How Stimulative are Low Real Interest Rates for Intangible Capital?*

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Abstract

We study a framework with heterogeneous firms and financial imperfections, in which firms need to finance large investment projects using both savings and external financing. In this framework, lower interest rates stimulate investment by allowing firms to borrow more given their assets, and we call this effect the Collateral Channel. However, lower interest rates also dampen investment by reducing the accumulated return on retained earnings for firms that are net savers, and we call this effect the Saving Channel. When firms need to finance technologies based on intangible assets that have low collateral value, they finance a much larger part of their acquisitions with accumulated savings compared to firms investing in tangible technologies. Therefore, these firms are more likely to be net savers in equilibrium when they receive an investment opportunity, and lower interest rates have a dampening effect on firm investment because the Saving Channel dominates on the Collateral Channel. In a realistically calibrated model we show that the rise of intangible capital substantially dampens the positive effects of low interest rates on investment because of this mechanism. We also find strong empirical support for this effect by studying the investment and innovation decisions of US firms. Our findings show that financial factors are important to explain the relation between the rise of intangible capital and a dampening in the transmission channels of monetary policy.

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1 Introduction

In the last 40 years, industrialized countries have experienced a sharp rise in the importance of intangible capital—such as information technology and knowledge, human, and organizational capital—in production, and a gradual reduction in the reliance on physical capital (See Panel A in Figure 1). In parallel, there has been a remarkable rise in corporate cash holdings, a phenomenon sometimes referred to as the "corporate savings glut" (See Panel B in Figure 1). Several authors argue that the increase in cash holdings is driven by the rise in intangibles, since intangible capital is difficult to finance with debt because of its low collateral value. Therefore, firms planning for large intangible investments are likely to accumulate cash to be able to invest.[1] In this paper, we explore theoretically and empirically the consequences of intangible capital financing for the firm-level relation between investment and interest rates and, in turn, for aggregate outcomes.

We start by considering a stylized framework with firms that finance one-time investment projects using both debt, which is limited by the collateral value of their assets, and retained earnings. We show that lower interest rates stimulate investment by allowing firms to borrow more per unit of investment, and we call this effect the "collateral channel". However, lower interest rates also dampen investment by reducing the accumulated value of retained earnings, and we call this effect the "saving channel". When firms need to finance tangible technologies, which use assets that have high collateral value, they can finance most of the acquisitions by borrowing. Lower rates make this financing easier by loosening borrowing constraints, and the "saving channel" is muted because the fraction of investment to be financed with internal savings is very small. However, when firms need to finance intangible technologies, which use assets that have low collateral value, they finance a much larger part of their acquisitions with accumulated savings. In this case, lower interest rates have a dampening effect on firm investment because the "saving channel" dominates the "collateral channel". It follows that aggregate investment could even fall in response to lower interest rates.

The remainder of the paper examines whether this result, which is at odds with the conventional wisdom that lower rates should always stimulate investment by reducing the user cost of capital, is empirically relevant. We first extend the stylized model to consider a framework in which young firms invest in large productivity-enhancing innovation projects. The collateral and saving channels described before imply that an exogenous decline in the interest rate negatively affects the innovation of young intangible firms relative to the innovation of young tangible firms.

[1] E.g. see Falato et al. (2018), among others.

We test this prediction using US data on public companies. We estimate capital tangibility at the firm level following Corrado, Hulten, and Sichel (2009) and Falato et al. (2018). Innovations are measured using firms' patenting activity, and we identify large innovation projects as those granted patents that generated the largest increases in market value. We consider exogenous variations in interest rates driven by well-identified monetary policy shocks. Both regression and local projection analyses strongly support our theoretical predictions. We further provide a robustness check, based on the sensitivity of the innovation value to the interest rate, which excludes alternative explanations based on the innovation decisions of financially unconstrained firms.

In the last part of the paper, we extend the model described above by relaxing many simplifying assumptions. First, we allow firms to have stochastic investment opportunities that happen several times during their lifetime. Because of this feature, firms are heterogeneous in their asset holdings, and it is no longer the case that all constrained firms that expect to invest in the future are net savers. More specifically, some constrained firms are net borrowers, and in the model, as in the data, average firm leverage increases in asset tangibility. Second, we allow for both financially constrained and unconstrained firms to coexist and have investment opportunities. We show that the results of the simple model extend to this setting, and using a realistically calibrated version of the model we are able to generate two additional testable predictions. First, lower interest rates increase the misallocation of capital by increasing the dispersion in its marginal productivity, and such increase is larger in intangible industries than in tangible industries. Second, the sensitivity of capital to interest rates is more negative in tangible than in intangible industries. Also in this case, we provide empirical evidence based on regression and local projection analysis that is consistent with both predictions.

Overall, this paper provides new evidence that the rise of intangible capital, because of the different nature of its financing, significantly alters the dynamic relation between interest rates, aggregate investment, and the allocation of resources across productive units. This finding has important implications for the transmission of monetary policy to real economic activity, and it also suggests a new channel through which persistently low real interest rates can increase capital misallocation.

Related Literature

This paper is related to several strands of literature. The main motivation of our analysis is the technological change towards intangible capital, documented by many authors, e.g. Corrado and Hulten (2010), Corrado et al. (2012), Haskel and Westlake (2017), Falato et al. (2018), among others. In our model, the rise of intangible capital causes a rise in corporate cash holdings and a shift in the corporate sector from net borrower to net saver. Such a shift has been documented in several papers (Armenter and Hnatkovska, 2016; Quadrini, 2016; Chen, Karabarbounis, and Neiman, 2016; Shourideh and Zetlin-Jones, 2016, among others).[2]

Our finding that declining interest rates can worsen the optimal allocation of resources in intangible economies is related to Gopinath et al (2017), who analyze capital misallocation in Spain during a period of falling interest rates, and more broadly to the literature that has documented a decline in aggregate productivity after 2000. Fernald (2015) and Kahn and Rich (2007, 2013) estimate that growth in labor productivity and total factor productivity (TFP) in the U.S. switched from a high-growth to a low-growth regime from around 2003-2004. Cette, Fernald, and Mojon (2016) report that Europe experienced a similar pre-crisis pattern.

