for our purposes, a follow-up question about what happened to the "hoarded" workers revealed that half of the 6% were assigned to "other work", including (in order of importance): cleaning, painting, maintenance of equipment, equipment overhaul and training, all of which are examples of what we would call investments in organizational capital. Since the Fay and Medoff

(1985) survey provides only a shapshot, we also consider capacity utilization as a proxy measure for lack of organizational investments, and we show that the dynamics of capacity utilization in the data (Fernald (2012)) are consistent with the predictions of our model, even though we do not target this variable in the calibration.

The interpretation of non-separabilities in production as organizational investment relates this paper to the literature on organizational and intangible capital. A number of papers show that organizational capital and other intangible assets are important part of the productivity and stock market value of firms (Prescott and Visscher (1980), Blanchard and Kremer (1997), Brynjolfsson and Hitt (2000), Lev, Radhakrishnan, and Zhang (2009), Hall (2000b), Eisfeldt and Papanikolaou (2013), McGrattan and Prescott (2012), Conesa and Domínguez (2013)). We contribute to this literature by analyzing the effect of organizational capital on business cycle dynamics. We also explore further ways to test our model using an empirical literature aiming to measure organizational capital (Atkeson and Kehoe (2005), Black and Lynch (2005), Corrado, Hulten, and Sichel (2009), Squicciarini and Mouel (2012)).

As an application of our framework, we analyze the emergence of the jobless recoveries after the recession of 1991. In some past recessions in the US, employment have remained low for a few months after the trough date, but after recent recessions, ending in March 1991 and November 2001, employment has been particularly slow to recover, taking 14 and 29 months respectively for employment to return to the level it was at the NBER trough date (Schreft and Singh (2003), Aaronson, Rissman, and Sullivan (2004)).[2] We argue that this change in business cycle dynamics is consistent with our model, since there has been an increase in the importance of organizational capital for production over the same time period (Corrado, Hulten, and Sichel (2009)), which is quantitatively consistent with the increase in persistence under our model. While hardly a “smoking gun”, this observation provides some further evidence for the mechanism proposed in this paper.

The remainder of this paper is organized as follows. To set the stage, in section 2 we first analyze a simplified business cycle model with adjustment cost in employment and use it to document the persistence puzzle for hiring. We continue working with this simple model in section 3, but add a non-separable production technology to show that the model then gives rise to delayed adjustment, both for non-convex (fixed) and for convex (quadratic) adjustment costs. Section 4 simply shows that the argument for hiring in the previous two sections goes through for investment as well. In section 5, we add a bit of realism to the model, which now features a non-separable production function in both labor and capital, calibrate it, and show that the delay in adjustment is quantitatively important and matches the persistence in hiring and investment observed

[2] Galí, Smets, and Wouters (2012) have argued that recent recoveries are not so much jobless, but overall slow, in terms of output as well as employment. Other studies find evidence for a change in the comovement of output and employment as well (Bachmann (2012), Berger (2012), Jaimovich and Siu (2018)). Since our model can generate an increase in persistence in investment as well as hiring, the distinction is not important for the purposes of this paper.

in the data. Section 6 aims to provide some evidence for the mechanism by documenting the dynamics for proxies of organizational investment and analyzing the implications of the model for differences across industries and changes over time (the emergence of the jobless recoveries). Section 7 concludes.

2 The dynamics of employment and hiring

In this section, we set up a model environment that allows us to illustrate the lack of propagation in standard business cycle models. A lack of persistence is present both in investment and in hiring, but the puzzle is more pronounced for hiring. Therefore, we focus on hiring and simplify the model by assuming the capital stock is fixed (we revisit the lack of propagation in investment in section 4). Our starting point is a business cycle model with adjustment costs. For reasons of exposition, we keep the model as simple as possible.

2.1 A simple model of employment adjustment

Our economy produces Y_t goods in each period t, according to a production technology that requires only labor N_t,

$$Y_t = A_t N_t^{1-\alpha} \tag{1}$$

where A_t is the state of technology, which is normalized to have mean 1, and diminishing returns to labor in production are measured by the parameter $\alpha \in (0, 1)$. We analyze the response of the model to a one-time, unexpected and permanent change in technology A_t. The deterministic case allows us to formally describe the model dynamics under a range of specifications for the adjustment costs function. In the quantitative analysis in section 5, we will allow A_t to follow a stochastic Markov process.

Employment N_t increases or decreases through hiring $h_t > 0$ or firing $h_t < 0$ according to the following law of motion,

$$N_t = N_{t-1} + h_t \tag{2}$$

where we assumed that employment does not depreciate, i.e. there are no exogenous separations.

We assume that both the goods market and the labor market are perfectly competitive, so that the equilibrium is efficient and we can consider the social planner's problem. Furthermore, we assume the utility function is linear in consumption and leisure, so that the intertemporal consumption allocation is irrelevant and the social planner's optimization problem is equivalent to maximizing profits,

$$\max_{\{h_t\}_{t=0}^{\infty}} \sum_{t=0}^{\infty} \left(\frac{1}{1+r}\right)^t \left[Y_t - \gamma N_t - g\left(h_t\right)\right] \tag{3}$$

subject to (2), where r is the discount rate, γ is the disutility from working (and the wage) and $g(.)$ is an adjustment costs function. The optimal hiring policy depends on the form of this function.

2.2 Optimal hiring policy

We analyze two cases for the adjustment costs function, which are both prevalent in the literature: fixed adjustment costs and quadratic adjustment costs. These two cases, which are in some sense opposite extremes, convey the intuition for the model dynamics under non-convex and convex adjustment costs more generally.

As a benchmark, first consider the frictionless optimal allocation. In the absence of adjustment costs, the planner sets hiring to achieve the optimal level of employment, so that we obtain the frictionless optimal level of employment N_t^* simply by maximizing (3), with $g(h_t) = 0$, over N_t.

$$N_t^* = \left(\frac{(1-\alpha) A_t}{\gamma} \right)^{1/\alpha} \tag{4}$$

In a model with adjustment costs, we can think of the frictionless optimal level as the desired level of employment. The optimal hiring policy aims to achieve a balance between bringing employment close to its desired level while keeping adjustment costs low.

2.2.1 Fixed adjustment costs

Fixed adjustment costs are represented by the cost function $g(h) = \psi$ for $h \neq 0$ and $g(0) = 0$. This cost function is non-convex around zero employment adjustment, which introduces a discontinuity in the optimal hiring policy. The idea is that making any changes to the number of workers in the firm implies costly adjustments, but once adjustments are being made, the number of workers that are being hired or fired is irrelevant.

With fixed adjustment costs, the optimal hiring policy is a "bang bang" adjustment, as described in lemma 1. In response to small shocks, no adjustment takes place, whereas in response to larger shocks employment is adjusted all the way to its frictionless optimal level. The proof of lemma 1 is a straightforward application of the theory of irreversible investment (see Dixit and Pindyck (1994), Caballero (1999)) and is given in appendix A.1.

Lemma 1 *With fixed adjustment costs, the optimal hiring policy in response to a change in technology in the employment adjustment problem described by equations (3), (1) and (2) depends on the distance of employment N_{t-1} from its frictionless optimal level N_t^*, as in equation (4), and can be characterized as follows:*

1. *It is optimal to neither hire nor fire if $N_t^* - N_{t-1}$ is sufficiently close to zero;*

2. *It is optimal to hire $N_t^* - N_{t-1}$ workers if $N_t^* - N_{t-1}$ is sufficiently positive and to fire $N_{t-1} - N_t^*$ workers if $N_t^* - N_{t-1}$ is sufficiently negative.*

The optimal policy described in lemma 1 is approximately symmetric around $N_t^* - N_t = 0$ and may be summarized as,

$$h_t = \begin{cases} N_t^* - N_{t-1} \text{ (hiring)} & \text{if } N_t^* - N_{t-1} > b\left(N_t^*\right) \\ 0 \text{ (inertia)} & \text{if } -b\left(N_t^*\right) < N_t^* - N_{t-1} < b\left(N_t^*\right) \\ N_t^* - N_{t-1} \text{ (firing)} & \text{if } N_t^* - N_{t-1} < -b\left(N_t^*\right) \end{cases} \tag{5}$$

where the width of the region of inertia $b\left(N_t^*\right) \simeq \sqrt{2r\psi N_t^*/\alpha\gamma} > 0$ is increasing in the adjustment costs ψ and the discount rate r, see appendix A.1.

The response of hiring to a change in technology under this policy is either zero, or a spike in hiring that immediately brings employment to its desired level, which is the frictionless optimal level. Whether hiring responds or not depends on the size of the shock, expressed as the distance between employment and its desired level relative to the adjustment costs. The intuition for this policy is that the planner adjusts employment if and only if the increase in the net present value of profits from having the optimal level of employment instead of the current level exceeds the adjustment costs.

The dynamics of hiring and employment under fixed adjustment costs are representative for the dynamics under any non-convex adjustment cost function. If adjustment costs increase proportionally in the size of the adjustment in addition to, or instead of, a fixed costs component, or if changes in productivity are not permanent, then it will no longer be optimal to adjust employment to the frictionless optimal level. However, the optimal hiring policy will still be characterized by a hiring region, a region of inertia and a firing region, which depend on the distance of employment from its desired level, see Caballero (1999). The intuition is that with non-convex adjustment cost functions, adjustments to employment lead to a loss in profits that is irreversible, i.e. that is not made good if the adjustment is reversed, so that by adjusting firms lose the option value of waiting for a shock to be reversed over time.

2.2.2 Quadratic adjustment costs

Convex adjustment costs give rise to qualitatively different dynamics than non-convex adjustment costs. We analyze the case of quadratic costs, $g\left(h\right) = \frac{1}{2}\psi h^2$, which we can think of as an approximation of any convex adjustment costs function. A convex cost function implies that adjustment costs get very small for small amounts of hiring, so that infinitesimal adjustment in employment are costless and therefore reversible. This provides an incentive to smooth out adjustment over time, and the optimal response to a change in technology under quadratic adjustment costs is to hire (or fire) a small number of workers in each period over a long time, as described in lemma 2.

Lemma 2 *With quadratic adjustment costs, the optimal hiring policy in response to a change in technology in the employment adjustment problem described by equations (3),* *(1) and (2) can be described by Euler equation (6) for hiring, and has the following properties:*

1. *Hiring (or firing) starts immediately and continues for all periods after the shock, eventually approaching zero as employment N_t approaches its desired level N_t^* as in (4); and*
2. *Hiring monotonically declines over time as employment N_t adjusts to close the gap from its desired level $N_t^* - N_t$.*

The proof of lemma 2 is immediate from the Euler equation for hiring (6), which is derived from a straightforward dynamic programming problem in appendix A.2,

$$h_t = \frac{\gamma}{\psi}\left(\left(\frac{N_t^*}{N_t}\right)^{\alpha} - 1\right) + \frac{1}{1+r}E_t h_{t+1} \simeq \frac{\alpha\gamma}{\psi}\left(\frac{N_t^* - N_t}{N_t^*}\right) + \frac{1}{1+r}E_t h_{t+1} \tag{6}$$

where the second equality follows from a first-order Taylor approximation. For comparability with the optimal policy under non-convex costs, we express the Euler equation in terms of N_t and N_t^*, the current and desired levels of employment respectively.

As in the case of fixed adjustment costs, the optimal policy under quadratic costs depends on the distance of employment N_t from its frictionless optimal level N_t^*. However, under convex costs, this dependence is continuous rather than "bang bang".

2.3 The dynamics of hiring in the model

The dynamics of hiring predicted by the model are quite different depending on the specification of adjustment costs, as illustrated above. A large strand of literature debates what adjustment cost specification is most appropriate for aggregate dynamics. Whereas there is good evidence for lumpiness in investment (Doms and Dunne (1998), Haltiwanger, Cooper, and Power (1999)) and hiring (Cooper, Haltiwanger, and Willis (2015)) at the plant level, these non-convexities may be less relevant in the aggregate level due to general equilibrium effects (Thomas (2002), Khan and Thomas (2008)), although they may still affect the propagation of shocks (Gourio and Kashyap (2007), Bachmann, Caballero, and Engel (2013)).

Here, we focus on a feature of the dynamics of hiring that is common across different specifications for adjustment costs. As shown above, for both fixed and quadratic adjustment costs, hiring h_t is (weakly) monotonic in the distance of employment from its desired level, and zero when that distance equals zero. We might label this feature of the optimal hiring policy the "flexible accelerator" property, following Clark (1917), Samuelson (1939) and Lucas (1967).

An implication of the flexible accelerator property is that hiring (or firing) is highest immediately after a shock hits the economy, when the distance between the desired and actual levels of employment is largest. This prediction seems inconsistent with the hump-shaped impulse responses that are typically estimated using structural VARs, as discussed in the introduction.

While we derived the flexible accelerator property and its corollary that hiring peaks on impact of a shock in a very specific and simple environment, these predictions are a good deal more general than the assumptions of our model. If the cost function includes elements of both non-convex and convex costs, i.e. functions that are in between the "extremes" of fixed and quadratic costs, if employment depreciates or if shocks are mean-reverting, then it is generally not optimal to adjust to the frictionless optimal level of employment. However, in all of these cases, hiring is still monotonic in the distance between the current level and some "desired" level of employment, and these models still predict that hiring peaks immediately after a shock.

2.4 A calibration target for persistence

In order to compare the dynamics of hiring in the model to those in the data, we would ideally want to know the response of hiring to the distance between the current and desired levels of employment. In general, it is not possible to estimate this response, because the desired level of employment N_t^* is not observed. However, in the context of our simple benchmark model, we can obtain an observable proxy. Using production function (1) to eliminate technology A_t from expression (4), we see that in our model the distance of employment from its desired level is log-proportional to labor productivity.

$$\frac{N_t^*}{N_t} = \left(\frac{1-\alpha}{\gamma} \frac{Y_t}{N_t} \right)^{1/\alpha} \tag{7}$$

Thus, under the assumptions of our model, we can measure the response of hiring h_t to a change in technology by regressing the hiring rate on lags of labor productivity Y_t/N_t.

A moving-average (MA) regression of the hiring rate on labor productivity provides a simple and intuitive way to summarize the comovement of hiring with other macroeconomic aggregates and is likely to be informative about the response of hiring to shocks. The advantage of this regression over estimated impulse responses from a structural VAR is that we do not have to take a stance on the type of shocks that drive changes in the desired level of employment, which makes it a useful calibration target. An even simpler target, like the autocorrelation of the hiring rate, would not be able to distinguish between persistence in hiring due to progation of the model and persistence that is due to persistence in the shocks that drive business cycles. As a final advantage of our calibration target for the dynamics in hiring, we note that the logic of the approach extends to other variables, and in particular that the dynamics of investment can be meaningfully summarized by a moving-average regression of investment on capital productivity, see section 4.

It is important to note that the MA regression we propose does not recover the impulse response function of hiring. Even in the context of our simple model, labor productivity is endogenous, and we make no claim of causality in the regression. There are two reasons for this. First, while many structural shocks will affect the labor market through labor productivity (technology shocks, but also monetary policy shocks and other consumption demand shocks), other shocks will not. In particular, to the extent that the response of hiring to exogenous changes in labor supply is different from its response to other shocks, this will not be captured by our regression. Second, extensions to our simple model may break the link between the desired level of employment and labor productivity. For example, if wages strongly comove with productivity, for instance because workers have strong bargaining power in wage negotiations, then the γ in expression (7) will be a function of labor productivity, partially offsetting the effect of productivity on the desired level of employment. Our claim is that while our moving-average regression does not equal any impulse response function, it will be informative about it, and we support this claim by showing below that the regression inherits many of the properties of the response of hiring to identified structural shocks to technology and monetary policy. In particular, the estimates show a clear hump shape in the dynamics of hiring.

In the next subsection, we use our moving-average measure to compare the dynamics of hiring implied by the model with those in the data.

2.5 The persistence puzzle

Figure 1 shows the dynamics of hiring (job finding rate), as measured by a moving-average regression of the hiring rate h_t on labor productivity Y_t/N_t in the model with adjustment costs in employment and in the data.[3] Our measure for the dynamics of hiring in the model closely mirrors the impulse response of hiring to a technology shock, and in particular inherits its property that hiring is largest upon impact of the shock. With quadratic adjustment costs, hiring peaks when productivity changes and then slowly reverts to zero.

In the data, hiring peaks more than two years after the distance between the desired and current levels of employment is largest. This is consistent with the hump-shaped impulse responses for hiring found in structural VAR models with identified technology (Canova, Lopez-Salido, and Michelacci (2010), Canova, Lopez-Salido, and Michelacci (2013)) or monetary policy shocks (White (2018)). Our benchmark models with adjustment costs cannot replicate this property.

The failure of standard models with adjustment costs to replicate the delayed response in hiring observed in the data is what we call the persistence puzzle. In the next section, we show how the model is able to match the observed dynamics in hiring if we allow for a non-separable production technology, and that this result does not depend on the specific form of adjustment costs.

[3]For the hiring rate, we use the job finding probability from Shimer (2012), and labor productivity is output per worker from the BLS Labor Productivity and Costs program.