Other recent papers have linked the rise of intangible capital to the productivity slowdown. Liu, Mian, and Sufi (2019), De Ridder (2020), and Aghion et al. (2019) argue that intangible technologies give incumbent and highly productive firms a competitive advantage by reducing their expansion costs. This factor deters competition, creative destruction, and aggregate productivity growth. Chiavari and Goraya (2020) document that intangible capital features larger fixed adjustment costs than tangible capital, and entails larger entry costs that reduce competition and increase concentration.

Finally, our paper is closely related to the research that attributes the rise in cash holdings to increasing firm-level precautionary saving motives driven by financial imperfections (among others, see Falato et al., 2018, and Begenau and Palazzo, 2016). Conversely, Dottling, Ladika, and Perotti (2019) argue that intangible capital requires less external finance than tangible capital because it is partly financed with deferred employee compensation (mostly in the form of stock options). In their framework, intangible firms still need to accumulate substantial cash holdings to insure the equity claims of workers. Other suggested motives for the high cash holdings in intangibles firms have to do with innovation in competitive markets (Lyandres and Palazzo, 2016). In this paper we focus on savings driven by financial frictions instead. Nonetheless, our main results about the interaction between the rise of intangibles and the interest rate sensitivity of corporate investment only rely on the "saving channel" being important for firms' investment decisions, regardless of the specific factors that drive intangibles firms to hold large amounts of liquid assets.

[2] Our paper is also related to the literature on the causes and consequences of falling real interest rates. Gagnon, Johannsen, and Lopez-Salido (2016) and Eggertsson, Mehrotra, and Robbins (2017) perform a quantitative theoretical analysis based on realistic demographic changes in the U.S. in recent decades, and both conclude that demographic factors—in particular, increased life expectancy and decreased fertility rates—can account for an important share of the real interest rate fall. Similar arguments have also been made by Baldwin and Teulings (2014), Rachel and Smith (2015), and Bean (2016). In this paper, we abstract from the factors driving the decline in the interest rate, and therefore our analysis is robust to these different drivers.

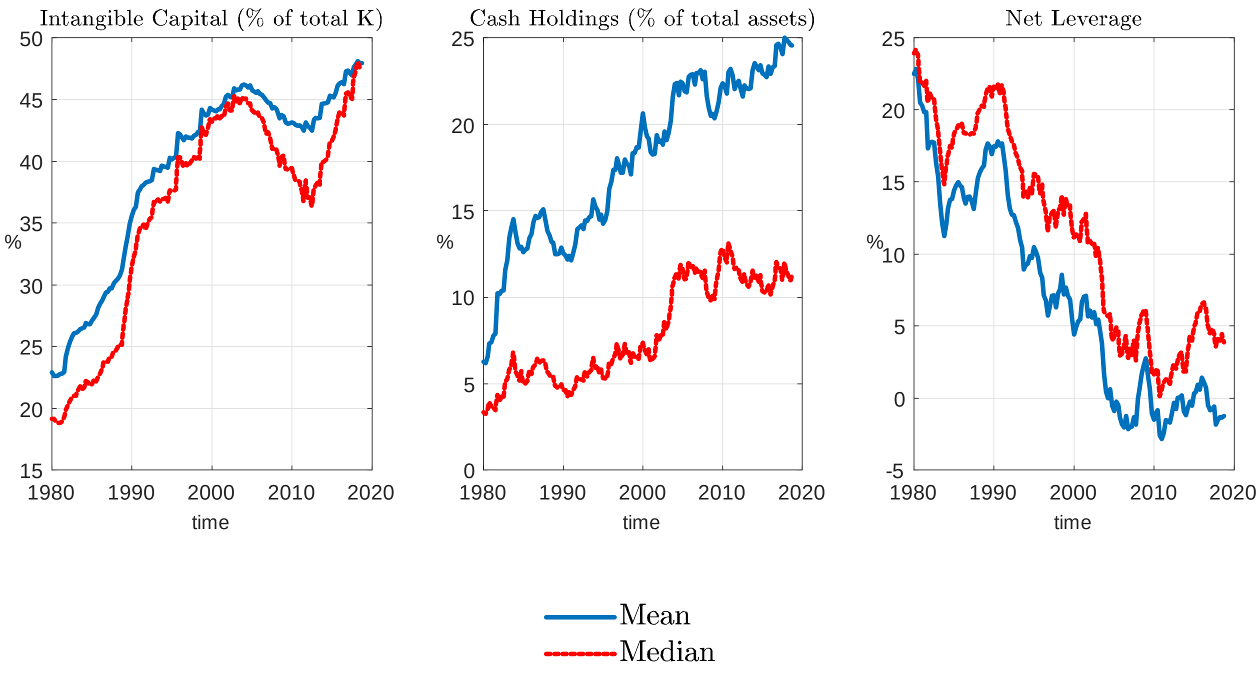


Figure 1: **Rise in intangible intensity and reduction in net leverage in U.S. non-financial listed firms**. The sample used to compute these series consists of U.S. public firms excluding utilities and financials. Intangible capital is the sum of knowledge capital and organizational capital, measured by capitalizing, respectively, R&D expenses and a fraction of selling, general and administrative (SG&A) expenses. Net leverage is equal to the ratio of total debt minus cash and short term investments to total book assets. Further discussion of the construction of these series is in Section 4.6. (Source: Compustat)

2 Motivating Empirical Evidence

Figure 1 shows the trends for intangible capital, cash holdings and net leverage for the 1980-2018 period.[3] The first panel confirms a positive trend of intangible capital as a share of total capital, both computed as mean or as median. A brief reversal, between 2005 to 2010, is followed by a further increase from 2010 onward. The second panel documents the increase in cash holdings as a percentage over total assets during the same period. The increase is stronger for the mean than the median, reflecting the fact that cash holdings are especially high among a small number of large firms, but it is also clearly noticeable for the median firm in the sample. Finally, the third panel shows net leverage, defined as total debt minus cash and short-term investments. This is decreasing over time, and reaching average values around zero or negative after 2005.