3 Delayed adjustment

In this section, we introduce the main idea of this paper: with a non-separable production function, the model predicts that hiring peaks not when a shock hits, but several periods after. We label this property of the model delayed adjustment. Below, we first examine delayed adjustment in the context of the simple model from the previous section. In section 5, we explore the quantitative importance of delayed hiring to match the data with an extended version of that model.

3.1 Non-separable production technology

Standard production functions, like (1), are separable over time. Labor input in period t contributes to production in the same period, and current-period labor is the only labor input in production. This is an extreme assumption that is unlikely to be satisfied. In reality, many tasks that workers perform do not immediately generate production, e.g. cleaning, maintenance, training or participating team meetings. Of course these tasks are productive; surely productivity would decrease if the office was never cleaned, machines were not maintained, workers never learned anything new and no meetings were held to coordinate between workers. However, the effect of these tasks on production realize in future periods and may last for a long time, so that they need to be performed only infrequently.

We model the effect of infrequent tasks on production by introducing an additional state variable, which we label organizational capital. When workers perform organizational, or infrequent, tasks their labor does not directly enter into the production function but is used to accumulate organizational capital. Organizational capital enters into the production function and depreciates when no workers invest into it by performing organizational tasks. This gives rise to the production function,

$$Y_t = \phi A_t \left(e_t N_t\right)^{1-\alpha} + \left(1-\phi\right) B_t L_t^{\rho} \tag{8}$$

where L_t is the stock of organizational capital, which evolves according to,

$$L_t = \left(1-\lambda\right) L_{t-1} + \tilde{\lambda} \left(\left(1-e_t\right) N_t\right)^{\frac{1-\alpha}{\rho}} \tag{9}$$

where e_t is the fraction of total labor input that is used for regular productive activities, which is a new choice variable, ϕ is a parameter governing the relative importance of current production versus organizational tasks, B_t represents shocks to the productivity of labor in producing organizational capital and -like A_t- is normalized to have mean 1. As in the simple model, we will analyze the response of hiring to a one-time, unexpected and permanent change in A_t, keeping $B_t = 1$ fixed for most of the analysis. The parameter λ denotes the rate of depreciation or organizational capital and $\tilde{\lambda} = \left[\left(r+\lambda\right) / \left(\left(1+r\right)\lambda^{1-\rho}\right)\right]^{1/\rho}$ is a correction factor to undo the effect of λ on the relative importance of organizational tasks versus current productive activities.[4] Finally, ρ is a parameter measuring diminishing returns to organizational tasks in the production versus the use of organizational capital. We would expect ρ to lie between $1-\alpha$, in which case the diminishing returns to organizational capital in production are the same as for regular labor but there are no diminishing returns in the production of organizational capital, and 1, which implies diminishing returns to organizational tasks in the production of organizational capital but no diminishing returns to organizational capital in the production of output.

The production technology described by equations (8) and (9) stays as close as possible to a standard production function while allowing for intertemporal non-separability in production. We assume that the only difference between regular productive tasks and organizational tasks is that the effect of organizational tasks on production is spread out over a long time period. How long this period is, is determined by the depreciation rate of organizational capital λ. Production function (8) reduces to (1) not only for $\phi = 1$ (no role for organizational capital in production), but also for $\lambda = 1$ ("organizational" tasks, like regular productive activities, affect production in the current period only), up to a normalization of the productivity shock.[5] In the frictionless optimal steady state, the two types of labor enter into the production function symmetrically, and the only difference is their relative productivity $\phi A_t / (1-\phi) B_t$, see equation (11) below. Our final assumption on the production function, and the only one that is not justified by symmetry, is additive separability, implying that output produced using regular labor is perfectly substitutable with output produced using organizational capital. This assumption is for simplicity, and we will show in section 5 that it is not qualitatively important for our results.

The non-separable production technology provides firms with a storage technology for labor, in the form of organizational capital. This storage technology allows them to intertemporally smooth labor input and adds an additional margin of labor adjustment: by postponing organizational tasks and reallocating labor to daily productive activities firms can temporarily increase output without increasing labor input. Below, we explore how this additional margin of adjustment changes the dynamics of hiring.

3.2 Optimal hiring policy

As before, the optimal hiring policy depends on the specification for adjustment costs, and we analyze the same two cases as in section 2 above: fixed and quadratic costs. We show that a non-separable production technology introduces delay in the optimal

[4] Notice that $\tilde{\lambda} = 1$ if $\lambda = 1$ and $\tilde{\lambda} \to \lambda$ for $r \to 0$. The reason that $\tilde{\lambda} \neq \lambda$ in general is due to the difference between the steady state and the static optimum allocation.

[5] With $\lambda = 1$ production is given by $Y_t = \phi A_t (e_t N_t)^{1-\alpha} + (1-\phi) B_t ((1-e_t) N_t)^{1-\alpha}$. Since the production function is now separable over time, the fraction of workers allocated to each type of labor e_t will be chosen statically to maximize production in each period, so that e_t satisfies $\phi A_t e_t^{-\alpha} = (1-\phi) B_t (1-e_t)^{-\alpha}$. Substituting the optimal e_t into the production function gives $Y_t = \phi A_t e_t^{-\alpha} N_t^{1-\alpha} = \tilde{A}_t N_t^{1-\alpha}$, where $\tilde{A}_t = \left[(\phi A_t)^{1/\alpha} + ((1-\phi) B_t)^{1/\alpha}\right]^{\alpha}$.

response of hiring, and that this happens for both specifications for adjustment costs.

The planner still maximizes the expected net present value of profits, as in (3), but she now has an additional choice variable e_t, the fraction of labor to allocate to regular productive versus organizational tasks.

$$\max_{\{e_t,h_t\}_{t=0}^{\infty}} \sum_{t=0}^{\infty} \left(\frac{1}{1+r}\right)^t \left[Y_t - \gamma N_t - g\left(h_t\right)\right] \tag{10}$$

where Y_t is given by production function (8), subject to the laws of motion for employment (2) and organizational capital (9).

It is again useful as a benchmark to solve for the frictionless allocation. Setting $g\left(h_t\right) = 0$, maximizing (10) over e_t and N_t, and assuming that the organizational capital was in steady state before technology changed, we find that the frictionless optimal level of employment $N_t^* = N^*$ is constant over time and given by,

$$N^* = \left(\frac{(1-\alpha)\,\phi A}{\gamma}\right)^{1/\alpha} + \left(\frac{(1-\alpha)\,(1-\phi)\,B}{\gamma}\right)^{1/\alpha} \tag{11}$$

with $e^* N^* = \left((1-\alpha)\,\phi A/\gamma\right)^{1/\alpha}$ workers are allocated to regular productive activities and the remaining $(1-e^*)\,N^*$ working on organizational tasks, see appendix B.1 for the derivation.

3.2.1 Fixed adjustment costs

With fixed adjustment costs, $g\left(h\right) = \psi$ for $h \neq 0$ and $g\left(0\right) = 0$, and a standard separable production function, firms either adjust employment (hire or fire some workers) in response to a change in technology or they do not, depending on the size of the shock, see lemma 1. With a non-separable production function, a third option arises: firms may choose not to adjust employment immediately, but to do so after a delay. Delaying is optimal in response to shocks of intermediate size, as described in proposition 3.

Proposition 3 *With fixed adjustment costs, the optimal hiring policy in response to an improvement in technology in the employment adjustment problem described by equations (3) and (2) and a non-separable production technology described by (8) and (9) depends on the distance of employment N_{t-1} from its frictionless optimal level N_t^*, as in equation (11), as well as on time, and can be characterized as follows:*

1. *It is optimal to neither hire nor fire if $N_t^* - N_{t-1}$ is sufficiently close to zero;*
2. *It is optimal to hire $N_t^* - N_{t-1}$ workers if $N_t^* - N_{t-1}$ is sufficiently positive and to fire $N_{t-1} - N_t^*$ workers if $N_t^* - N_{t-1}$ is sufficiently negative;*
3. *It is optimal to hire $N_t^* - N_{t-1}$ workers or $N_{t-1} - N_t^*$ workers after a delay if $N_t^* - N_{t-1}$ is in an intermediate range.*

The proof of proposition 3 is given in appendix B.2. In broad strokes, the argument runs as follows. If the planner does not immediately adjust employment in response to a shock to technology, then she will reallocate some workers from organizational tasks to current production to make up for the shortfall in labor input. Over time, this will deplete the organizational capital stock and reduce production and profits, so that the value of the planner's program falls over time. Therefore, if $N_t^* - N_{t-1}$ is initially small enough so that it is optimal not to hire workers immediately, but not too small, the planner would eventually regret her decision not to hire. In this case, the policy to hire $N_t^* - N_{t-1}$ after a delay dominates both the policy to immediately hire these workers and the policy to never hire. The intuition is that by delaying hiring, the planner also delays the payment of the hiring costs ψ, which because of discounting has a first-order positive effect increasing profits by $r\psi$. Since the organizational capital stock was initially at its optimal level, the fall in L_t has only a second-order effect on profits, so that the benefits exceed the costs of delaying.

The length of the delay increases with adjustment costs ψ and decreases with the size of the shock. For very large shocks it is still optimal to immediately adjust employment whereas for very small shocks it is still optimal to never adjust, as in the case of a separable production technology described in lemma 1. The length of the delay also increases with the discount rate, which increases the incentive for delaying the adjustment costs, and decreases with the depreciation rate of organizational capital, which determines how fast the organizational capital stock depletes when the planner starts underinvesting in it. This last parameter will be important as a lever to match the data, see section 5 below.

3.2.2 Quadratic adjustment costs

With convex adjustment costs, $g(h) = \frac{1}{2}\psi h^2$, and a standard separable production function, hiring jumps in response to a change in technology, and then slowly and monotonically declines to zero as employment approaches its frictionless optimal level, see lemma 2. With a non-separable production technology, hiring still only jumps on impact of the shock, and eventually declines to zero as employment approaches the frictionless optimal. However, the decline in hiring need not be monotonic. For a relevant range of parameter values, hiring first increases after the shock before starting to decrease and declining to zero, as described in proposition 4. Thus, peak hiring happens after a delay.

Proposition 4 *With quadratic adjustment costs, the optimal hiring policy in response to a change in technology in the employment adjustment problem described by equations (3) and (2) and a non-separable production technology described by (8) and (9) has the following properties:*

1. *Hiring (or firing) starts immediately and continues for all periods after the shock, eventually approaching zero as employment N_t approaches its desired level N_t^* as*

in (11); and

2. *Hiring (firing) is delayed, in the sense that it first increases after its initial jump, then peaks, and finally declines over time, if the discount rate $r > 0$, adjustment costs $\psi > 0$, the relative importance of organizational capital in production $1-\phi \in [0,1]$ are sufficiently high, and the depreciation rate of organizational capital $\lambda \in [0,1]$ and diminishing returns in organizational capital $\rho \in [1-\alpha, 1]$ are sufficiently low.*

3. *If the parameter conditions for delayed adjustment are satisified, then the amount and length of delay (the difference between peak hiring and initial hiring) increases with the discount rate $r > 0$, adjustment costs $\psi > 0$ and the relative importance of organizational capital $1-\phi \in [0,1]$, and decreases with the depreciation rate of organizational capital $\lambda \in [0,1]$.*

The proof of proposition 4 is a straightforward application of dynamical systems, and is implemented numerically, see appendix B.3. The intuition for the result can be seen from the Euler equation for hiring,

$$h_t = \frac{\gamma}{\psi}\left(\left(\frac{e^*}{e_t}\frac{N^*}{N_t}\right)^{\alpha} - 1\right) + \frac{1}{1+r}h_{t+1} \simeq \frac{\alpha\gamma}{\psi}\left(\frac{e^*-e_t}{e^*} + \frac{N^*-N_t}{N^*}\right) + \frac{1}{1+r}E_t h_{t+1} \quad (12)$$

which may be compared with the Euler equation (6) for the model with separable production technology. With a non-separable production technology, the urgency of hiring or firing is no longer summarized by the deviation of employment from its desired level N^*-N_t, but depends also on the fraction of labor that is optimally allocated to current production e^*-e_t, which in turn depends on the state of organization in the firm. If the organizational capital stock was at its optimal steady state level before an unexpected increase in technology, then it still is after the shock hits. Therefore, it is initially costless for firms to disinvest in organization, reallocating workers from organizational to current productive tasks. This reduces the incentive for hiring. Over time, however, organizational capital gets depleted, which negatively affects production and profits. When this happens, more workers are allocated to organizational tasks again, and firms need to hire more workers to achieve the desired level of output.

As in the case of fixed costs, the length of the delay increases with adjustment costs ψ and the discount rate r, both of which increase the incentive to postpone incurring the adjustment costs, and decrease with the depreciation rate of organizational capital λ, which determines how fast underinvestment in organizational tasks leads to a decline in the organizational capital stock. Different from the fixed-costs case, the length of delay does not depend on the size of the shock and the predictions of the model change very little when we linearize the equilibrium conditions.

3.3 Persistence in hiring

The optimal hiring policy with a non-separable production technology is summarized in figure 2, which shows the response of hiring to an increase in technology for fixed and quadratic adjustment cost. While the hiring policy looks quite different depending on the specification of adjustment costs, the optimal policy in both cases involves delay, in the sense that either all or most hiring takes place later than the impact of the shock.

While delayed adjustment in the model with non-convex adjustment costs is a non-linear effect, which depends on the size of the shock, this is not the case for the model with convex adjustment costs. With convex adjustment costs, whether there is delayed adjustment depends on parameters. In this model, we can linearize the equilibrium conditions without qualitatively affecting the dynamics, which greatly facilitates incorporating non-separabilities into larger-scale macroeconomic models.

If firm-level dynamics are well described by a model with fixed adjustment costs, then aggregate dynamics may look like the dynamics predicted by a model with convex costs in our framework. In a model with heterogeneous firms and fixed adjustment costs, in response to an aggregate shock some firms will adjust employment immediately, some will never adjust employment and some will adjust after a delay, see proposition 3. Therefore, we would expect aggregate hiring to jump on impact of the shock, and then to continue while more and more firms adjust. Depending on the distribution of firm heterogeneity, as well as other model parameters, aggregate hiring may be monotonically decreasing after the shock, or may peak after a delay, just as in the case of quadratic adjustment costs, see proposition 4. This result echoes the aggregation result in Thomas (2002) and Khan and Thomas (2008) for models with standard separable production technology.

The intuition for why delayed adjustment may be optimal in our model is straightforward. The non-separable production technology, in particular the slow-moving organizational capital stock, acts as a storage (or smoothing) technology for labor. This storage technology provides firms with an intensive margin for labor adjustment: firms may postpone organizational tasks and reallocate workers to current productive activities, effectively borrowing labor from the future. Using this intensive margin immediately increases production and therefore profits. And the intensive margin is initially costless, because the organizational capital stock is slow to depreciate, and remains at its current level even when organizational investment drops. Eventually, however, the borrowed labor needs to be paid back. The (slow) depreciation of the organizational capital stock negatively affects production and profits, and this cost increases over time, so that the firm is forced to allocate more workers to organizational tasks again. Having exhausted the intensive margin of adjustment, firms must then turn to the extensive margin and hire more workers.

The type of delay predicted by our model is endogenous, in the sense that delayed adjustment is optimal in response to a single shock, even if no further shocks hit the economy. This makes it different from the delay discussed e.g. in Dixit and Pindyck

(1994) in the context of investment, and used e.g. in Bachmann (2012) in the context of employment, which we might call exogenous delay. In a model with non-convex adjustment costs, but with a separable production technology, as in these studies, a firm may choose not to respond to a shock while it is "waiting for new information" (Dixit and Pindyck (1994, p.9)), i.e. to take a "wait and see" approach (Schreft, Singh, and Hodgson (2005)). However, new information in this context means new shocks. If those new shocks are such as to further increase the benefits of adjustment, then the firm may decide to adjust after a "delay". However, if the new shocks revert the effect of the first shock, then adjustment may never happen. In our model with a non-separable production technology, on the other hand, delayed adjustment *will* happen in response to some shocks, but it does not happen immediately. The distinction is important, because estimated impulse responses from a VAR, if correctly identified, describe the response of the economy to a single shock. Therefore, only a model with endogenously delayed adjustment can explain the hump shapes in the estimated response of hiring.

We will turn to the quantitative implications of our model in section 5 below, but first take a brief detour into the dynamics of capital and investment in the next section.

4 The dynamics of capital and investment

The impulse response of capital investment to technology and monetary policy shocks, like that of hiring, shows a clear hump-shape (Altig, Christiano, Eichenbaum, and Linde (2011)). For this reason, the DSGE literature often assumes so called "cost-of-change adjustment costs", i.e. costs that are quadratic in the change in investment i_t rather than its level, $g\left(i_t, i_{t-1}\right) = \frac{1}{2}\psi\left(i_t/i_{t-1}\right)^2$ (Christiano, Eichenbaum, and Evans (2005), Christiano, Eichenbaum, and Trabandt (2018)). In this section, we argue that standard "level" adjustment costs, $g\left(i_t\right) = \frac{1}{2}\psi i_t^2$, in combination with a non-separable production technology, give rise to very similar dynamics as cost-of-change adjustment costs with a standard separable production technology. We show that the persistence puzzle we documented for hiring in section 2.5 holds for investment as well, and argue that, since the model is symmetric in capital and labor, our results for the dynamics of hiring with a non-separable production function apply equally to investment in a model with fixed labor.

The model in sections 2 and 3 assumed that production requires only labor. In order to focus on the dynamics of investment, we can make the opposite extreme assumption that production requires only capital K_t. Then, the simple production function (1) would be replaced by $Y_t = A_t K_t^\alpha$, where $\alpha \in (0,1)$ is the capital share, whereas if we allow for intertemporal non-separability, production function (8) becomes

$$Y_t = \phi A_t \left(u_t K_t\right)^\alpha + \left(1-\phi\right) B_t L_t^\rho \tag{13}$$

and

$$L_t = \left(1-\lambda\right) L_{t-1} + \tilde{\lambda}\left(\left(1-u_t\right) K_t\right)^{\frac{\alpha}{\rho}} \tag{14}$$

where all parameters have the same interpretation as before and u_t is the fraction of the capital stock that is used for current production, with $1 - u_t$ of capital being used for investing in organizational or intangible capital. Perhaps the easiest way to interpret $1 - u_t$ is as the fraction of machines that are shut down for maintenance. The planner may adjust the capital stock by investing or disinvesting in it, $K_t = K_{t-1} + i_t$.

This model for capital adjustment is almost completely symmetric to the model for labor adjustment, with the capital share α playing the role of the labor share $1 - \alpha$ in that model, except that the way investment affects profits is slightly different from the way hiring does. Maintaining the same assumptions of linear utility and competitive markets as before, the planner maximizes the expected net present value of profits,

$$\max_{\{i_t\}_{t=0}^{\infty}} \sum_{t=0}^{\infty} \left(\frac{1}{1+r}\right)^t [Y_t - i_t - g(i_t)] \tag{15}$$

The difference with the labor adjustment model is that *investment* in capital lowers profits, whereas the *stock* of labor reduces profits (or utility) in objective function (3). The Euler equation for investment in this model, is given by

$$i_t = \frac{r}{(1+r)\psi} \left(\left(\frac{u^*}{u_t} \frac{K^*}{K_t} \right)^{1-\alpha} - 1 \right) + \frac{1}{1+r} i_{t+1} \tag{16}$$

where $u_t = u^* = 1$ if $\phi = 1$ or $\lambda = 1$, see appendix C for the derivation. Comparing this equation to Euler equation for hiring (12), it is clear that the model for capital adjustment model is symmetric to the one for labor adjustment under a parameter restriction on the value of leisure in that model, $\gamma = r/(1+r)$.

The symmetry between the models for capital and labor adjustment allows us to extend our results for hiring dynamics to investment.

The desired capital stock is log-proportional to capital productivity for $\phi = 1$,

$$\frac{K_t^*}{K_t} = \left(\frac{\alpha(1+r)}{r} \frac{Y_t}{K_t} \right)^{1/(1-\alpha)} \tag{17}$$

see appendix C and compare to (7). Therefore, a regression of log investment on an MA for log capital productivity is a meaningful summary of the persistence in investment, see the discussion in section 2.4. The bottom panel in figure 1 shows the dynamics of investment in the data (private non-residential fixed investment, net of consumption of fixed capital, from the NIPA), as well as in the model with a standard separable production function ($\phi = 1$). The figure documents a persistence puzzle for investment, which is very similar as the puzzle for hiring that we documented earlier, although less severe. In the model, investment monotonically declines after the initial impact of the shock, whereas in the data the response is hump-shaped and peaks only after 5-8 quarters (compared to 8-12 quarters for hiring).

A non-separable production function brings the dynamics of investment closer to the data.

Proposition 5 *The optimal investment policy in response to a change in technology in the capital adjustment problem described by equation (15) and a non-separable production technology described by (13) and (14) exhibits delayed adjustment, both for fixed adjustment costs and for quadratic adjustment costs, as described in propositions 3, and 4 replacing hiring with investment and employment with capital.*

Qualitatively, a non-separable production technology can explain the peristence puzzle in hiring as well as in investment. Whether this mechanism is sufficient to match the data is a quantitative question, to which we now turn. Since production in macroeconomic models usually requires both labor and capital, there is an additional quantitative question whether the model can match the persistence in both hiring and investment for the same parameter values.

5 Persistence in macroeconomic models

We showed that in a simple model with non-separable production technology the optimal policy for hiring and investment involves delayed adjustment. In this section, we argue that this delay is quantitatively relevant, in the sense that it brings the model dynamics substantially closer to the data. As a by-product, we also show that the result goes through if there are adjustment costs in both capital and labor and if we extend the model in other dimensions to make it more similar to the type of DSGE models typically used in the literature. The main quantitative exercise is to calibrate the model parameters to the literature as much as possible, and then to evaluate whether there exist values for the free parameters describing the non-separability in production, that generate peristence in hiring and investment as observed in the data. In section 6 we think about whether the parameters we need are reasonable, and whether we can find additional evidence to test our story.

5.1 Quantitative analysis

We use the following production technology for output using labor and capital,

$$Y_t = \left[\phi \left(A_t \left(u_t K_t\right)^{\alpha} \left(e_t N_t\right)^{1-\alpha}\right)^{\frac{\sigma-1}{\sigma}} + \left(1-\phi\right)\left(B_t L_t^{\rho}\right)^{\frac{\sigma-1}{\sigma}}\right]^{\frac{\sigma\theta}{\sigma-1}} \tag{18}$$

where organizational capital L_t evolves according to,

$$L_t = \left(1-\lambda\right) L_{t-1} + \tilde{\lambda}\left(\left(1-u_t\right) K_t\right)^{\frac{\alpha}{\rho}} \left(\left(1-e_t\right) N_t\right)^{\frac{1-\alpha}{\rho}} \tag{19}$$

which is a straightforward extension of (8) and (13). There are only two new parameters: θ, which measures decreasing returns to scale in production, and σ, the elasticity of substitution between current production and organizational capital. We need decreasing returns, because otherwise the model (with linear utility) does not have a steady state. Decreasing returns arise for instance if firms are monopolistically competitive and face elastic demand for their product, as in a standard new Keynesian model.[6] We assume technology A_t is stochastic and follows an exogenous Markov process, and keep the technology for organizational capital production B_t fixed at unity for most of the analysis.

There are adjustment costs in both labor and capital. Consistent with the literature, we let the adjustment cost functions be quadratic in the relative adjustment, i.e. in hiring and investment as a fraction of employment and capital respectively, so that $g_N(h_t) = \frac{1}{2}\psi_N (h_t/N_t)^2$ and $g_K(i_t) = \frac{1}{2}\psi_K (i_t/K_t)^2$. Furthermore, we assume that the stocks of both employment and capital depreciate,

$$N_t = (1 - \delta_N) N_{t-1} + H_t = N_{t-1} + h_t \tag{20}$$

$$K_t = (1 - \delta_K) K_{t-1} + I_t = K_{t-1} + i_t \tag{21}$$

where δ_N is the separation rate and δ_K is the depreciation rate for physical capital. Notice that our timing assumptions imply that depreciated employment and capital may be reinstalled within the period, so that δ_N and δ_K are gross depreciation rates. Also note that we assume that adjustment costs depend on hiring h_t and investment i_t net of replacement hiring/investment, rather than on total hiring H_t and investment I_t.

We maintain the assumption that utility is linear, but we allow for a preference shock as a stand-in for all non-technology shocks. Thus, we assume that per-period welfare is given by $Z_t [Y_t - I_t - g_N(h_t) - g_K(i_t)] - \gamma N_t$, where Z_t is stochastic and follows an exogenous Markov process that is independent of A_t. This second shock brings the correlation matrix of the model variables closer in line with data by breaking the almost-perfect comovement between variables in a one-shock model, and is also needed to help a simple RBC models like ours match the relative volatility of labor market variables, hiring and employment. The equilibrium conditions for the quantitative model are listed in appendix D.

The calibration of the model is summarized in table 1. For most of the parameters, we choose values that are commonly used in the literature. In this spirit, we calibrate the quarterly discount rate r to 3% to match the average return on equity, the capital share α to 0.33, $\theta = 0.87$ to match the markup of 12.5% of a monopolistically competitive firm (Galí (2015, p.67)), choose a depreciation rate for capital δ_K of 2.5% (King and Rebelo (1999b)), a (gross) separation rate δ_N of 30% per quarter (Gali and van Rens (2020)), and calibrate the marginal rate of substitution between consumption and leisure γ to match the average employment population ratio $\bar{N} = 0.7$. We set the autocorrelation of A_t to match the corresponding parameter for total factor productivity in the data, normalize

[6] Maximizing profits $P_t C_t -$costs(C_t) subject to the demand equation $C_t =$const$\cdot P_t^{-\varepsilon} \Leftrightarrow P_t = C_t^{-1/\varepsilon}$ is equivalent to maximizing $C_t^{(\varepsilon-1)/\varepsilon} -$costs$(C_t)$. In this example, $\theta = (\varepsilon - 1)/\varepsilon$.

the standard deviation of innovations in A_t to 1% and set the stochastic process for Z_t equal to that for A_t, loosely based on the estimates in Smets and Wouters (2007, Table 1B) showing that the autocorrelations and standard deviations of non-technology shocks are in the same order of magnitude as those of technology shocks.

The parameters ϕ, ρ, σ and λ, which describe the non-separability in the production technology are specific to our model and consequently there is no guidance in the literature on how to calibrate these parameters. In our quantitative exercise, we treat these as free parameters and explore how they affect the prediction of the model for the dynamics of hiring and investment. Since there are few direct estimates of adjustment costs, the literature often sets these parameters to match a volatility target. We follow this practice and set adjustment costs for employment ψ_N, together with ϕ, ρ, σ and λ, to match the response of hiring. We then treat the response of investment as an overidentifying restriction, setting the adjustment costs for capital equal to those for employment, $\psi_K = \psi_N$, and evaluate the performance of the model to match the response of investment for the same parameter values that we calibrated to the response of hiring.

5.2 The dynamics of hiring and investment

Figure 3 shows the model impulse responses employment, hiring, and capital and investment for the model with a separable and a non-separable production technology. The three lines in this figure correspond to increasing shares of organizational capital in production: 0 (separable production function), 15% (the calibrated baseline) and 30%. The model with a non-separable production function can replicate the hump-shaped impulse responses for hiring and investment, and the length of the delay increases in the share of organizational capital in production. Thus, the results we proved in sections 3 and 4 hold for a more general model, in which production requires both capital and labor, with a standard calibration for the parameters.

Next, we ask the question whether we can find parameters for the production technology so that the dynamics of hiring and investment match the persistence observed in the data. As a summary measure of the dynamics of hiring and investment, we use MA regressions of these variables on labor and capital productivity respectively, as introduced in sections 2.5 and 4. We vary parameters ϕ, ρ, σ, λ and ψ_N and for each set of values for these parameters recalibrate the other parameters to match their targets, simulate the model and run the same regression we ran on the actual data on the model-simulated data. We look for parameter values that minimize the distance between the estimated response of hiring from the data and the model. The results of this exercise are presented in figure 4, and the values for ϕ, ρ, σ and λ we used for these figures are reported in table 1.

It is clear from figure 4 that the model has no trouble replicating the persistence in hiring observed in the data, and it also gets close to matching the responses of investment with the same parameter values, even though we did not target this response in the calibration. Hiring responds little initially and peaks after just over two years in the data, whereas investment jumps more on impact but peaks around the same time as hiring. The calibrated model matches the response of hiring almost perfectly. The model also gets close to matching the amount of delay (0.39 in the model as well as in the data) and the lenth of the delay (8 quarters in the model versus 7 in the data), even though we did not target this response in the calibration.

The share of organizational capital we need to assume in order to match the hiring dynamics observed in the data is $1 - \bar{u} = 1 - \bar{e} = 15\%$, corresponding to $\phi = 0.56$, see table 1. Organizational capital is slightly less persistent than physical capital, with a depreciation rate of 2.7%. In section 6 below, we discuss some evidence on whether these are reasonable parameter values and try to find ways to test our story.

5.3 Robustness

The non-standard element in our model is the production technology, and this is where we focus our robustness analysis. We start with varying the parameters ϕ, which measures the importance of organizational capital in production, and λ, its depreciation rate, which have the expected effect on the results. These and all other results discussed in this subsection are reported in table 2.

We then consider the elasticity of substitution between current production and organizational capital σ, which is qualitatively important for the predictions of the model. For an increase in productivity to have a positive effect on the fraction of workers e_t allocated to current production, σ needs to be sufficiently greater than one. The reason is that for smaller values of σ an increase in technology A_t affects the productivity of organizational capital production just as much as or even more than that of current productive activities. If we set $B_t = A_t$, then varying σ leaves the impulse responses virtually unaltered, suggesting that it is not the degree of substitutability that is important, but the effect of changes in A_t on the relative productivity of current production over organizational investments. Thus, we need to think of a boom as a period of high *relative* productivity of current production. Organizational investments are no more productive in a boom than in a recession. Then, because capital and labor are overall more valuable, firms will substitute organizational investments for productive inputs in a boom and vice versa in a recession.

Next, we turn to the symmetry in the production function between labor and capital. In the simple model with only labor in section 3, it was relatively straightforward to justify our non-separable production technology in equations (8) and (9) as the smallest possible deviation from a standard separable production function as in (1). But in the full model with both labor and capital, as in (18) and (19), further assumptions were required, importantly the assumption that the capital and labor shares in current productive activities are the same as in organizational capital production. Relaxing this assumption, we replace equation (19) with

$$L_t = (1-\lambda) L_{t-1} + \tilde{\lambda} \left((1-u_t) K_t\right)^{\frac{\alpha_L}{\rho}} \left((1-e_t) N_t\right)^{\frac{1-\alpha_L}{\rho}} \tag{22}$$

We start from the extreme case that organizational capital production requires only labor, $\alpha_L = 0$, and gradually increase the capital share in organizational capital production. As we may have expected, the model is able to generate delay in investment only if it requires capital.

Finally, we explore the robustness of our results if we assume adjustment costs over gross rather than net hiring, $H_t = h_t + \delta_N N_{t-1}$, and investment, $I_t = i_t + \delta_K K_{t-1}$. In this case, the model is still able to generate delayed adjustment, see table 2, and the amount of delay is only slightly lower.

6 Evidence and implications

We showed that an otherwise standard macroeconomic model with a non-separable production technology can match the persistence in hiring and investment observed in the data, because the non-separability creates an additional margin of adjustment that firms may use to increase factor inputs into current production by postponing other types of activities. The most direct evidence for this mechanism comes from a, somewhat dated, survey by Fay and Medoff (1985). In this survey, plant managers were asked how many workers they had been forced to let go in the previous recession, and how many they could have fired while still meeting production requirements. The results showed that there was labor hoarding in the amount of 6% of workers, who were not needed during the recession but who had nevertheless not been laid off. Importantly for this paper, the survey then asked managers to indicate how they employed these "extra" workers. The answers indicated that these workers were assigned to "other work", including (in order of frequency) cleaning, painting, maintenance of equipment, equipment overhaul, or sent on training. In the context of our model, these types of "other work" can all be considered organizational tasks, because they do not affect production immediately, but are likely to improve productivity in the longer run. The estimate of 6% lines up well with our calibrated model, which predicts a decrease in e_t of 6.2% in the first year (from 12% in the first quarter to 2% in the fourth quarter) after a one-standard-deviation shock.

We model non-separabilities production as an additional state variable, which we label organizational capital, because there is evidence that organization is important in economics: for the existence of firms (Prescott and Visscher (1980)), to explain the large drop in output in the transition from a planned to a market economy (Blanchard and Kremer (1997)), for understanding the link between information technology and skill-biased technological change (Brynjolfsson and Hitt (2000)), for stock market value (Lev, Radhakrishnan, and Zhang (2009), Hall (2000a)), for asset returns (Eisfeldt and Papanikolaou (2013)), and it is often meaningful to think of organization as a stock of "capital" that positively affects productivity (Hall (2000b)). Organizational or intangible capital has also been shown to be important for measured productivity and business cycles (McGrattan and Prescott (2010), McGrattan and Prescott (2012), McGrattan (2017)), for optimal taxation (Conesa and Domínguez (2013), Conesa and Dominguez (2018)), and for the rise in the relative volatility of labor market variables (Mitra (2019)). This offers further opportunities for testing the model, building on a literature trying to measure organizational capital.

An ideal test of our explanation would compare the predictions of our model for the dynamics of (investments in) organizational capital directly to the data. This requires good estimates of organizational capital, at sufficiently high frequency and over a sufficiently long time period. Since such an idea test is not feasible due to lack of data, we try to build our case based on a compendium of indirect evidence. In subsection 6.1, we discuss some of the attempts to measure organizational capital, and show that the estimated share of organization in production is roughly in line with what our model needs to match the data on persistence in hiring and investment. Section 6.2 uses capacity utilization as an observable proxy for allocation of labor and capital to production versus organization, and shows that its dynamics are consistent with the dynamics predicted by our model. Finally, we attempt a test of our mechanism by checking whether *differences* in organizational capital line up with *differences* in persistence across industries (in subsection 6.3) and over time (in subsection 6.4).