Our premise is that financial factors are important determinants of these parallel trends. Because intangible capital is less collateralizable than tangible capital, intangible firms need to

[3]The figure extends the evidence shown by Falato et al. (2018) up to 2010. The sample used to compute these series consists of U.S. public firms excluding utilities and financials. A detailed description of the construction of these series is in Section 4.6.

accumulate more cash to finance investment projects the tangible firms. As mentioned above, there are several pieces of evidence consistent with this assumption.

First, several authors have emphasized both that tangibility is important in determining firms access to credit (e.g. Almeida and Campello, 2007), and that firms investing in intangible projects face financial frictions. Hall (2002) documents, in an extensive survey of the literature, that "*R&D-intensive firms feature much lower leverage, on average, than less R&D-intensive firms*". She concludes that "*small and new innovative firms experience high costs of capital that are only partly mitigated by the presence of venture capital*". Brown, Fazzari, and Petersen (2009) document that U.S. firms finance most of their R&D expenditures out of retained earnings and equity issues. Gatchev, Spindt, and Tarhan (2009) document that, in addition to R&D, marketing expenses and product development are also mostly financed out of retained earnings and equity. Dell'Ariccia et al. (2017) document that the increased usage of intangible assets by firms helps explain why banks have shifted out of business lending and into residential real estate lending in the U.S. in recent decades. In contrast, tangible assets are mostly financed with debt.[4]

Second, other authors provide direct evidence that financial frictions are driving the rising in corporate cash holdings. Falato et al. (2018) show that the parallel trends in Figure 1 are interrelated. Cash holdings rise the most in the industries that became more reliant on intangible capital over time, and the positive correlation is also found within firms over time. They also show, in a quantitative dynamic model of corporate cash holdings, that one key feature to explain this correlation over time and across firms is financial frictions. Begenau and Palazzo (2016) introduce evidence showing that an important determinant of the increase in cash holdings of public firms is the increase in frequency of new firms that are very R&D intensive and hold large amounts of cash, and show that these trends are consistent with a model in which firms precautionary save because of high financing costs.

3 Simple and Intuitive Explanation of the Mechanisms

The objective of this section is to develop the simplest possible model that can describe our proposed mechanisms and deliver analytical results on the effect of capital tangibility on the relation between interest rates and investment. To this end, in this section we introduce a series of simplifying assumptions that will later be later relaxed in sections 4 and 5.

[4]Eisfeldt and Rampini (2009) report that a big share of machinery, equipment, buildings and other structures is financed with debt. Inventory investment and other tangible short-term assets attract substantial debt finance in the form of trade credit and bank credit lines (Petersen and Rajan, 1997; Sufi, 2009). Finally, investment in commercial real estate is primarily financed with mortgage loans (Benmelech, Garmaise, and Moskowitz, 2005).

A key element in our mechanism is the presence of large occasional investments at the firm level, which interact with financial frictions to drive firms to retain earnings and adopt a net saver position. Empirically, it is well known that individual investment is lumpy, because of the presence of non-convex adjustment costs, arising for example from fixed costs of investment.[5] Examples of these costs are those required to develop a new production plant, to introduce a new product, or to expand into new export markets. Other examples of lumpy investments are those generated by opportunities to innovate, or to merge with or acquire another company. Our results hold regardless of the nature of the investment, and apply to all investment projects that are infrequent, large relative to the size of the firm, and that cannot be financed mostly with external funds and need, as a result, to rely significantly on internal finance.

We consider a partial equilibrium model of an industry with a large number N of firms. Firms exit with exogenous probability Ψ in any given period, and exiting firms are substituted by newborn ones with initial endowment a_0. Firms produce consumption goods using a nondurable factor as the only input, and generate a constant net cash flow π every period. They do not distribute their earnings (an optimal choice, as will be clear later) and have access to a one-period safe financial asset a_t that generates a constant return $1 + r$ per period. The firm's law of motion of wealth is thus:

$$a_{t+1} = (1 + r)a_t + \pi, \tag{1}$$

where $r > \underline{r}$ is the exogenous real interest rate. All the results derived in this section are valid for negative real interest rates, as long as they are above a lower bound $\underline{r} < 0$ determined below.

Investment "lumpiness" is introduced in a very stylized way, assuming that firms have access to a one-time investment opportunity of fixed size F. This investment is profitable, so that firms will always implement it when they have enough financial resources to do so. From now onward, we will identify F with an "innovation investment", for expositional convenience. In period t, the firm can borrow one period debt b_t and repay $(1+r)b_t$ the next period. If the firm does not repay the debt, the lenders can liquidate the firm and recover a value θF. Therefore, θ represents the collateral value of the investment F, and the firm faces the borrowing constraint $(1 + r)\, b_t \leq \theta F$, which can be written as:

$$b_t \leq \frac{\theta}{1 + r} F, \tag{2}$$

The innovation is feasible at the beginning of period t if current assets a_t plus new borrowing

[5] Evidence of lumpy investment at the microeconomic level can be found in Doms and Dunne (1998), Caballero (1999) and Gourio and Kashyap (2007). While these papers focus on tangible investments, Kaus, Slavtchev, and Zimmermann (2020) and Chiavari and Goraya show that some types of intangible investment (R&D, software, and patents) are even lumpier than tangible investment.