6.1 Organizational capital share in production

Although measuring organizational capital is far from straightforward (Lev, Radhakrishnan, and Zhang (2009)), the literature has made a number of strong attempts. Atkeson and Kehoe (2005) estimate a structural model based on Prescott and Visscher (1980) and find that 8% of output is due to intangibles. Hall (2000a) uses a weight of 9% for e-capital in production and find that accumulation of e-capital contributed 15% to productivity growth over the 1990-98 period. Black and Lynch (2005) argue that employer-provided training is an important component of organizational investments and more easily measured, and find that 30% of output growth is due to "workplace practices", mostly training. The sources-of-growth analysis by Corrado, Hulten, and Sichel (2009) considers investments in IT and training, but also R&D and advertising and find an income share of 15% due to intangibles in 2000-03, with growth in the share of intangibles contributing 27% to growth in labor productivity from 1995 to 2003. Finally, Squicciarini and Mouel (2012) develop a measure of organizational investments in organization by using O*Net to identify occupations, in which workers perform tasks that are classified as organizational: organising, planning and prioritising work; building teams, matching employees to tasks, and providing training; supervising and coordinating activities; communicating across and within groups. They find that over 20% of employees work primarily on organizational tasks, double the estimates used in Corrado, Hulten, and Sichel (2009).

There seems to be broad consensus in this empirical literature that the share of organizational capital in output is somewhere between 8 and 20%, and that accumulation of organizational capital accounts for a much larger contribution to growth in output and productivity. We find that in order to match the observed persistence in hiring and investment with our model, we need to assume that 15% of labor and capital are being used for organizational tasks in steady state, well in line with these estimates. Since we did not target the organizational capital share, nor any of the series that are used to estimate it, but instead calibrated it to the response of hiring and investment, we interpret this as evidence in favor of our model.

6.2 The dynamics of factor input allocation

Our model has strong predictions for the dynamics of factor input allocation. Reallocating workers and capital services from current production to organization acts as an intensive margin of adjustment that makes it possible for firms to delay adjusting labor and capital. As a consequence, we would expect factor allocation to respond immediately when a shock hits the firm, and the response of e_t and u_t should not show a hump shape. To test this prediction, we need an empirical counterpart of e_t or u_t.

There is little direct evidence on the allocation of workers or capital within a firm, beyond the one-time survey by Fay and Medoff (1985). Empirical measures of organizational investment are of limited use as well, because they are available at best an annual frequency and for relatively short periods. We argue that capacity utilization is a good measure for e_t and u_t, as it measures changes in (current) output that cannot be explained by changes in factor inputs. Basu, Fernald, and Kimball (2006) argue that changes in hours-per-worker are a good proxy for changes in both labor effort and capital utilization, and Fernald (2012) provides a long quarterly time series for capacity utilization based on this idea, which we use to test the predictions of our model for the dynamics of e_t and u_t.[7]

In figure 5, we show the result of the same MA regression on productivity for capacity utilization as we showed for hiring and investment in figure 1. The response of utilization to changes in the economy is immediate, without evidence for a delayed response as for hiring or investment, consistent with the predictions of our model. This is further evidence in favor of the mechanism proposed in this paper.

6.3 Cross-industry evidence

The response of sectoral investment to macroeconomic shocks is hump-shaped, just as in aggregate data (Zorn (2016)). This finding implies that the delayed response of investment in aggregate data is not due to a composition effect but to a mechanism that operates within-industries. Therefore, we can use the variation in the response of hiring

[7] Alternative proxies we considered are effort (Shea (1990)) and skill acquisition (DeJong and Ingram (2001), Dellas and Sakellaris (2003)). While the cyclicality of these measures is consistent with our model as well, the data are annual, which makes it difficult to estimate the dynamics precisely.

(and investment) across industries to provide some further evidence for the mechanism we propose in this paper.

We explore to what extent the response of hiring and investment to shocks across industries is correlated with various measures of organizational capital intensity. Our model predicts that adjustment of employment and capital in industries with a higher share of organizational capital should exhibit more delay. A range of measures of organizational or intangible capital intensity is available for the US at the industry level, although at a relatively high level of aggregation: data on information capital intensity as suggested by Brynjolfsson, Hitt, and Yang (2002) and provided by the Bureau of Labor Statistics (2019a); data on intangible capital, organizational capital and training intensity constructed using the perpetual inventory method from a broad range of investments, including things that are usually treated as intermediate costs in the NIPA, from INTAN-Invest (Carol Corrado (2016)); a task-based measure of organizational investments produced by Squicciarini and Mouel (2012); data on e-capital from Hall (2000a); and data on employer-provided training as suggested by Black and Lynch (2005) as a measure for organizational capital and provided by the Bureau of Labor Statistics (2019b). We match these data to measures of delay in hiring and investment calculated from the US KLEMS (Bureau of Labor Statistics (2019a)), see appendix E for a more detailed description of the data and the measures for delay and organizational capital intensity.

The correlations between delay in hiring and organizational capital intensity we find tend to be positive, ranging from 0.7 for the percentage of workers that received formal training provided by their employer over the past year to zero for e-capital intensity, see appendix E. Unfortunately, the number of industries at which the measures of organizational capital intensity are provided is too low (between 8 and 28) to estimate these correlations with any reasonable degree of certainty. We conclude that the cross-industry evidence is at least not inconsistent with the explanation for delayed adjustment proposed in this paper.

6.4 Jobless recoveries

There is evidence that persistence in the US economy substantially increased some time in the 1980s. This change in business cycle dynamics has been documented in a small literature on the emergence of so called jobless recoveries (Schreft and Singh (2003), Aaronson, Rissman, and Sullivan (2004), Bachmann (2012), Jaimovich and Siu (2018)) or slow recoveries (Galí, Smets, and Wouters (2012)). When we run our MA regressions for hiring on labor productivity and for investment on capital productivity separable for the pre and post 1985 sample, it is clear that delays increased substantially over time, particularly for hiring, see figures 6 and 7.

As a further test of our explanation for persistence, we ask if we can attribute the increase in persistence to an increase in the importance of non-separabilities in production. Corrado, Hulten, and Sichel (2009) document that the share of intangible capital in output increased by more than 50% from 1975 to 1995 (and then further increased by over 30% from 1995 to 2015, see Carol Corrado (2016)). When we double the share of organizational capital in our model, from 15% to 30%, we find that the length of the delay in hiring increases from 8 to 9 quarters, and the length of delay in investment increases from 8 to 11 quarters, see table 2. These model predictions are roughly consistent with the change in persistence in hiring and investment in the data, see figures 6 and 7.

Compared to other explanations for the emergence of jobless recoveries (Bachmann (2012), Koenders and Rogerson (2005), Berger (2012), Jaimovich and Siu (2018)), our explanation is perhaps most similar to Koenders and Rogerson (2005), who also argue that reorganizations will be postponed when productivity is relatively high. The main difference is that in the model in Koenders and Rogerson (2005), reorganization will be postponed for as long as an expansion lasts, whereas in this paper postponing organizational tasks is a temporary solution. Therefore, whereas their model can explain the emergence of the jobless recoveries following the longer expansions since the 1980s, it cannot match the hump-shaped impulse responses in hiring and investment, which were the main motivation for this study.

7 Conclusions

We offered an explanation for the hump-shaped impulse responses in hiring and investment in US data that relies on non-separabilities in production in combination with standard adjustment costs in labor and capital. A non-separable production technology means that firms can intertemporally substitute labor and capital, allowing them to adjust factor inputs without the need for hiring and investment or firing and disinvestment. In combination with adjustment costs in labor and capital, this new intensive margin of adjustment generates an incentive to postpone hiring and investment in response to a shock, a feature of the model which we labelled delayed adjustment. Delayed adjustment in our model is endogenous, i.e. adjustment eventually happens in response to a single shock and does not require a specific sequence of shocks, nor does it depend on the specific type of adjustment costs (non-convex or convex). We discussed some evidence that the organizational capital share in production the model needs to match the persistence in hiring and investment observed in the data, is consistent with empirical estimates of organizational and intangible capital.

Compared to the early literature on propagation (Cogley and Nason (1995); Rotemberg and Woodford (1996)), we draw a sharp distinction between the persistence in stock and flow variables, arguing that whereas adjustment costs may explain persistence and hump-shaped responses in the stocks (capital and employment), they cannot by themselves account for persistence in the flows (investment and hiring). This is the same observation that led Christiano (2011) to dismiss adjustment costs in capital as a "failed approach". Following Christiano, Eichenbaum, and Evans (2005), the literature has addressed the problem by assuming adjustment costs in the change in investment rather than in capital, i.e. $g\left(i_t, i_{t-1}\right) = \frac{1}{2}\psi\left(i_t/i_{t-1}\right)^2$ instead of $g\left(i_t\right) = \frac{1}{2}\psi i_t^2$, see e.g. Christiano, Eichenbaum, and Trabandt (2018). We show that with a reasonably calibrated non-separable production technology, a model with standard adjustment costs generates impulse responses that are very similar to a model with cost-of-change adjustment costs.

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Parameter	Target	Value
Discount rate r	S&P500	0.03
Capital share α	RBC literature	0.33
Technology shock A_t persistence	RBC literature	0.979
Technology A_t innovation std dev	normalization	0.01
Preference shock Z_t persistence	same stochastic process as A_t	0.979
Preference Z_t innovation std dev	same stochastic process as A_t	0.01
Decreasing returns to scale $\theta = \frac{\varepsilon-1}{\varepsilon}$	markup 12.5%	0.87
Depreciation capital δ_K	RBC literature	0.025
Separation rate (gross) δ_N	data (CPS)	0.30
Disutility from working (wage) γ	empl-pop ratio $\bar{N} = 0.7$	0.53
AC capital ψ_K	$\psi_K = \psi_N$ in the baseline	40
AC employment ψ_N	hiring response	40
Diminishing returns to OC	hiring response	0.97
Importance organization in production ϕ	hiring response	0.56
Depreciation organizational capital λ	hiring response	0.027
EOS current production and organization σ	hiring response	3.9

Table 1: Calibration

	Hiring amount delay	Hiring length delay	Investment amount delay	Investment length delay
Data (1948:Q1-2007:Q4)	0.89	8	0.39	7
— Pre-84 (1948:Q1-1984:Q4)	0.83	8	0.32	5
— Post-84 (1985:Q1-2007:Q4)	1.65	11	0.63	7
$\phi = 1$ (no OC, $e = u = 1$)	0.00	0	0.00	0
$\phi = 0.56$ (baseline, $e = u = 1 - 0.15$)	0.52	8	0.39	8
$\phi = 0.5$ (more OC, $e = u = 1 - 0.30$)	0.84	9	0.61	11
$\lambda = 0.015$ (OC depreciates less)	0.84	9	0.64	11
$\lambda = 0.027$ (baseline)	0.52	8	0.39	8
$\sigma = 3$ (OC more complementary)	0.01	1	0.02	4
$\sigma = 3.9$ (baseline)	0.52	8	0.39	8
$\sigma = 5$ (OC more substitutable)	0.76	9	0.74	9
$B_t = A_t$, $\sigma = 3$ (OC more complementary)	0.41	11	0.23	8
$B_t = A_t$, $\sigma = 3.9$	0.58	12	0.50	10
$B_t = A_t$, $\sigma = 5$ (OC more substitutable)	0.59	12	0.51	10
$\alpha_L = 0$ (OC requires only labor)	0.81	10	0.00	0
$\alpha_L = 0.15$ (OC requires more labor)	0.95	11	0.18	6
$\alpha_L = \alpha = 0.33$ (baseline)	0.52	8	0.39	8
$\alpha_L = 0.5$ (OC requires less labor)	0.00	0	0.73	11
AC over gross hiring/investment	0.40	7	0.59	8

Table 2: Robustness analysis. The amount of delay is measured as peak minus impact hiring or investment as a fraction of peak hiring/investment. The length of delay is the difference between the time of peak hiring/investment and the time of impact measured in quarters.

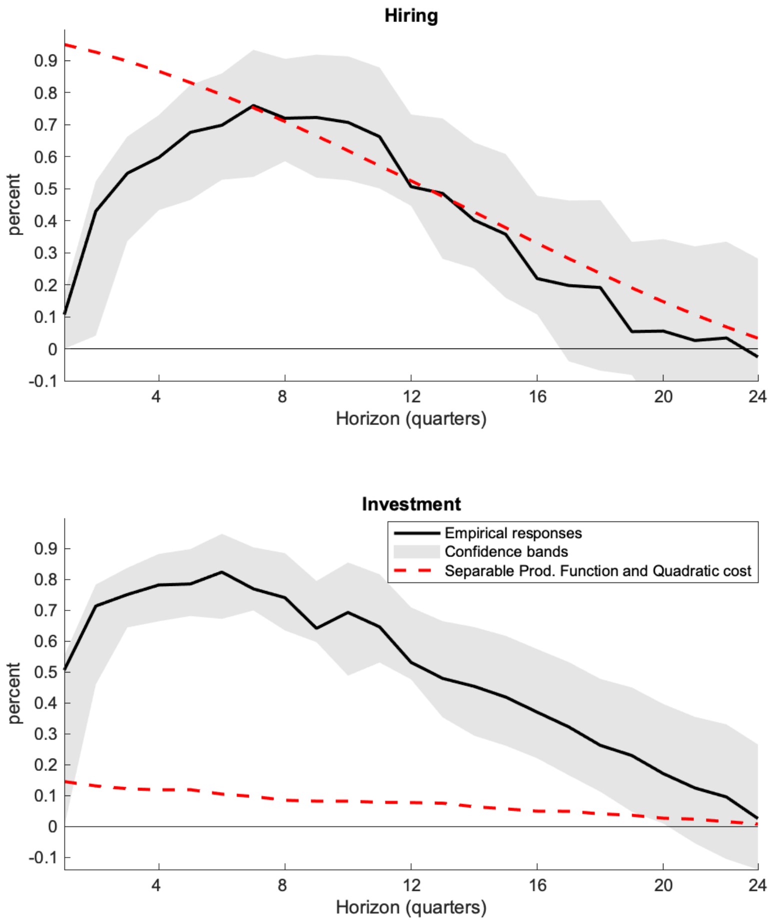

Figure 1: Persistence in hiring and investment in the data (black solid line with grey standard error bands) and in a model with standard separable production function with convex adjustment costs (red dashed line). The figure shows the coefficients of an MA regression of hiring h_t on labor productivity (output per hour) Y_t/N_t and investment i_t on capital productivity Y_t/K_t for the period from 1948:Q1 to 2007:Q4, and the response over a simulated sample of the model over $100,000$ periods.

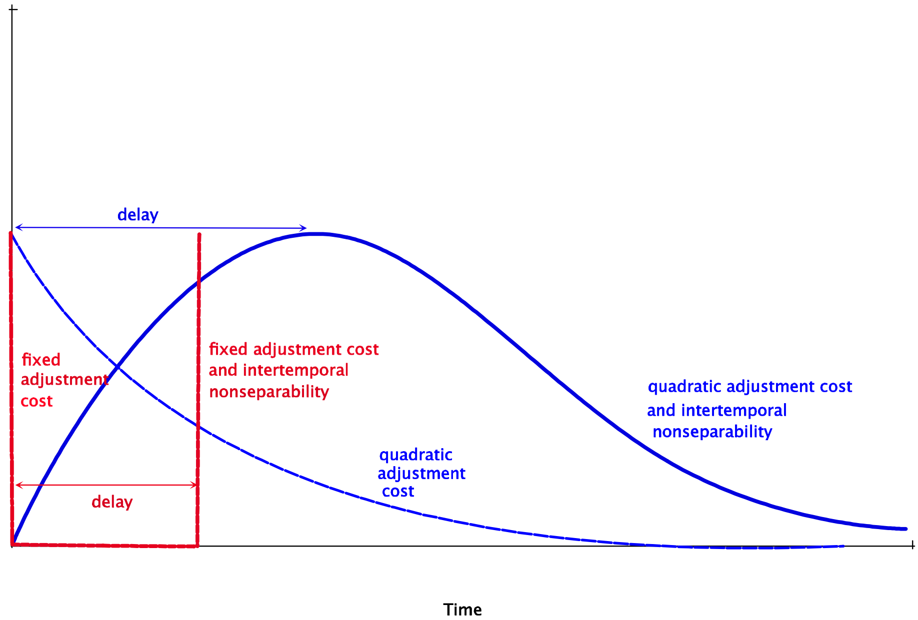

Figure 2: Delayed hiring in a model with fixed and quadratic adjustment costs.

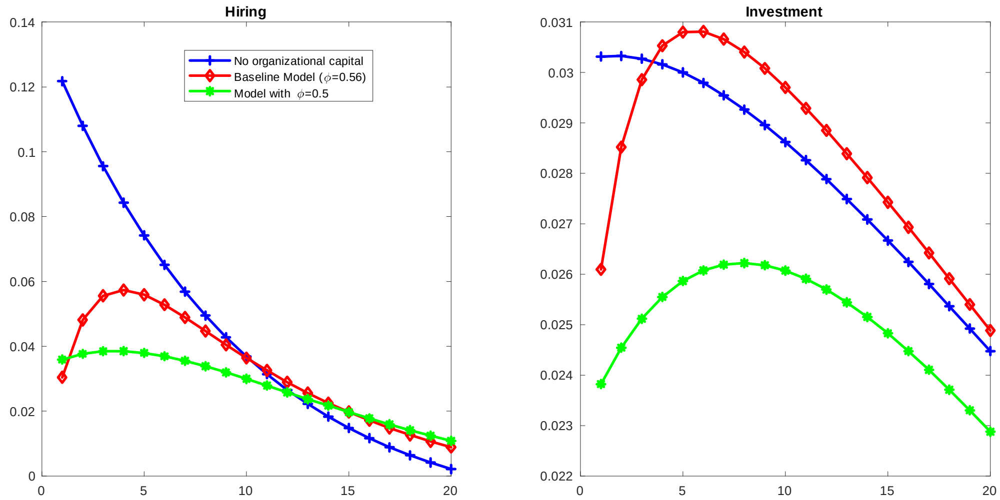

Figure 3: Impulse response functions of the model with separable and non-separable production technology, $\phi = 1$ ($e = u = 1$), 0.56 ($e = u = 1 - 0.15$) and 0.5 ($e = u = 1 - 0.3$).

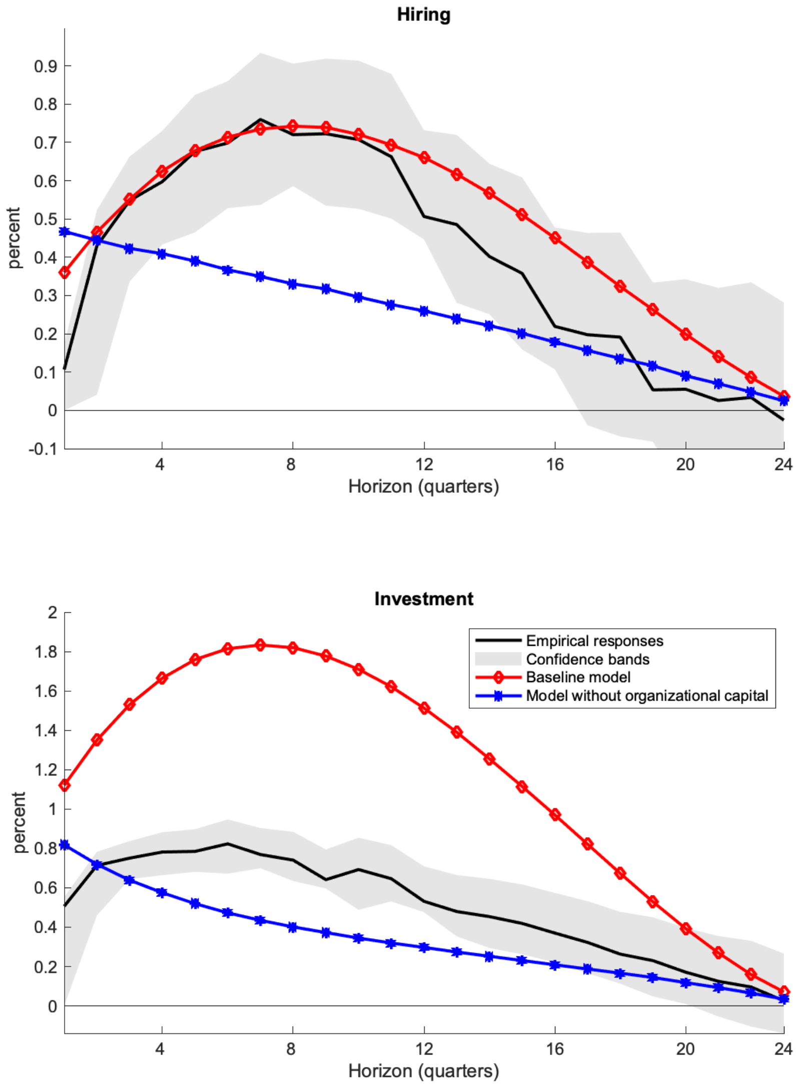

Figure 4: Persistence in hiring and investment in the data (black solid line with grey standard error bands), in our baseline model (red line with diamonds), and in the model without organizational capital (blue line with stars). The figure shows the coefficients of an MA regression of hiring H_t on labor productivity (output per worker) Y_t/N_t and investment I_t on capital productivity Y_t/K_t for the period from 1948:Q1 to 2007:Q4, and the response over a simulated sample of the model over $100,000$ periods.

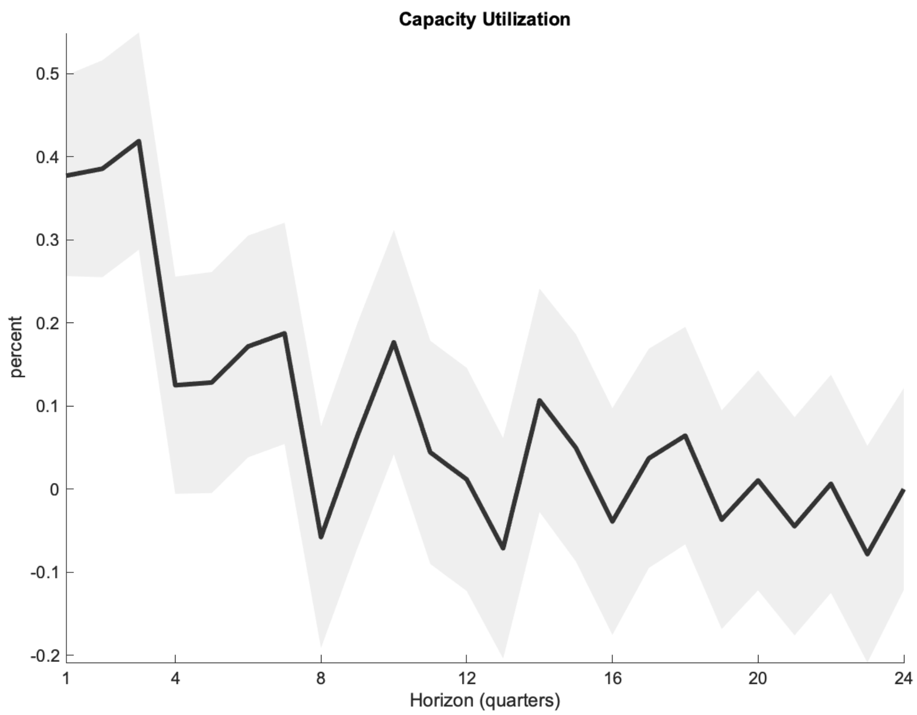

Figure 5: Persistence in capacity utilization. The figure shows the coefficients of an MA regression of capacity utilization on capital productivity Y_t/K_t. Unlike for hiring and investment, there is no evidence for delayed adjustment in utilization.

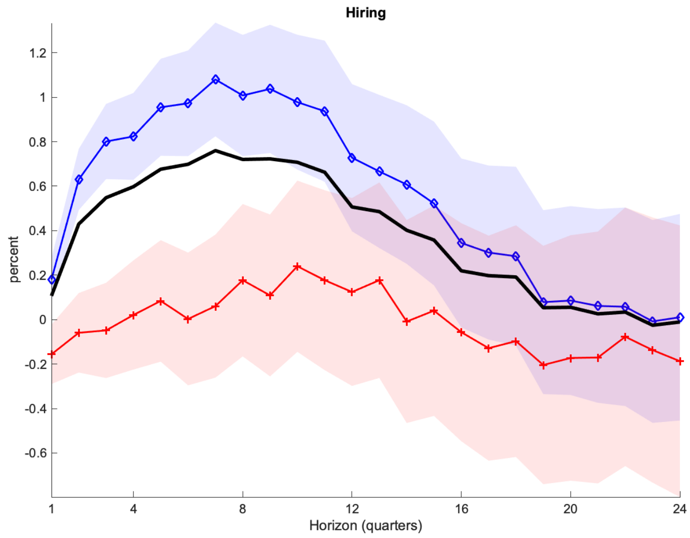

Figure 6: The emergence of the slow and jobless recoveries. MA regression of hiring on labor productivity before (blue diamonds) and after (red plusses) 1985.

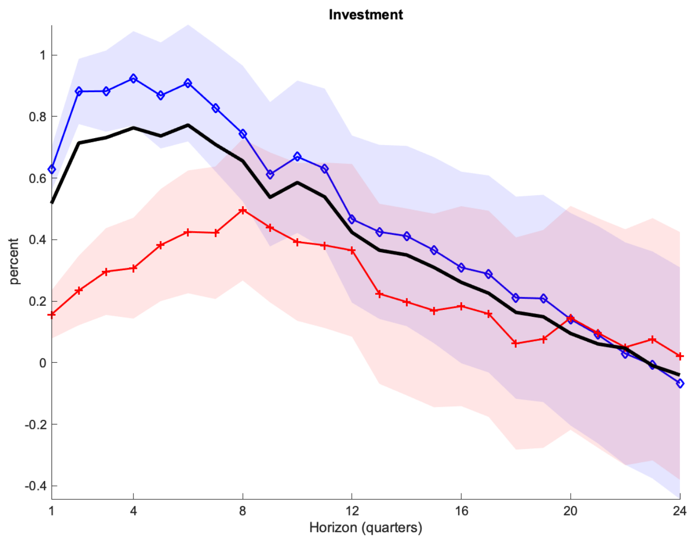

Figure 7: The emergence of the slow recovery of investment. MA regression of investment on capital productivity before (blue diamonds) and after (red plusses) 1985.

Delayed Adjustment and Persistence in Macroeconomic Models

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Appendices
(for online publication)

A Proofs and derivations for separable production

A.1 Optimal hiring policy (5) with fixed adjustment costs

The only state variable in our benchmark model is the level of employment inherited from last period N_{t-1}, which evolves through hiring and firing as in law of motion (2). Since we analyze a one-time permanent shock to technology, i.e. $A_{t+s} = A_t$ for all $s \geq 0$, we treat the state of technology A_t as a parameter rather than a state variable. Let $V(N_t)$ denote the value of the planner's program.

At time t, when the shock hits, the planner decides whether to adjust employment, by hiring or firing some workers, or not. If she decides not to adjust, then the value function evolves according to the following Bellman equation.

$$V(N_{t-1}) = A_t N_{t-1}^{1-\alpha} - \gamma N_{t-1} + \frac{1}{1+r} V(N_{t-1}) \tag{A.1}$$

This equation is readily solved explicitly for the value function

$$V(N_{t-1}) = \frac{1}{r}\left(A_t N_{t-1}^{1-\alpha} - \gamma N_{t-1}\right) \tag{A.2}$$

for all periods from t onwards.

If the planner decides to adjust employment, then she pays the adjustment costs ψ. The advantage is that she then gets to hire or fire any number of workers in period t to achieve a new level of employment. Since adjustment costs are independent on the amount of hiring or firing, and given our assumption that the level of technology is constant from period t onwards, it is clear that the planner will adjust employment to the frictionless optimal level, i.e. $h_t = N_t^* - N_{t-1}$. Therefore, the continuation value of the program equals $V(N_t^*) - \psi$ in this case.

The planner decides to adjust employment or not in order to maximize the continuation value of the program, i.e. she adjusts employment if $V(N_t^*) - \psi > V(N_{t-1})$, where $V(.)$ as in (A.2).

$$V(N_t^*) - V(N_{t-1}) = A N_t^{*1-\alpha} - \gamma N_t^* - A_t N_{t-1}^{1-\alpha} + \gamma N_{t-1} > r\psi \tag{A.3}$$

The planner adjusts employment if the increase in the net present value of profits from having the optimal level of employment instead of the current level exceeds the adjustment costs. Using expression (4) for N_t^* to eliminate the level of technology A_t, the condition for adjusting employment

$$\frac{1}{r}\left[\frac{\gamma}{1-\alpha}\left(1-\left(\frac{N_{t-1}}{N_t^*}\right)^{1-\alpha}\right) - \gamma\left(1-\frac{N_{t-1}}{N_t^*}\right)\right] > \frac{\psi}{N_t^*} \tag{A.4}$$

depends only on the ratio of employment to its desired level N_t^*, adjustment costs as a fraction of the desired level of employment and other model parameters.

Condition (A.4) can be used to prove the following properties of the optimal hiring policy:

1. For N_{t-1} close to N_t^*, the planner does not adjust employment, because the limit for $N_{t-1} \to N_t^*$ of the left-hand side of the condition equals zero, whereas the right-hand side is strictly greater than zero.

2. For N_{t-1} sufficiently large, it is optimal to hire some workers, because for $N_{t-1} \to \infty$ the left-hand side of the condition tends to infinity. For N_{t-1} sufficiently small, it is optimal to hire some workers if $\psi < \frac{1}{r}\left[\frac{1}{1-\alpha}\gamma N_t^* - \gamma N_t^*\right] = \frac{1}{r}\left[A N_t^{*1-\alpha} - \gamma N_t^*\right]$, i.e. if adjustment costs are smaller than the net present value of profits in the frictionless optimum, a parameter restrictions which we assumed to be satisfied.

3. If it is optimal to adjust employment (hire) for $N_{t-1} < N_t^*$, then it is also optimal to adjust for $N'_{t-1} < N_{t-1}$, because the derivative of the left-hand side of the condition is negative if $N_{t-1} < N_t^*$. Similarly, if it is optimal to adjust employment (fire) for $N_{t-1} > N_t^*$, then it is also optimal to adjust for $N'_{t-1} > N_{t-1}$, because the derivative of the left-hand side of the condition is positive in this case.

Combining properties 1 and 2 and using that the left-hand side of condition (A.4) is continuous in $N_{t-1} > 0$, by the intermediate value theorem there exist values $0 < b_H(N_t^*) < N_t^*$ and $b_F(N_t^*) > 0$ for any value of N_t^*, such that the planner is indifferent between adjusting employment or not if $N_{t-1} = N_t^* - b_H(N_t^*)$ and $N_{t-1} = N_t^* + b_F(N_t^*)$. By property 3, these bounds are unique, and it is optimal to hire if and only if $N_{t-1} < N_t^* - b_H(N_t^*)$ and it is optimal to fire workers if and only if $N_{t-1} < N_t^* + b_F(N_t^*)$. This proves lemma 1 in the main text.

The adjustment process guarantees that employment N_{t-1} will not deviate very far from its frictionless optimal level N_t^*. Therefore, we can simplify condition (A.4) by approximating it around $N_{t-1} = N_t^*$.

$$\frac{\psi}{N_t^*} < \frac{1}{r}\left[\frac{1}{2}\alpha\gamma\left(\frac{N_{t-1} - N_t^*}{N_t^*}\right)^2 + \mathcal{O}\left(\left(\frac{N_{t-1} - N_t^*}{N_t^*}\right)^3\right)\right] \tag{A.5}$$

Note that the first-order terms evaluate to zero, because N_t^* is the optimal level of employment, so that $V'(N_t^*)$. Setting higher-order terms to zero and requiring that this approximate condition holds with equality in the bounds, we get an approximate expression for the bounds.

$$\frac{\psi}{N_t^*} = \frac{1}{r}\frac{1}{2}\alpha\gamma\left(\frac{b(N_t^*)}{N_t^*}\right)^2 \Rightarrow b_H(N_t^*) = b_F(N_t^*) = b(N_t^*) = \sqrt{\frac{2r\psi N_t^*}{\alpha\gamma}} \tag{A.6}$$

so b is increasing in adjustment costs and discount rate, and depends on the production and utility functions and N_t^* as well. This latter dependence is because the adjustment costs matter as a fraction of the (desired) MPL. This proves expression 5 in the main text.

A.2 Optimal hiring policy (6) with convex adjustment costs

The Bellman equation with quadratic adjustment costs is given by

$$V\left(N_{t-1}\right)=\max_{h_t}\left\{A_t\left(N_{t-1}+h_t\right)^{1-\alpha}-\gamma\left(N_{t-1}+h_t\right)-\frac{\psi}{2}h_t^2+\frac{1}{1+r}E_tV\left(N_{t-1}+h_t\right)\right\} \tag{A.7}$$

The first-order condition for hiring h_t

$$(1-\alpha)\,A_tN_t^{-\alpha}-\gamma-\psi h_t+\frac{1}{1+r}E_tV'\left(N_t\right)=0 \tag{A.8}$$

and the envelope condition for employment N_t

$$V'\left(N_{t-1}\right)=(1-\alpha)\,A_tN_t^{-\alpha}-\gamma+\frac{1}{1+r}E_tV'\left(N_t\right) \tag{A.9}$$

can be combined in the usual way to get an Euler equation for hiring

$$V'\left(N_{t-1}\right)=\psi h_t$$

$$\psi h_t=(1-\alpha)\,A_tN_t^{-\alpha}-\gamma+\frac{\psi}{1+r}E_th_{t+1} \tag{A.10}$$

Using condition (4) for the frictionless optimal level of employment to eliminate the level of technology A_t, we can write the Euler equation in terms of the ratio of employment over its frictionless optimal level.

$$\psi h_t=\gamma\left(\left(\frac{N_t^*}{N_t}\right)^{\alpha}-1\right)+\frac{\psi}{1+r}E_th_{t+1} \tag{A.11}$$

Since the adjustment process guarantees that N_t will not deviate too much from N_t^*, the Euler equation can be simplified by taking a linear approximation in N_t around N_t^*. The result is expression (6) in the main text.