b_t are sufficient to finance F:

$$a_t + b_t \geq F. \tag{3}$$

We assume that newly created firms have zero endowment ($a_0 = 0$) and that $\frac{\theta}{1+r} < 1$. It follows that, even borrowing up to the limit with $b_0 = \frac{\theta}{1+r}F$, condition (3) is not satisfied in period 0. Newborn firms cannot access enough external funds to innovate, and they need to accumulate retained earnings for a number of periods (denoted T^*) to be able to invest F. Firms choose optimally not to pay dividends while this constraint is binding, and optimally save to finance the innovation (as discussed earlier), because the return to funds kept internally is larger than the external return. Therefore, Equation (1) implies that accumulated wealth after T periods is equal to:

$$a_T = \pi \left[1 + (1+r) + ... + (1+r)^{T-1}\right] = \pi \left[\frac{(1+r)^T - 1}{r}\right] \tag{4}$$

Substituting the binding borrowing constraint (2) into (3), we obtain that the minimum financial wealth required to be able to invest in F, denoted a^*, is fixed and equal to:

$$a^* = F\left[1 - \frac{\theta}{1+r}\right]. \tag{5}$$

We substitute $a_T = a^*$ into (4) and we solve for T^*, the number of periods necessary to accumulate enough wealth to invest:[6]

$$T^* = \left\lceil \frac{\ln\left(1 + \frac{ra^*}{\pi}\right)}{\ln(1+r)} \right\rceil, \tag{6}$$

A solution for T^* requires $1 + \frac{ra^*}{\pi} > 0$, which means $\pi > -ra^*$ and $r > -\frac{\pi}{a^*} \equiv \underline{r}$. In other words, a negative interest rate is consistent with Equation (6) as long as profits π are larger than the interest payments from savings $-ra^*$.

Every period, $N\delta$ new firms enter the industry, and the fraction surviving until age T^* is equal to $(1-\delta)^{T^*}$. Therefore, each period aggregate investment I^F is equal to:

$$I^F = N\delta\,(1-\delta)^{T^*} F. \tag{7}$$

Having introduced this simple framework, we now turn to our questions of interest. How do variations in the exogenous interest rate r affect the amount of aggregate investment I^F? Since $0 < \delta < 1$, from Equation (7) it follows that a reduction in T^* increases aggregate investment I^F. Intuitively, the lower is T^*, the larger is the number of firms that are able to innovate

[6] This computation assumes that the innovation opportunity is taken up after the current period's cash flow π from regular operations is produced. Note that, to be more precise, the exact number of periods is the value of n^* rounded up to the nearest integer.

before having to exit the economy. Therefore, in order to understand the effect of r on I^F, it is sufficient to analyze the relation between r and T^*.

Equations (4), (5) and (6) show that the relation between r and T^* is ambiguous. On the one hand, Equation (5) implies that a reduction in r increases borrowing and reduces the minimum wealth a^* necessary to invest:

$$\frac{\partial a^*}{\partial r} = \frac{F\theta}{(1+r)^2} > 0,$$

which is an effect we call the "*collateral channel*". A lower interest rate increases the amount the firm can borrow with a given collateral, and shortens the number of periods T^* needed to have enough internal and external funds to innovate.

On the other hand, from equation (4) it is straightforward to see that the lower is r the more periods T^* are necessary to reach a given terminal wealth a^*, and it follows that $\frac{\partial T^*}{\partial r} < 0$. In other words, lower r reduces wealth accumulation and increases T^*, the more so the larger is a^*. We call it the "*Saving Channel*".

Our main result in this section is that the strength of these two channels varies depending on θ. A higher value of θ increases $\frac{\partial a^*}{\partial r}$ and the strength of the collateral channel. Moreover, it reduces a^* (see Equation 5), and therefore reduces the importance of the saving channel. We now define as a "tangible firm" a firm whose technology is based on tangible assets and therefore has high value of θ. Conversely, an "intangible firm" has low θ. For tangible firms, a^* is small and very sensitive to r ($\frac{\partial a^*}{\partial r}$ is large), so the *collateral channel* dominates, and a reduction in the interest rate reduces T^*. For intangible firms, the opposite is true. a^* is large, and is not so sensitive to changes in r ($\frac{\partial a^*}{\partial r}$ is small). Therefore, the Collateral Channel is weaker, and the Saving Channel stronger, and the stimulating effect of lower interest rate is dampened, and can even be reversed.

We introduce a simple numerical example to clarify these points in Figure 2. The left hand side of the figure (panel A) considers an industry with high tangibility of capital ($\theta = 0.9$). The minimum wealth a^* needed to invest, indicated by the dashed, horizontal lines, is relatively small, and the drop in the interest rate from 10% to 0% reduces it substantially, from 1.8 to 1. The two solid, upward sloping curves in the figure represent wealth accumulation over time, for a given value of r. The curve for $r = 0\%$ is flatter than the curve for $r = 10\%$, reflecting the slowing-down of wealth accumulation when the return on savings is lower. Through this effect, lower r increases the periods T^* firms need to accumulate enough wealth to be able to invest but, with high-tangibility capital, this negative effect of low r is dominated by the relaxation of the borrowing constraint (which reduces the minimum wealth a^* needed to invest) and, overall,