B Proofs and derivations for non-separable production

B.1 Frictionless optimal level of employment (11)

Bellman equation

$$V\left(L_{t-1}\right)=\max_{e_t,N_t}\left\{\phi A_t\left(e_tN_t\right)^{1-\alpha}+\left(1-\phi\right)B_t\left(\left(1-\lambda\right)L_{t-1}+\tilde{\lambda}\left(\left(1-e_t\right)N_t\right)^{\frac{1-\alpha}{\rho}}\right)^{\rho}-\gamma N_t\right.$$
$$\left.+\frac{1}{1+r}V\left(\left(1-\lambda\right)L_{t-1}+\tilde{\lambda}\left(\left(1-e_t\right)N_t\right)^{\frac{1-\alpha}{\rho}}\right)\right\} \tag{B.12}$$

The first-order conditions for e_t and N_t are given by

$$0=\left(1-\alpha\right)\phi A_te_t^{-\alpha}N_t^{1-\alpha}-\rho\frac{1-\alpha}{\rho}\left(1-\phi\right)B_tL_t^{\rho-1}\tilde{\lambda}\left(1-e_t\right)^{\frac{1-\alpha}{\rho}-1}N_t^{\frac{1-\alpha}{\rho}}$$
$$-\frac{1-\alpha}{\rho}\tilde{\lambda}\left(1-e_t\right)^{\frac{1-\alpha}{\rho}-1}N_t^{\frac{1-\alpha}{\rho}}\frac{1}{1+r}V'\left(L_t\right) \tag{B.13}$$

$$0=\left(1-\alpha\right)\phi A_te_t^{1-\alpha}N_t^{-\alpha}+\rho\frac{1-\alpha}{\rho}\left(1-\phi\right)B_tL_t^{\rho-1}\tilde{\lambda}\left(1-e_t\right)^{\frac{1-\alpha}{\rho}}N_t^{\frac{1-\alpha}{\rho}-1}-\gamma$$
$$+\frac{1-\alpha}{\rho}\tilde{\lambda}\left(1-e_t\right)^{\frac{1-\alpha}{\rho}}N_t^{\frac{1-\alpha}{\rho}-1}\frac{1}{1+r}V'\left(L_t\right) \tag{B.14}$$

Envelope condition for L_t

$$V'\left(L_{t-1}\right)=\rho\left(1-\phi\right)\left(1-\lambda\right)B_tL_t^{\rho-1}+\frac{1-\lambda}{1+r}V'\left(L_t\right) \tag{B.15}$$

Combine the two FOC to eliminate $V'\left(L_t\right)$

$$\left(1-\alpha\right)\phi A_t\left(e_tN_t\right)^{-\alpha}=\gamma \tag{B.16}$$

which tells us that e_tN_t jumps immediately to its optimal steady state level $\left(\left(1-\alpha\right)\phi A_t/\gamma\right)^{1/\alpha}$.

Combining the FOC for e_t with the EC for L_t gives an Euler equation for for $\left(1-e_t\right)N_t$.

$$\left(\left(1-e_t\right)N_t\right)^{1-\frac{1-\alpha}{\rho}}=\tilde{\lambda}\frac{\left(1-\alpha\right)\left(1-\phi\right)B_t}{\gamma}L_t^{\rho-1}+\frac{1-\lambda}{1+r}\left(\left(1-e_{t+1}\right)N_{t+1}\right)^{1-\frac{1-\alpha}{\rho}} \tag{B.17}$$

Combined with the LOM for OC, $L_t=\left(1-\lambda\right)L_{t-1}+\tilde{\lambda}\left(\left(1-e_t\right)N_t\right)^{\frac{1-\alpha}{\rho}}$, this is a system of two difference equations, one stable and one unstable, in $\left(1-e_t\right)N_t$ and L_t.

In general, $\left(1-e_t\right)N_t$ and L_t will slowly converge to steady state. However, it is worth noticing that the dynamics of these variables do not depend on A_t (this is an implication of additive separability of the production function), so if there is only a (one-time permanent) shock only A_t and L_t was initially in steady state, then L_t and $\left(1-e_t\right)N_t$ remain in steady state. Since e_tN_t is constant as well, that means that $e_t=e^*$, $N_t=N^*$ and $L_t=L^*$ are all constant in the frictionless optimum, assuming that L_t was in steady state to start with.

Thus, the frictionless optimum steady state is given by:

$$e^* N^* = \left(\frac{(1-\alpha)\,\phi A}{\gamma} \right)^{1/\alpha} \tag{B.18}$$

which implies

$$L^* = \frac{\tilde{\lambda}}{\lambda} \left(\frac{(1-\alpha)(1-\phi)\,B}{\gamma} \right)^{\frac{1-\alpha}{\alpha\rho}} = \left(\frac{r+\lambda}{(1+r)\,\lambda} \right)^{1/\rho} \left(\frac{(1-\alpha)(1-\phi)\,B}{\gamma} \right)^{\frac{1-\alpha}{\alpha\rho}} \tag{B.19}$$

$$\frac{e^*}{1-e^*} = \left(\frac{\phi A}{(1-\phi)\,B} \right)^{1/\alpha} \tag{B.20}$$

$$N^* = \left(\frac{(1-\alpha)\,\phi A}{\gamma} \right)^{1/\alpha} + \left(\frac{(1-\alpha)(1-\phi)\,B}{\gamma} \right)^{1/\alpha} \tag{B.21}$$

which is expression (11) in the main text.

B.2 Proposition 3 for fixed adjustment costs

There are now two endogenous state variables in the problem, the level of employment N_{t-1} and the organizational capital stock L_{t-1}, and $V(N_{t-1}, L_{t-1})$ denotes the value of the planner's programme. We analyze a one-time permanent shock to technology A_t, as in appendix A.1, treating $A_t = A$ as a parameter, and keep the productivity of organizational capital production fixed at $B_t = 1$. Since the model with non-convex adjustment costs is highly non-linear and potentialy asymmetric, we consider only a positive shock, i.e. an increase in technology A_t. We also assume that organizational capital L_t is in steady state when the change in technology A_t occurs.

At each time t, the planner decides whether or not to adjust employment, whereas even if she decides not to adjust employment, she can still choose the allocation of workers e_t optimally, so that the value function satisfies the following Bellman equation,

$$V(N_{t-1}, L_{t-1}) = \max \left\langle \max_N V(N, L_{t-1}) - \psi \right., \tag{B.22}$$

$$\left. \max_{e_t} \left\{ \phi A (e_t N_t)^{1-\alpha} + (1-\phi) L_t^{\rho} - \gamma N_{t-1} + \frac{1}{1+r} V(N_{t-1}, L_t) \right\} \right\rangle \tag{B.23}$$

where

$$L_t = (1-\lambda) L_{t-1} + \tilde{\lambda} \left((1-e_t) N_t \right)^{\frac{1-\alpha}{\rho}} \tag{B.24}$$

as in (9) and $N_t = N_{t-1}$ if employment is not adjusted.

B.2.1 Outline of the proof

We show that for an intermediate sized shock, the optimal policy involves employment adjustment after a delay. The proof runs by contradiction. Suppose that delayed adjustment is not optimal. Then, the optimal policy must be either to immediately hire some more workers or to never do so. In sections B.2.2 and B.2.3, we solve for the net present value of profits under each of these policies, which we denote by V_{IA} and V_{NA} respectively. In section B.2.4, we then show that there exists a feasible adjustment strategy involving delayed adjustment that gives a higher net present value of profits V_{DA} than never adjusting employment, $V_{DA} - \psi > V_{NA}$ at time $t \to \infty$, and than immediately adjusting employment, $V_{NA} > V_{IA} - \psi$ at time $t = 0$. Therefore, neither of the two possible strategies without delay is optimal and it must be that the optimal policy involves delay.

B.2.2 Immediate adjustment

If employment is adjusted immediately after the increase in productivity, it is set to maximize the value of the program henceforward. Since the optimal amount of hiring will depend on the initial value of the organizational capital stock, in general it is hard to solve for V_{IA}, but the problem simplifies considerably with our assumption that the economy was initially in steady state. In this case, the economy will be in steady state after the one-time permanent increase in technology A_t as well, see the discussion below equation (B.15) above, and there are no dynamics beyond the initial adjustments in e_t and N_t.

Conditional on adjusting employment, the optimal level of employment is the same as in the frictionless case, so that the value of the program with immediate adjustment, after the adjustment costs are sunk, simply equals the value in the frictionless model, which equal the net present value of an infinite stream of constant profits, see (B.12),

$$V_{IA}\left(N_{t-1}, L^*\right) = V\left(N^*, L^*\right) = \frac{1+r}{r}\left[\phi A\left(e^* N^*\right)^{1-\alpha} + (1-\phi)\left(L^*\right)^{\rho} - \gamma N^*\right] \quad \text{(B.25)}$$

where L^*, e^* and N^* as in (B.19), (B.20) and (4), respectively.

B.2.3 No adjustment

If the planner decides not to adjust employment, Bellman equation (B.22) reduces to

$$V\left(N_{t-1}, L_{t-1}\right) = \max_{e_t}\left\{\phi A\left(e_t N_{t-1}\right)^{1-\alpha} + (1-\phi) L_t^{\rho} - \gamma N_{t-1} + \frac{1}{1+r} V\left(N_{t-1}, L_t\right)\right\} \quad \text{(B.26)}$$

In this case the first order condition for e_t and the envelope condition for L_t may be combined to get an Euler equation for the fraction of workers assigned to current productive tasks e_t.

$$\phi A \left(e_t N_{t-1}\right)^{-\alpha} = (1-\phi) L_t^{-\alpha} + \frac{1-\lambda}{1+r} A \left(e_{t+1} N_{t-1}\right)^{-\alpha} \tag{B.27}$$

The Euler equation and the law of motion for organizational capital (B.24) constitute a system of two difference equations that describes the joint dynamics of e_t and L_t. The system is close to linear, and with a quadratic production function it would have been exactly linear. We can linearize it by simply linearizing the marginal product function around the frictionless steady state, i.e. e_t around $e^* N^*/N_{t-1}$ and L_t around L^*. The linear system has one stable root, $1-\lambda$, and one unstable root, $(1+r)/(1-\lambda)$, so that the solution is unique. When technology changes, e_t jumps to the saddle path and then e_t and L_t gradually converge to their new steady state, which is different from the frictionless optimal one.

The steady state of the system is given by

$$\frac{\bar{e}}{1-\bar{e}} = \left(\frac{\phi A}{1-\phi}\right)^{1/\alpha} = \frac{e^*}{1-e^*} \tag{B.28}$$

which is the same as in the frictionless optimum steady state, and organizational capital

$$\bar{L} = \frac{\tilde{\lambda}}{\lambda}\left(1-e^*\right) N_{t-1} = \frac{N_{t-1}}{N^*} L^* \tag{B.29}$$

where L^* does not depend on A, so is the same before and after the improvement in technology.

Recall that before the change in technology employment was at its frictionless optimal level, so that $N_{t-1} < N^*$ after the increase in A_t. Therefore, the new steady state for organizational capital is lower than L^* and L_t slowly decreases. For e_t two things happen. First, the increase in technology raises its steady state e^*. Second, initially $L_t > \bar{L}$, which by the Euler equation implies $e_t > e_{t+1}$, so that e_t overshoots its already higher steady state and therefore declines over the transition.

The value of the program without employment adjustment is found by substituting the optimal policy for e_t into Bellman equation (B.26). The effects of e_t and L_t on the value of the program work in the same direction.

$$V_{NA}\left(N_t, L_t\right) = \sum_{s=0}^{\infty} \left(\frac{1}{1+r}\right)^s \left(\frac{A_t}{1-\alpha}\left(e_{t+s} N_t\right)^{1-\alpha} + \frac{B_t}{1-\alpha} L_{t+s}^{1-\alpha} - \gamma N_t\right) \tag{B.30}$$

After the increase in A, both L_t and e_t decrease, so that V_{NA} decreases as well.

Comparing (B.25) and (B.30), it is clear that initially the value of the firm is higher if employment is immediately adjusted, $V_{IA}\left(N_{t-1}, L^*\right) > V_{NA}\left(N_{t-1}, L^*\right)$, simply because $V_{IA}\left(N_{t-1}, L^*\right) = V\left(N^*, L^*\right) = \max_N V_{NA}\left(N, L^*\right)$. Of course, that observation does not imply that it is always preferrably to adjust employment, because of the adjustment costs. More importantly for the proof, the value of the program without adjusting employment is not constant over time. Since the value function is strictly increasing in L_t, $V_{NA}(N_t, L_t)$ decreases over time as the organizational capital stock is slowly depleted and, after an initial major rellocation towards production, workers are gradually allocated back from production to organizational tasks.

B.2.4 Delayed adjustment

Now consider the decision whether or not to hire extra workers, and suppose that the firm is only allowed to adjust employment immediately or not at all. Comparing (B.25) and (B.30), we see that the difference between the net present value of profits in either case $V_{IA}(N_{t-1}, L^*) - V_{NA}(N_{t-1}, L^*)$ is increasing in the size of the shock $N^* - N_{t-1}$. Therefore, if the shock is sufficiently small, then $V_{IA} - V_{NA} < \psi$ and the firm prefers not to adjust employment at $t = 0$, whereas if the shock is sufficiently large, then $V_{IA} - V_{NA} > \psi$ and the firm prefers to immediately hire more workers.

An interesting situation arises if $N^* - N_{t-1}$ is small enough so that $V_{IA} - V_{NA} < \psi$, i.e. the firms prefers no hiring over immediately hiring, but not by much. Since V_{NA} decreases over time, in this case the inequality is reverted at some point, i.e. $V_{IA} - V_{NA} > \psi$ for some $t > T$, at which point the firm would regret not having adjusted employment immediately. Of course, immediately adjusting and never adjusting employment are not the only two choices available to the firm, and the fact that firms may regret their decision to not adjust employment immediately if these were the only two options does not immediately imply that delayed adjustment is the optimal policy. However, we will show that there exists a feasible policy involving delayed adjustment that dominates both the option to immediately adjust and the option to never adjust employment. This will complete the proof of proposition 3.

Consider the following adjustment policy. When productivity increases, initially no new workers are hired but the fraction of workers assigned to current productive tasks is set to the level e^* that is optimal in the new steady state. Then, after a long time T, new workers are hired, setting employment to the same levels that would have been optimal if these workers would have been hired immediately, maintaining the fraction of workers assigned to current production at e^*. While not necessarily optimal, because the organizational capital stock will no longer be at L^* when employment is adjusted, this policy is clearly feasible. We will show that this adjustment policy results in higher profits both than adjusting immediately and than never adjusting employment.

If we let the time of adjustment $T \to \infty$, then the value of the program under the proposed policy with delayed adjustment approaches the value of the program if employment is never adjusted at time zero $V_{DA} \to V_{NA}$. On the other hand, at time T, when employment adjustment has just happened, the value of the program under delayed adjustment equals the value of the program under immediate adjustment, except that the organizational capital stock is at its steady state level under no adjustment, $V_{DA}(N^*, L_T) = V_{IA}\left(N^*, \frac{N_{t-1}}{N^*} L^*\right)$. Delayed adjustment dominates both immediate adjustment and no adjustment if it preferred over immediate adjustment at time zero and over not adjusting at time T and onwards. Thus, we need the following two conditions to hold simultaneously:

$$V_{NA}\left(N_{t-1}, L^*\right) > V_{IA}\left(N^*, L^*\right) - \psi \tag{B.31}$$

$$V_{IA}\left(N^*, \frac{N_{t-1}}{N^*}L^*\right) - \psi > V_{NA}\left(N_{t-1}, \frac{N_{t-1}}{N^*}L^*\right) \tag{B.32}$$

For each N_{t-1}/N^*, we can find a ψ for which both inequalities are satisfied, which implies that for each ψ, we can also find a shock N_{t-1}/N^* which satisfies both conditions.