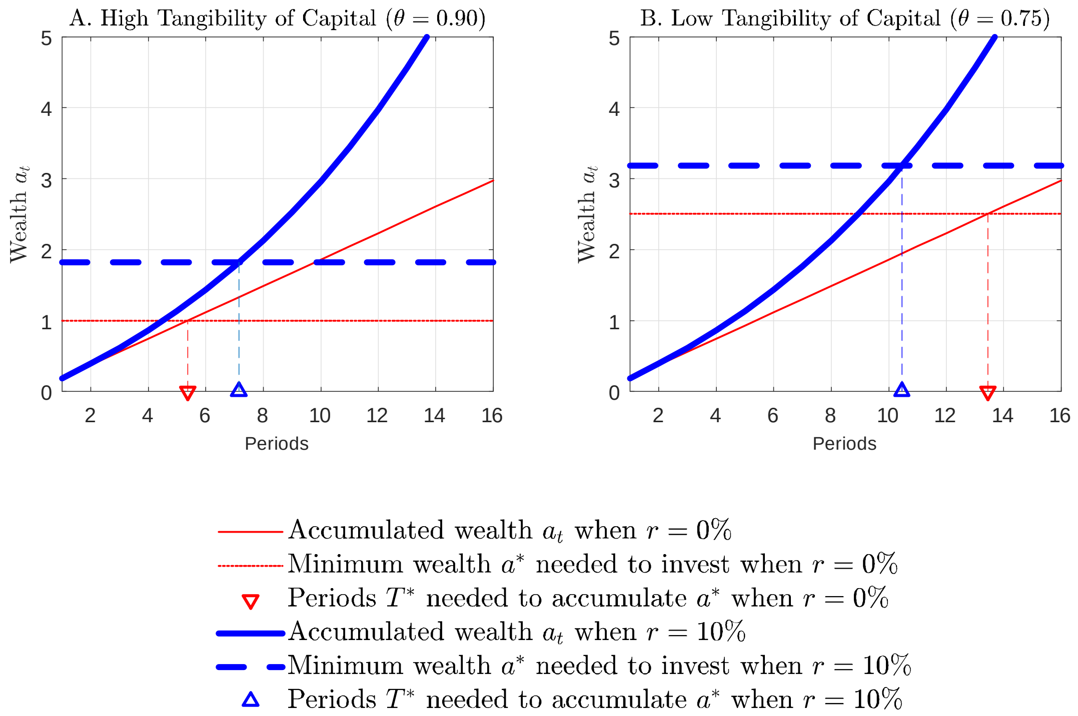


Figure 2: Numerical Example of the Savings Channel - Effect of interest rate changes on the time needed to reach the level of wealth necessary to invest

the drop in r reduces T^*. This reduction in T^* when r drops will be shown in the models of sections 4 and 5 to increase investment at the industry and aggregate levels when tangibility is high, as is common in existing models.

The right hand side of Figure 2 (panel B) considers an industry with lower tangibility (in the example, $\theta = 0.75$). The minimum wealth a^* needed to invest (the dashed, horizontal lines) for any given r is significantly higher with lower tangibility. This means that, for any given r, firms take longer to be able to invest when tangibility is low: when r=10%, for example, less tangible firms take 10.5 periods to reach a*, while more tangible firms take only 7.2 periods. Furthermore, the reduction in a^* when r drops from 10% to 0% is lower: a 21% reduction, from 3.2 to 2.5, compared to a 45% reduction in the high tangibility case. The fact that the sensitivity of a^* is lower in less tangible firms means that the overall effect of interest rate changes reverses sign. As before, wealth accumulation (the solid curve) when $r = 0\%$ is slower than when $r = 10\%$, and this effect now dominates the reduction in a^*: lower r increases the periods T^* firms need to accumulate enough wealth to be able to invest and is not compensated enough by the (relatively small) relaxation of the borrowing constraint that only reduces the minimum wealth a^* needed to invest minimally. This increase in T^* when r drops will be shown in the models of sections 4 and 5 to either reduce investment, or at least dampen its growth, at the industry and aggregate levels when tangibility is low. This is the main insight of our paper.

3.1 Considerations

We have developed a very stylized model with two main assumptions. First, firms invest in lumpy investment projects. Second, intangible capital has lower collateralizability than tangible capital and, therefore, if equity finance and/or uncollateralised debt are limited by financial frictions, intangible capital acquisition is financed relatively more with cash than with credit, compared to tangible capital. In this situation, we have shown that the relation between investment projects and the interest rate is driven by two counteracting effects: the *Collateral Channel* and the *Saving Channel.* The saving channel dominates when capital is highly intangible; it dampens the negative relation between interest rate and investment and, if strong enough, can reverse it.

Because of its simplicity, this model has some important limitations. It is too stylized to derive testable predictions or general equilibrium implications. Moreover, it implies that firms invest only once, and that all firms with investment opportunities are financially constrained and are net savers, while in reality firms invest repeatedly, and many firms with investment opportunities are financially unconstrained and/or are net borrowers. Therefore, in the next sections we extend the model to show that our main results arise also in a more realistic setting, and we generate a set of predictions that can be empirically tested. We do so in two steps.

First, in Section 4, we keep most of the simplifying assumptions defined above, but we define in more details the industry equilibrium and the nature of the investment F, which we interpret as the accumulated R&D expenditures necessary to generate a productivity enhancing innovation. The objective of this section is to generate testable predictions on the relation between intangibles, interest rates, and innovation at the firm level.

Second, in Section 5, we consider a version of the model without productivity enhancing innovation, but in which both financially constrained and unconstrained firms have investment opportunities, and these opportunities happen more than once during the firms lifetime. Because of this feature, firms are heterogeneous in their asset holdings, and it is no longer the case that all firms are net savers. More specifically, some firms are net borrowers, and average firm leverage increases in assets tangibility. Not only this model is consistent with the empirical evidence that firms in more intangible industries hold less debt, but also allows us to highlight another channel, which we call the "*Net Debtor Channel*": Firms that are net borrowers benefit from a reduction in the interest rate because of lower interest payments. We show that the results of the simple model extend to this more realistic setting, and we are able to generate additional testable implications.

One assumption that we maintain in both sections, is the inability of the constrained firms to raise equity. On the one hand, this assumption is realistic, as several paper document that firms which face borrowing constraints also face equity financing constraints (among others, see Altinkilic and Hansen, 2000; Gomes, 2001; Belo, Lin and Yang, 2016). On the other hand, it is without loss of generality, because in the more general model in Section 5 we introduce unconstrained firms which have frictionless access to both equity and debt financing, and we show that our main results are confirmed for a realistic calibration of the share of output produced by constrained firms.

Finally, notice that this "two step strategy" is not strictly necessary, because we could move directly to a more general model with all the ingredients described above, rather than consider two separate extensions of the simple model. However, this strategy has an important advantage: that both extensions considered in the next sections allow for a closed form solution. On the contrary, a more general model would not yield additional insights, would require a numerical rather than analytical solution, and would make it more difficult to disentangle and interpret all the different effects.

4 Industry Model with Innovation Projects

With respect to the simple model in the previous section, we introduce a production function that incorporates labor, tangible capital, and intangible capital as complementary factors of production, and we model the one-time investment F as a productivity-enhancing innovation. Furthermore, we solve for an industry equilibrium, specify a detailed calibration, and simulate the model numerically to analyze some comparative static exercises and to run regressions using the simulated data. Finally, we show that our results are robust to assuming that intangible technologies are more productive than tangible technologies.

We introduce a framework that builds on the firm dynamics model of Midrigan and Xu (2014). The economy is populated by a measure 1 of firms, which operate a technology that uses tangible capital, intangible capital, and labor as inputs. Firms occasionally receive an innovation opportunity which allows them to pay a fixed cost to permanently increase the productivity of their technology. Firms that have not yet innovated produce output y_t^l (l for "low productivity") using:

$$y_t^l = z^{1-\xi} \left(l_t^{1-\alpha} k_t^{\alpha} \right)^{\xi}, \tag{8}$$

where α ($0 < \alpha \leq 1$) regulates the capital intensity in production and ξ ($0 < \xi \leq 1$) determines the degree of returns to scale.[7] The term k_t represents capital installed in period $t-1$ that produces output in period t, and l_t is labor. We assume that capital k_t is a combination of tangible and intangible capital, which are complementary inputs:

$$k_t = \min\left(\frac{k_{T,t}}{1-\mu}, \frac{k_{I,t}}{\mu}\right), \tag{9}$$

where $0 < \mu < 1$. The terms $k_{T,t}$ and $k_{I,t}$ represent tangible and intangible capital, respectively. We adopt this simple Leontief structure because it implies that all firms choose the same intangible share of total capital, and this facilitates aggregation in the model in the next section.[8] From the Leontief structure of the production function, it follows that $k_{T,t} = \frac{1-\mu}{\mu} k_{I,t}$ and

$$k_{I,t} = \mu k_t \quad \text{and} \quad k_{T,t} = (1-\mu)\, k_t. \tag{10}$$

We assume for simplicity that the two types of capital have the same depreciation rate δ, and therefore the law of motion of capital can be written as:

$$k_{t+1} = i_t - (1-\delta)\, k_t \tag{11}$$

where $i_{I,t} = \mu i_t \quad \text{and} \quad i_{T,t} = (1-\mu)\, i_t$.

We denote with θ_I and θ_T the collateral value of intangible capital and tangible capital, respectively. Condition (10) implies that:

$$\theta = \mu\theta_I + (1-\mu)\,\theta_T. \tag{12}$$

Since we assume that $\theta_I < \theta_T$, the degree of intangibles intensity (μ) negatively affects the collateral value θ of the composite capital input k_t. Following Midrigan and Xu (2014) and Caggese (2019), we assume that firms can perform a technology adoption investment F to increase their productivity from z to $(z+\lambda)$. This innovation opportunity occurs with probability γ. Firms that have invested F to adopt the more productive technology produce output y_t^h (h for "high productivity") using:

$$y_t^h = (z+\lambda_t)^{1-\xi}\left(l_t^{1-\alpha} k_t^{\alpha}\right)^{\xi}. \tag{13}$$

[7] In this model, the firm can invest to increase z_t, and therefore we elevate it at the power of $1-\xi$ so that the production function is constant returns to scale in all factors of production. We do so to maintain symmetry with the production function in the next section, which is also constant returns to scale in terms of the variable inputs.

[8] Using a more standard Cobb-Douglas or CES function instead of the Leontief function would imply that the optimal ratio between tangible and intangible capital varies with the intensity of financial frictions. More constrained firms would use more intensely tangible capital, because its higher collateral value becomes more attractive, and this would create an additional distortion in the allocation of resources across firms. See Perez-Orive (2016) for a study of this type of distortion.

The investment F requires the same Leontief shares of tangibles and intangibles inputs as k, and therefore it has also the same collateral value θ. Notice that innovation and intangibility are two independent dimensions of the analysis. A tangible innovation process is something that use relatively more tangible assets such as machineries and laboratories, while an intangible one uses relatively more intangible assets such as patents, software, and human capital. Notice also that, as in Midrigan and Xu (2014), in this model firms can implement an investment opportunity only once in their lifetime. This assumption is not restrictive for the purpose of this section, but it will be relaxed in the next section.

Every firm's technology becomes obsolete each period with probability ψ. In this case, the firm liquidates all of its capital, pays out as dividends all of its financial wealth, and exits. Exiting firms are replaced with newborn ones, with initial endowment a_0.

4.1 Budget and Financing Constraints

The budget constraint of firms is given by the following dividend equation:

$$d_t^J = y_t^J - w_t l_t + (1 + r_t)a_t - a_{t+1} - (k_{t+1} - (1 - \delta)k_t) - I_t F, \tag{14}$$

where $J \in \{l, h\}$ indicates whether the firm operates the low or high technology; r_t is the interest rate paid or received in date t; w_t is the wage; and $I_t \in \{0, 1\}$ is an indicator function that takes value 1 if the firm innovates this period, and 0 otherwise. The term $a_t > 0$ indicates that the firm is a net saver, and $a_t < 0$ indicates that the firm is a net borrower.