B.3 Proposition 4 for convex adjustment costs

B.3.1 Derivation of the quilibrium conditions

Bellman equation

$$V\left(N_{t-1}, L_{t-1}\right) = \max_{e_t, h_t}\left\{\phi A_t\left(e_t N_t\right)^{1-\alpha} + (1-\phi) B_t L_t^{\rho} - \gamma N_t - \frac{1}{2}\psi h_t^2 + \frac{1}{1+r} V\left(N_t, L_t\right)\right\} \tag{B.33}$$

where

$$N_t = N_{t-1} + h_t \tag{B.34}$$

$$L_t = (1-\lambda) L_{t-1} + \tilde{\lambda}\left(\left(1-e_t\right) N_t\right)^{\frac{1-\alpha}{\rho}} \tag{B.35}$$

FOC(h_t)

$$\begin{aligned} 0 = {} & (1-\alpha)\phi A_t\left(e_t N_t\right)^{-\alpha} e_t + \rho(1-\phi) B_t L_t^{\rho-1}\frac{1-\alpha}{\rho}\tilde{\lambda}\left(\left(1-e_t\right)N_t\right)^{\frac{1-\alpha}{\rho}-1}\left(1-e_t\right) - \gamma - \psi h_t \\ & + \frac{1}{1+r}\left\{V_{1,t+1} + \frac{1-\alpha}{\rho}\tilde{\lambda}\left(\left(1-e_t\right)N_t\right)^{\frac{1-\alpha}{\rho}-1}\left(1-e_t\right) V_{2,t+1}\right\} \end{aligned} \tag{B.36}$$

EC(N_{t-1})

$$\begin{aligned} V_{N,t} = {} & (1-\alpha)\phi A_t\left(e_t N_t\right)^{-\alpha} e_t + \rho(1-\phi) B_t L_t^{\rho-1}\frac{1-\alpha}{\rho}\tilde{\lambda}\left(\left(1-e_t\right)N_t\right)^{\frac{1-\alpha}{\rho}-1}\left(1-e_t\right) - \gamma \\ & + \frac{1}{1+r}\left\{V_{N,t+1} + \frac{1-\alpha}{\rho}\tilde{\lambda}\left(\left(1-e_t\right)N_t\right)^{\frac{1-\alpha}{\rho}-1}\left(1-e_t\right) V_{L,t+1}\right\} \end{aligned} \tag{B.37}$$

which imply

$$V_{N,t} = \psi h_t \tag{B.38}$$

and an Euler equation for hiring

$$\begin{aligned} \psi h_t = {} & (1-\alpha)\phi A_t\left(e_t N_t\right)^{-\alpha} e_t + \rho(1-\phi) B_t L_t^{\rho-1}\frac{1-\alpha}{\rho}\tilde{\lambda}\left(\left(1-e_t\right)N_t\right)^{\frac{1-\alpha}{\rho}-1}\left(1-e_t\right) - \gamma \\ & + \frac{1}{1+r}\left\{\psi h_{t+1} + \frac{1-\alpha}{\rho}\tilde{\lambda}\left(\left(1-e_t\right)N_t\right)^{\frac{1-\alpha}{\rho}-1}\left(1-e_t\right) V_{L,t+1}\right\} \end{aligned} \tag{B.39}$$

FOC(e_t)

$$
\begin{aligned}
0 &= (1-\alpha)\,\phi A_t\,(e_t N_t)^{-\alpha} N_t - \rho\,(1-\phi)\,B_t L_t^{\rho-1}\frac{1-\alpha}{\rho}\tilde{\lambda}\,((1-e_t)\,N_t)^{\frac{1-\alpha}{\rho}-1} N_t \\
&\quad - \frac{1}{1+r}\frac{1-\alpha}{\rho}\tilde{\lambda}\,((1-e_t)\,N_t)^{\frac{1-\alpha}{\rho}-1} N_t V_{L,t+1} \qquad \text{(B.40)}
\end{aligned}
$$

EC(L_t)

$$
V_{L,t} = \rho\,(1-\phi)\,B_t L_t^{\rho-1}\,(1-\lambda) + \frac{1-\lambda}{1+r}V_{L,t+1} \qquad \text{(B.41)}
$$

Use the FOC for e_t to further simplify the Euler equation for h_t

$$
\psi h_t = (1-\alpha)\,\phi A_t\,(e_t N_t)^{-\alpha} - \gamma + \frac{1}{1+r}\psi h_{t+1} \qquad \text{(B.42)}
$$

which is exactly the same as for the model with separable production function, except for the ϕ and the e_t, so that any change in the dynamics for h_t will need to come through dynamics in e_t. Using the expression for the frictionless optimum steady state $e^* N^*$, see equation (11), to elimate the technology shock, $(1-\alpha)\,\phi A_t = \gamma\,(e^* N^*)^{\alpha}$, the Euler equation for hiring can be rewritten as (12) in the main text.

Combine the FOC for e_t and the EC for L_t in the usual way to get a second Euler equation.

$$
V_{L,t} = \rho\frac{1-\lambda}{\tilde{\lambda}}\phi A_t\frac{(e_t N_t)^{-\alpha}}{((1-e_t)\,N_t)^{\frac{1-\alpha}{\rho}-1}} \qquad \text{(B.43)}
$$

$$
\frac{(e_t N_t)^{-\alpha}}{((1-e_t)\,N_t)^{\frac{1-\alpha}{\rho}-1}} = \tilde{\lambda}\frac{(1-\phi)\,B_t}{\phi A_t}L_t^{\rho-1} + \frac{1-\lambda}{1+r}\frac{A_{t+1}}{A_t}\frac{(e_{t+1} N_{t+1})^{-\alpha}}{((1-e_{t+1})\,N_{t+1})^{\frac{1-\alpha}{\rho}-1}} \qquad \text{(B.44)}
$$

which again forms a saddle-path stable system of difference equations in combination with the LOM for OC

$$
L_t = (1-\lambda)\,L_{t-1} + \tilde{\lambda}\,((1-e_t)\,N_t)^{\frac{1-\alpha}{\rho}} \qquad \text{(B.45)}
$$

B.3.2 The dynamics of hiring

Summarizing, the dynamics of hiring h_t, joint with those for e_t, N_t and L_t are given by the following dynamic system.

$$
\psi h_t = (1-\alpha)\,\phi A_t\,(e_t N_t)^{-\alpha} - \gamma + \frac{1}{1+r}\psi h_{t+1} \qquad \text{(B.46)}
$$

$$
\frac{(e_t N_t)^{-\alpha}}{((1-e_t)\,N_t)^{\frac{1-\alpha}{\rho}-1}} = \tilde{\lambda}\frac{(1-\phi)\,B_t}{\phi A_t}L_t^{\rho-1} + \frac{1-\lambda}{1+r}\frac{A_{t+1}}{A_t}\frac{(e_{t+1} N_{t+1})^{-\alpha}}{((1-e_{t+1})\,N_{t+1})^{\frac{1-\alpha}{\rho}-1}} \qquad \text{(B.47)}
$$

$$
N_t = N_{t-1} + h_t \qquad \text{(B.48)}
$$

$$
L_t = (1-\lambda)\,L_{t-1} + \tilde{\lambda}\,((1-e_t)\,N_t)^{\frac{1-\alpha}{\rho}} \qquad \text{(B.49)}
$$

These are four difference equations in four unknowns, which we solve numerically using Dynare.

For some parameter values, the model predicts a delay in hiring, in the sense that the response of hiring to an increase in technology peaks not on impact of the shock but one or more periods later. To explore how these dynamics depend on parameter values, we define the following summary statistics:

1. We say that the response of hiring exhibits delay if hiring initially increases after a shock, i.e. if $|h_{\tau+1}| > |h_\tau|$ where τ is the period that the change in technology A_t occurs.

2. If there is delay, then we define the amount of delay as the relative increase in hiring after impact. Let h_τ be hiring in the period the change in technology occurs, and let h_p denote hiring in the peak period. Then, the amount of delay is defined as $(|h_p| - |h_\tau|) / |h_p|$.

3. The length of the delay is defined simply as the time between the period in which hiring peaks and the period when the shock hit, $p - \tau$.

Figures B.1 and B.2 show for which combinations of adjustment costs ψ, share $1 - \phi$ and depreciation rate λ of organizational capital delayed hiring occurs. Figures B.3, B.4, B.5, B.6 and B.7 show the amount and length of the delay as a function of adjustment costs ψ, the discount rate r, the organizational capital share $1 - \phi$, the depreciation rate of organizational capital λ, and diminishing returns in organizational capital ρ, respectively. Delayed adjustment is more likely to occur, larger and longer for higher adjustment costs, a higher discount rate, a higher organizational capital share and a lower depreciation rate of organizational capital. Delay becomes less likely as diminishing returns in the use of organizational capital in production disappear, i.e. for $\rho \to 1$ and the length of the delay seems to be maximized for ρ around $1 - \alpha = 0.67$, i.e. if diminishing returns are entirely in the use rather than the production of organizational capital.

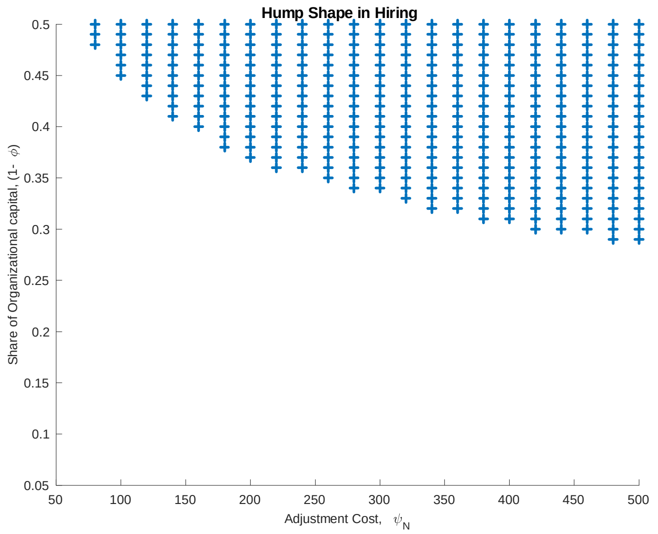

Figure B.1: Delayed adjustment (+) for different values of adjustment costs ψ and the share of organizational capital in production $1 - \phi$

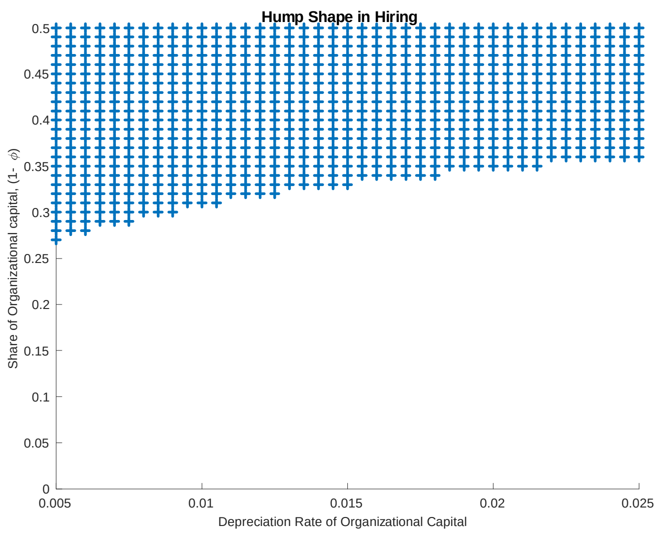

Figure B.2: Delayed adjustment (+) for different values of the depreciation rate of organizational capital λ and the share of organizational capital in production $1 - \phi$

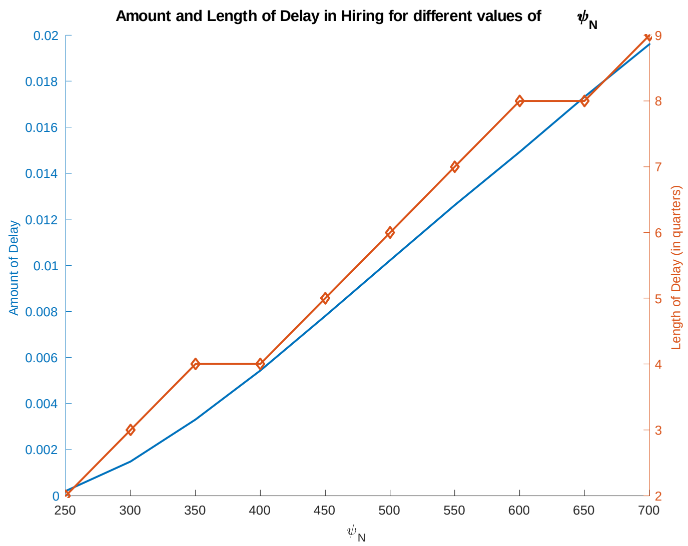

Figure B.3: Amount and length of delay in hiring for different values of adjustment costs ψ

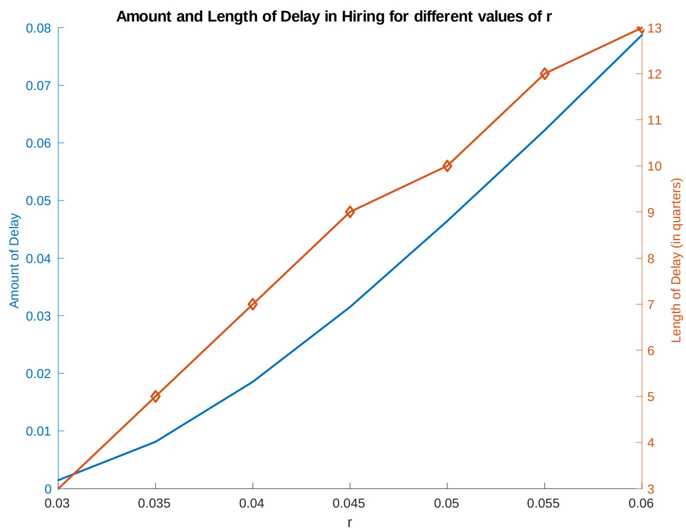

Figure B.4: Amount and length of delay in hiring for different values of the discount rate r

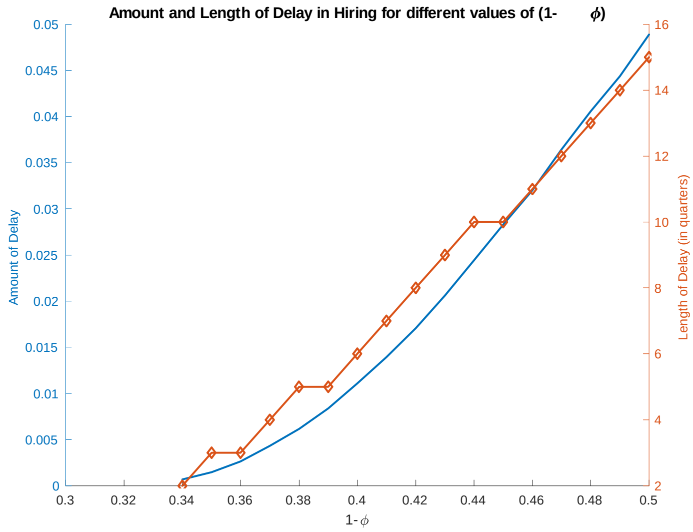

Figure B.5: Amount and length of delay in hiring for different values of the share of organizational capital in production $1 - \phi$

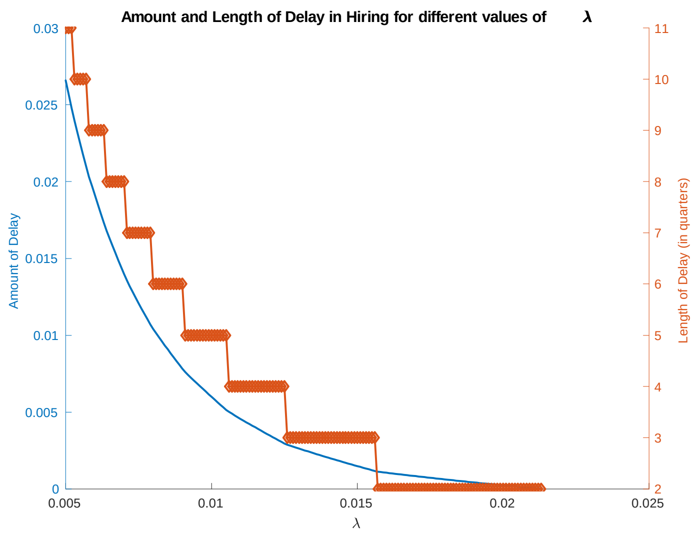

Figure B.6: Amount and length of delay in hiring for different values of the depreciation rate of organizational capital λ

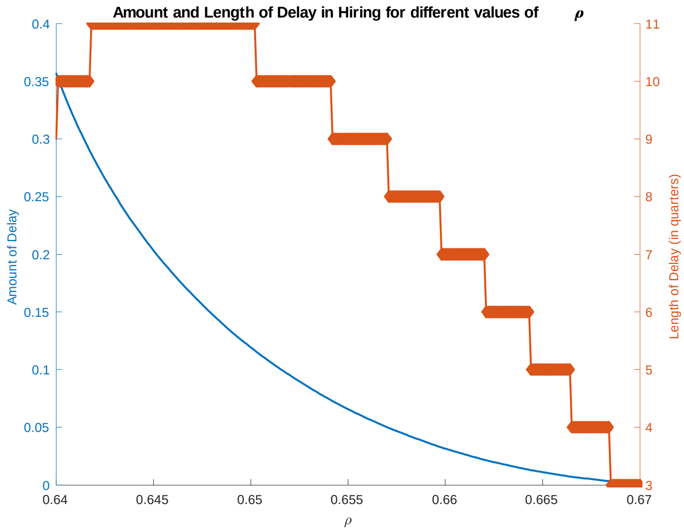

Figure B.7: Amount and length of delay in hiring for different values of diminishing returns to organizational capital ρ

C Capital adjustment

The Bellman equation is given by

$$V\left(K_{t-1}, L_{t-1}\right)=\max_{u_t, i_t}\left\{\phi A_t\left(u_t K_t\right)^\alpha+(1-\phi) B_t L_t^\rho-i_t-\frac{\psi}{2} i_t^2+\frac{1}{1+r} E_t V\left(K_t, L_t\right)\right\} \tag{C.50}$$

where

$$K_t=K_{t-1}+i_t \tag{C.51}$$

$$L_t=(1-\lambda) L_{t-1}+\tilde{\lambda}\left(\left(1-u_t\right) K_t\right)^{\frac{\alpha}{\rho}} \tag{C.52}$$

Following the same steps as in appendix B.3 (combining the first-order condition for i_t with the envelope condition for K_t to get an Euler equation, and then using the first-order condition for u_t to simplify it), we get the following Euler equation for investment

$$\psi i_t=\alpha \phi A_t\left(u_t K_t\right)^{\alpha-1}-\frac{r}{1+r}+\frac{1}{1+r} \psi h_{t+1} \tag{C.53}$$

Setting $\psi=0$ for the frictionless allocation gives,

$$\alpha \phi A_t\left(u_t^* K_t^*\right)^{\alpha-1}=\frac{r}{1+r} \tag{C.54}$$

so that we can rewite the Euler equation as,

$$\psi i_t=\left(\frac{u_t}{u_t^*} \frac{K_t}{K_t^*}\right)^{\alpha-1} \frac{r}{1+r}-\frac{r}{1+r}+\frac{1}{1+r} \psi h_{t+1} \tag{C.55}$$

which simplifies to equation (16) in the main text.