To simplify the analysis, we assume that the firm can pay for capital and labor costs with the revenues from production, so that the only investment affected by financial frictions is F. We will relax this assumption in Section 5. Firms can pay for the technology adoption cost F with internal finance and by borrowing one-period riskless debt at the rate r_{t+1}, subject to the constraint that they can pledge, as collateral, the fraction θ of the cost F. Therefore the maximum face value of debt is θF, which translates into the following inequality:

$$(1 + r_{t+1})\, a_{t+1} \geq -\theta F, \tag{15}$$

Furthermore, firms are unable to issue equity, which means that dividends are subject to a non-negativity constraint:

$$d_t \geq 0. \tag{16}$$

4.1.1 Optimal Policies

Firms make their investment, savings, and innovation decisions in order to maximize the net present value of their dividends, discounted at interest rate r_t. Since we assume capital k and labor l acquisitions are not financially constrained, their optimal choice only depends on the productivity level z^J and their marginal costs. We define $V^h(z^h)$ as the value functions of a high technology firm, where $z^h = z + \lambda$, as the net present value of the firms profits. Furthermore, we define as $V^l(z^l)$ the value function of a low technology firm conditional on never investing in innovation, so that $z^l = z$. For their derivation, see Appendix A.

We consider calibrations of the model so that the gain from innovation is greater than its cost, namely that $V^h(z^h) - F > V^l(z^l)$. It follows that low technology firms that face the opportunity to innovate always prefer to do so, but might not be able to finance the technology adoption cost F if their internal funds are not sufficient. For this reason, low-technology firms never pay dividends (constraint (16) is binding and $d_t = 0$) and accumulate as many retained earnings as possible, while high-technology firms are indifferent between retaining or distributing dividends.

Substituting a_{t+1} and d_t in Equation (14) using constraints (15) and (16) binding with equality, we obtain that a low-technology firm will be able to innovate when it has the opportunity as long as

$$F < \frac{n_t}{1 - \frac{\theta}{1+r_{t+1}}}, \tag{17}$$

$$n_t \equiv y_t^l - w_t l_t + (1 + r_t)a_t + (1 - \delta)k_t, \tag{18}$$

where n_t is total net worth available to invest in innovation and $1 - \frac{\theta}{1+r_{t+1}}$ is the downpayment necessary to finance one unit of innovation investment. This is the unitary cost minus the term $\frac{\theta}{1+r_{t+1}}$, which is the amount that can be financed by borrowing. Denote with n_t^* the minimum level of net worth that enables a firm to innovate:

$$n_t^* = F\left(1 - \frac{\theta}{1 + r_{t+1}}\right). \tag{19}$$

Which is analogous to Equation (5) in the simple model in Section 3. We can now characterize the optimal policies of all firms. First, low productivity firms with an innovation opportunity that satisfy $n_t > n_t^*$ will innovate ($I_t = 1$). All other firms will not innovate ($I_t = 0$). Second, all firms are unconstrained in their capital and labor choices and k_{t+1} satisfies:

$$\frac{dy_{t+1}^J}{dk_{t+1}} = r_{t+1} + \delta \tag{20}$$

where $J \in \{l, h\}$, while l_t satisfies:

$$\frac{dy_t^J}{dl_t} = w_t. \tag{21}$$

Dividend and saving or borrowing decisions depend on whether firms face future innovation opportunities or not. Low productivity firms that have not yet innovated and do not satisfy condition (17) choose $d_t = 0$ and retain all earnings:

$$a_{t+1} = y_t^l + (1 + r_t)a_t - q_t\left(k_{t+1} - (1 - \delta)k_t\right) - w_t n_t. \tag{22}$$

All other firms are indifferent between accumulating retained earnings or paying them out to shareholders.

4.2 Competitive Industry Equilibrium

The total number of low productivity N_t^l and high productivity N_t^h firms is constant and normalized to one:

$$N_t^y + N_t^h = 1. \tag{23}$$

New firms that enter are born with no endowment of capital or net worth ($a_0 = 0$). Labor supply is also normalized to one. Labor demand of low-productivity firms and high productivity firms, respectively $l^l(w_t)$ and $l^h(w_t)$, is decreasing in w_t according to Equation (21), and therefore the equilibrium wage w_t clears the labor market:

$$l^l(w_t)N_t^l + l^h(w_t)N_t^h = 1. \tag{24}$$

The measure of each type of firm, in turn, is determined by the threshold n_t^* and the distribution $\Phi(n_t)$ of net worth n_t in the subset of low-productivity firms. The evolution of shares of firms is given by

$$N_{t+1}^l = \psi + (1 - \psi)\left[(1 - \gamma) + \gamma\Phi(n_t^*)\right]N_t^l \tag{25}$$

$$N_{t+1}^h = (1 - \psi)N_t^h + \gamma(1 - \psi)\left[1 - \Phi(n_t^*)\right]N_t^l \tag{26}$$

4.3 Steady State

In steady state, the distribution of firm types satisfies:

$$N^l = \frac{\psi}{\psi + \gamma(1 - \psi)\left[1 - \Phi(n^*)\right]} \tag{27}$$

$$N^h = \frac{\gamma(1 - \psi)\left[1 - \Phi(n^*)\right]}{\psi + \gamma(1 - \psi)\left[1 - \Phi(n^*)\right]} \tag{28}$$

To get at these expressions, we can solve for N^l and N^h in the steady state versions of (25) and (26). The interest rate r is constant and determined exogenously, since we do not model the household sector. The equilibrium wage w is constant and determined by the steady state condition:

$$l^l(w)N^l + l^h(w)N^h = 1. \tag{29}$$

To solve for the steady state equilibrium we also need to determine the innovation threshold n^*. Details are provided in the Appendix B.

4.4 Calibration

We set our parameters either to typical values in the literature, or to match the average value, over the 1980-2015 period, of selected empirical moments. Our benchmark calibration is illustrated in Table 1. We set the fraction of intangible assets μ to broadly match the average value for Compustat firms over the 1980-2015 period in our data ($\mu = 40\%$, also in line with Falato et al, 2018). We match r to the average short term real interest rate during the same period; around 3% in annualized terms. The productivity parameter z, which corresponds to the TFP of the low productivity firms, is normalized to 1.