D Equilibrium conditions quantitative model

Bellman equation

$$V\left(N_{t-1},K_{t-1},L_{t-1}\right)=\max_{e_t,u_t,h_t,i_t}\left\{Z_t\left[\phi\left(A_t\left(u_tK_t\right)^{\alpha}\left(e_tN_t\right)^{1-\alpha}\right)^{\frac{\sigma-1}{\sigma}}+\left(1-\phi\right)\left(B_tL_t^{\rho}\right)^{\frac{\sigma-1}{\sigma}}\right]^{\frac{\sigma\theta}{\sigma-1}}\right.$$
$$\left.-\gamma N_t-Z_ti_t-\delta_KZ_tK_{t-1}-\frac{\psi_N}{2}Z_th_t^2-\frac{\psi_K}{2}Z_ti_t^2+\frac{1}{1+r}E_tV\left(N_t,K_t,L_t\right)\right\} \tag{D.56}$$

where

$$N_t=N_{t-1}+h_t \tag{D.57}$$

$$K_t=K_{t-1}+i_t \tag{D.58}$$

$$L_t=\left(1-\lambda\right)L_{t-1}+\tilde{\lambda}\left(\left(1-u_t\right)K_t\right)^{\frac{\alpha}{\rho}}\left(\left(1-e_t\right)N_t\right)^{\frac{1-\alpha}{\rho}} \tag{D.59}$$

D.1 Labor

Combining FOC(h_t) and EC(N_{t-1}) to get an Euler equation for h_t

$$V_N\left(N_{t-1},K_{t-1},L_{t-1}\right)=\psi_NZ_th_t \tag{D.60}$$

$$Z_t\psi_Nh_t=\theta\left[...\right]^{\frac{\sigma\theta}{\sigma-1}-1}Z_t\left[\left(1-\alpha\right)\phi\left(A_t\left(u_tK_t\right)^{\alpha}\left(e_tN_t\right)^{1-\alpha}\right)^{\frac{\sigma-1}{\sigma}}\frac{1}{N_t}\right.$$
$$\left.+\left(1-\alpha\right)\left(1-\phi\right)\left(B_tL_t^{\rho}\right)^{\frac{\sigma-1}{\sigma}}\frac{1}{L_t}\tilde{\lambda}\left(\left(1-u_t\right)K_t\right)^{\frac{\alpha}{\rho}}\left(\left(1-e_t\right)N_t\right)^{\frac{1-\alpha}{\rho}}\frac{1}{N_t}\right]-\gamma$$
$$+\frac{1-\alpha}{\rho}\tilde{\lambda}\left(\left(1-u_t\right)K_t\right)^{\frac{\alpha}{\rho}}\left(\left(1-e_t\right)N_t\right)^{\frac{1-\alpha}{\rho}}\frac{1}{N_t}\frac{1}{1+r}E_tV_L\left(N_t,K_t,L_t\right)+\frac{\psi_N}{1+r}E_tZ_{t+1}h_{t+1} \tag{D.61}$$

Simplify using FOC(e_t)

$$\psi_Nh_t=\theta\left[...\right]^{\frac{\sigma\theta}{\sigma-1}-1}\left(1-\alpha\right)\phi\left(A_t\left(u_tK_t\right)^{\alpha}\left(e_tN_t\right)^{1-\alpha}\right)^{\frac{\sigma-1}{\sigma}}\frac{1}{e_tN_t}-\frac{\gamma}{Z_t}+\psi_NE_t\left[\frac{1}{1+r}\frac{Z_{t+1}}{Z_t}h_{t+1}\right] \tag{D.62}$$

D.2 Capital

Combine FOC(i_t) and EC(K_{t-1}) to get an Euler equation for i_t

$$V_K\left(N_{t-1},K_{t-1},L_{t-1}\right)=Z_t\left(1-\delta_K+\psi_Ki_t\right) \tag{D.63}$$

$$
\begin{aligned}
Z_t\left(1-\delta_K+\psi_K i_t\right) = \theta\,[...]^{\frac{\sigma\theta}{\sigma-1}-1} Z_t & \left[\alpha\phi\left(A_t\left(u_t K_t\right)^{\alpha}\left(e_t N_t\right)^{1-\alpha}\right)^{\frac{\sigma-1}{\sigma}}\frac{1}{K_t}\right. \\
& \left. +\alpha\left(1-\phi\right)\left(B_t L_t^{\rho}\right)^{\frac{\sigma-1}{\sigma}}\frac{1}{L_t}\tilde{\lambda}\left(\left(1-u_t\right)K_t\right)^{\frac{\alpha}{\rho}}\left(\left(1-e_t\right)N_t\right)^{\frac{1-\alpha}{\rho}}\frac{1}{K_t}\right] - Z_t\delta_K \\
& + \frac{\alpha}{\rho}\tilde{\lambda}\left(\left(1-u_t\right)K_t\right)^{\frac{\alpha}{\rho}}\left(\left(1-e_t\right)N_t\right)^{\frac{1-\alpha}{\rho}}\frac{1}{K_t}\frac{1}{1+r}E_t V_L\left(N_t,K_t,L_t\right) \\
& + \frac{1}{1+r}E_t\left[1-\delta_K+\psi_K i_{t+1}\right]
\end{aligned}
\tag{D.64}
$$

Simplify using the FOC(u_t)

$$
\begin{aligned}
\psi_K i_t = {} & \theta\,[...]^{\frac{\sigma\theta}{\sigma-1}-1}\alpha\phi\left(A_t\left(u_t K_t\right)^{\alpha}\left(e_t N_t\right)^{1-\alpha}\right)^{\frac{\sigma-1}{\sigma}}\frac{1}{u_t K_t} \\
& -\left(\frac{r+\delta_K}{1+r}-\frac{1-\delta_K}{1+r}\frac{Z_{t+1}-Z_t}{Z_t}\right)+\psi_K E_t\left[\frac{1}{1+r}\frac{Z_{t+1}}{Z_t}i_{t+1}\right]
\end{aligned}
\tag{D.65}
$$

D.3 Organizational capital

Combine FOC(e_t) and FOC(u_t) to get a restriction on the allocations of labor and capital

$$
0 = \theta\,[...]^{\frac{\sigma\theta}{\sigma-1}-1} Z_t\left[\phi\left(A_t\left(u_t K_t\right)^{\alpha}\left(e_t N_t\right)^{1-\alpha}\right)^{\frac{\sigma-1}{\sigma}}\left(\frac{1-e_t}{e_t}-\frac{1-u_t}{u_t}\right)\right]
\tag{D.66}
$$

which implies

$$
e_t = u_t
\tag{D.67}
$$

EC(L_{t-1})

$$
V_L\left(N_{t-1},K_{t-1},L_{t-1}\right) = \theta\,[...]^{\frac{\sigma\theta}{\sigma-1}-1} Z_t\rho\left(1-\phi\right)\left(B_t L_t^{\rho}\right)^{\frac{\sigma-1}{\sigma}}\frac{1-\lambda}{L_t}+\frac{1-\lambda}{1+r}E_t V_L\left(N_t,K_t,L_t\right)
\tag{D.68}
$$

Combine FOC(e_t) and EC(L_{t-1}) to get a third Euler equation

$$
V_L\left(N_{t-1},K_{t-1},L_{t-1}\right) = \rho\frac{1-\lambda}{\tilde{\lambda}}\theta\,[...]^{\frac{\sigma\theta}{\sigma-1}-1} Z_t\phi\frac{\left(A_t\left(u_t K_t\right)^{\alpha}\left(e_t N_t\right)^{1-\alpha}\right)^{\frac{\sigma-1}{\sigma}}}{\left(\left(1-u_t\right)K_t\right)^{\frac{\alpha}{\rho}}\left(\left(1-e_t\right)N_t\right)^{\frac{1-\alpha}{\rho}}}\frac{1-e_t}{e_t}
\tag{D.69}
$$

$$
\Omega_t\frac{1-e_t}{e_t} = \frac{1-\phi}{\phi}\tilde{\lambda}\frac{\left(B_t L_t^{\rho}\right)^{\frac{\sigma-1}{\sigma}}}{L_t}+\left(1-\lambda\right)E_t\left[\frac{1}{1+r}\frac{Z_{t+1}}{Z_t}\frac{\Theta_{t+1}}{\Theta_t}\Omega_{t+1}\frac{1-e_{t+1}}{e_{t+1}}\right]
\tag{D.70}
$$

where

$$
\Theta_t = \theta\,[...]^{\frac{\sigma\theta}{\sigma-1}-1},\ \Omega_t = \frac{\left(A_t\left(u_t K_t\right)^{\alpha}\left(e_t N_t\right)^{1-\alpha}\right)^{\frac{\sigma-1}{\sigma}}}{\left(\left(1-u_t\right)K_t\right)^{\frac{\alpha}{\rho}}\left(\left(1-e_t\right)N_t\right)^{\frac{1-\alpha}{\rho}}}
\tag{D.71}
$$

D.4 Summary of equilibrium conditions

Definitions

$$\Theta_t = \theta \left[\phi \left(A_t \left(u_t K_t\right)^{\alpha} \left(e_t N_t\right)^{1-\alpha} \right)^{\frac{\sigma-1}{\sigma}} + (1-\phi) \left(B_t L_t^{\rho}\right)^{\frac{\sigma-1}{\sigma}} \right]^{\frac{\sigma\theta}{\sigma-1}-1} \tag{D.72}$$

$$\Omega_t = \frac{\left(A_t \left(u_t K_t\right)^{\alpha} \left(e_t N_t\right)^{1-\alpha} \right)^{\frac{\sigma-1}{\sigma}}}{\left(\left(1-u_t\right) K_t\right)^{\frac{\alpha}{\rho}} \left(\left(1-e_t\right) N_t\right)^{\frac{1-\alpha}{\rho}}} \tag{D.73}$$

Euler equation for hiring

$$\psi_N h_t = \Theta_t (1-\alpha) \phi \left(A_t \left(u_t K_t\right)^{\alpha} \left(e_t N_t\right)^{1-\alpha} \right)^{\frac{\sigma-1}{\sigma}} \frac{1}{e_t N_t} - \frac{\gamma}{Z_t} + \psi_N E_t \left[\frac{1}{1+r} \frac{Z_{t+1}}{Z_t} h_{t+1} \right] \tag{D.74}$$

Euler equation for investment

$$\begin{aligned} \psi_K i_t = {} & \Theta_t \alpha \phi \left(A_t \left(u_t K_t\right)^{\alpha} \left(e_t N_t\right)^{1-\alpha} \right)^{\frac{\sigma-1}{\sigma}} \frac{1}{u_t K_t} \\ & - \left(\frac{r+\delta_K}{1+r} - \frac{1-\delta_K}{1+r} \frac{Z_{t+1}-Z_t}{Z_t} \right) + \psi_K E_t \left[\frac{1}{1+r} \frac{Z_{t+1}}{Z_t} i_{t+1} \right] \end{aligned} \tag{D.75}$$

Labor and capital allocation

$$e_t = u_t \tag{D.76}$$

Euler equation for organizational investment

$$\Omega_t \frac{1-e_t}{e_t} = \frac{1-\phi}{\phi} \tilde{\lambda} \frac{\left(B_t L_t^{\rho}\right)^{\frac{\sigma-1}{\sigma}}}{L_t} + (1-\lambda) E_t \left[\frac{1}{1+r} \frac{Z_{t+1}}{Z_t} \frac{\Theta_{t+1}}{\Theta_t} \Omega_{t+1} \frac{1-e_{t+1}}{e_{t+1}} \right] \tag{D.77}$$

Laws of motion

$$N_t = N_{t-1} + h_t \tag{D.78}$$

$$K_t = K_{t-1} + i_t \tag{D.79}$$

$$L_t = (1-\lambda) L_{t-1} + \tilde{\lambda} \left(\left(1-u_t\right) K_t\right)^{\frac{\alpha}{\rho}} \left(\left(1-e_t\right) N_t\right)^{\frac{1-\alpha}{\rho}} \tag{D.80}$$

This is a system of 7 difference equations in 7 variables: e_t, u_t, h_t, i_t, N_t, K_t and L_t.

E Cross-industry evidence

The industry-level evidence for a positive correlation between delayed adjustment and organizational capital intensity, discussed in section 6.3 in the main text, is summarized in table E.1.

The measures of delay in hiring and investment were calculated from the US KLEMS dataset provided by the Bureau of Labor Statistics (2019a),[8] which contains information on labor and capital input (employment and capital services) and labor and capital productivity (output employee and per unit of capital services) as indices (2007=100) by 6-digit NAICS industries and year, for the period 1987-2018. We calculated (net) hiring and investment as the (annual) first difference in labor and capital input, respectively.

In order to obtain a scalar measure of delay, we first regress the first differences of hiring and investment on an MA(6) in the first differences of labor and capital productivity, respectively, where 6 annual lags correspond to the 24 quarterly lags we use for aggregate data. We impose the constraint that the sum of the coefficients in this MA regression equals zero, so that hiring and investment return to zero after 6 years, and construct the response of hiring and investment in levels. Then, we calculate the amount of delay as the difference between peak hiring/investment and hiring/investment on impact, as a fraction of peak hiring/investment.

We aggregated the 6-digit NAICS data to the appropriate level to match with data from other sources on organizational capital intensity. Information Capital intensity is reported in the same dataset at the 3-digit NAICS level, but only for manufacturing industries (NAICS codes 331-339, 18 industries). Data on intangible capital, organizational and training intensity (Carol Corrado (2016, table 5, p.100)) are from INTAN-Invest,[9] and are organized at major NACE (Nomenclature des Activités Économiques dans la Communauté Européenne) sectors. We use the NAICS 2017 to ISIC Rev.4 crosswalk provided by the Census Bureau,[10] in combination with ISIC REV.4 - NACE REV.2 crosswalk,[11] to match and aggregate to major NACE sectors. E-capital is calculated and reported by Hall (2000a, table 5, p.100) at the 2-digit SIC level (22 industries spanning almost the entire economy), whereas employer-provided training is reported by the Bureau of Labor Statistics (2019b, table 5, p.100) from the 1995 Survey of Employer Provided Training (SEPT) at the level of 9 major industries,[12] with a mapping provided to 2-digit SIC codes. We used the NAICS to SIC crosswalk from the NAICS Association,[13] to assign 4-digit SIC codes to the industries in our data, which we then aggregate to 2-digit SIC and BLS major industries. We average labor and capital input and productivity measures weighting by labor compensation cost in million US dollars as a measure of size of the different industries.

[8] https://www.bls.gov/mfp/
[9] http://www.intaninvest.net/
[10] https://www.census.gov/eos/www/naics/concordances/concordances.html
[11] https://ec.europa.eu/eurostat/ramon/relations/index.cfm?TargetUrl=LST_REL&IntCurrentPage=10
[12] https://www.bls.gov/news.release/sept.nws.htm
[13] https://www.naics.com/naics-to-sic-crosswalk-search-results/

Measure of OC intensity	Sample	Correlation with delay in hiring	investment
IC capital intensity (%)	3-digit NAICS ($N = 18$)	0.23	0.09
(BLS)	(manufacturing only)	[0.67]	[0.15]
Intangible capital intensity	NACE major industries ($N = 12$)	0.32	
(INTAN Invest)		[0.63]	
Organizational capital int	NACE major industries ($N = 12$)	−0.07	
(INTAN Invest)		[0.08]	
Training intensity	NACE major industries ($N = 12$)	−0.08	
(INTAN Invest)		[0.09]	
e-Capital (log)	2-digit SIC ($N = 15$)	−0.02	
		[0.01]	
CHS measure OC investment	Approx 3-digit NAICS ($N = 28$)	0.28	
(Squicciarinii & Le Mouel 2012)		[0.27]	
Task-based measure OC inv	Approx 3-digit NAICS ($N = 28$)	0.22	
(Squicciarinii & Le Mouel 2012)		[0.34]	
Employer-provided training	BLS major ind ($N = 8$)	0.69	
(% workers formal training)		[0.44]	
Employer-provided training	BLS major ind ($N = 8$)	0.38	
(hours of formal training)		[0.98]	

Table E.1: Persistence across industries. The amount of delay is measured as peak minus impact hiring or investment as a fraction of peak hiring/investment. Standard errors for the correlation coefficients were calculated using the delta method.