The parameter λ determines the profitability after innovating, and therefore also the value of the innovation. We calibrate it using balance sheet and patents data of US public firms. We use the market value of all new granted patents for each firm-year observation in Compustat, from Kogan et al. (2017). In the data, innovations are frequent and have different magnitudes, while in the model we focus on a one-time large innovation opportunity. Therefore, for the purpose of calibrating the model we focus on the 10% of innovations with largest value over total assets. We choose λ so to calibrate the same moment in the model, where we define the value of an innovation as

$$value\_inn^{model} = \Big(V^h(z^h) - V^l(z^l)\Big) - \Big(k^h - k^l\Big) - F, \tag{30}$$

or the difference in the equity value between a high-productivity and a low-productivity firm, net of the cost of innovation F and the additional capital investment necessary to increase the firm scale to the larger optimal scale associated with the high productivity after innovation. The total assets of the firm in our model are calculated as total capital k_t plus total liquid assets n_t.

The probability of an innovation opportunity γ is set to match the fraction of large innovations in the data as defined above. The cost of innovation F matches the average of the R&D costs, computed as a sum over the 3 years before the patent related to the large innovation is granted, over total assets. The comparison between simulated moments and targeted moment is presented in Table 2.

Table 1: Parameter Values

Parameter	Symbol	Value	Source/Target
Capital share	α	0.4	
TFP (Low-prod. tangibles)	z	1	
TFP (High-prod. tangibles)	$(z+\lambda)$	3.6	
TFP-intangibility relationship	η	0.6	
Decreasing returns to scale	ξ	0.85	Restuccia-Rogerson (2008)
Prob. of innovation (quarterly)	γ	0.1	
Collateral value tangible	θ^T	1	Falato, et al. (2018), Döttling and Perotti (2016)
Collateral value intangible	θ^I	0.2	Falato, et al. (2018), Döttling and Perotti (2016)
Cost of innovation	F	0.4	
Exit probability (quarterly)	Ψ	0.01	
Depreciation (quarterly)	δ	0.025	
Interest rate (annual)	r	3%	
Intangible share	μ	0.4	Falato, et al. (2018)

The probability of exit Ψ is such that the model simulations generate an average age of firms in line with the data. The pledgeability parameters of tangible capital θ^T and intangible capital θ^I are equal to 1 and 0.2, respectively.[9]

We set the degree of decreasing returns to scale to $\xi = 0.85$, based on estimates surveyed in Restuccia and Rogerson (2008), and the elasticity of output with respect to capital α to 0.4, a common value used in most of the literature.[10] The quarterly depreciation rate of capital is set at $\delta = 0.025$, which is a standard value for quarterly Real Business Cycle (RBC) models. In Section 5 we will analyze the implications of allowing different depreciation rates of tangible and intangible capital.

4.5 Relation between intangible capital, interest rate and innovation: simulated data

We use the model described in the previous section to analyze how the relation between interest rates and innovation changes between tangible and intangible industries. Figure 3 compares simulations of two industries that have all the benchmark parameters except that one is tangibles-intensive, with $\mu = 0.1$, and another one is intangibles-intensive, with $\mu = 0.6$. $\mu = 0.1$ is a value sufficiently low to emphasise the importance of the collateral channel and the positive effects of falling interest rates for investment. In our Compustat sample, we observe a value of $\mu \leq 0.1$ for around 23% of firm-year observations, while we observe a value of $\mu \geq 0.6$ for around 35% firm-year observations. For each industry, the lines represent a comparative static

[9] Falato et al. (2018) argue, based on data on syndicated loans from LPC DealScan and on corporate debt structure from Capital IQ, that θ^I for all intangible assets except patents and brands should be set to 0. They estimate θ^T, on the other hand, to be between 0.9 and 1. Unlike in the model of Falato et al. (2018), in our model we do not allow any equity issuance, even though it would be realistic to assume that financially constrained firms have some ability—even if limited—to issue equity. Rather than complicating the model further, we compensate the lack of equity financing by assuming a larger values of θ^I than Falato et al (2019) assume. The overall tangibility of capital in the industry depends on these two values and μ according to equation (12).

[10] See King and Rebelo (1999) or Corrado, Hulten and Sichel (2009).

Table 2: Calibration Targets

Source/Target	Data	Model
$\frac{Value\ Innovation}{Total\ Assets}$	2.29[1]	1.57
$\frac{R\&D\ costs\ of\ innovative\ firms}{Total\ Assets}$	2.55[2]	2.67
Average firm age (years)	23	24.75
Innovative Firms (Annual % of total)	2.34%	2.10%

1) Mean of $\frac{Value\ Innovation}{Total\ Assets}$ among radical innovations, defined as the 10% innovations with highest $\frac{Value\ Innovation}{Total\ Assets}$. $Value\ Innovation$ is the market value of the innovation from Kogan et al (2017). $Total\ Assets$ is the book value of tangible and intangible assets in the same year of the innovation. We exclude observations with less than 100.000$ of total assets (around 2% of total). 2) $R\&D\ costs\ of\ innovative\ firms$ is the sum of R&D expenditures in years $t, t-1$ and $t-2$, where year t is the year when the firm patents an innovation.

exercise in which we compute different equilibria for different values of the real interest rate r, ranging from 6% to 0% in annualized terms, while keeping all the other parameters constant at the benchmark level. Panel A highlights that the Intangible-Intensive industry is characterized by a collateralizability of capital much lower than in the Tangible-Intensive industry. The other panels show innovation outcomes measured relative to the outcome for $r = 6\%$. Panel B shows that a fall in the interest rate increases the fraction of innovative firms in the tangible industry, but it reduces it in the intangible one. The intuition of this result is the same as for the simple model in Figure (2). For the intangible industry, the low collateral value of capital implies that the decline in the interest rate hurts the accumulation of wealth (the savings channel), and the collateral value channel is very weak because firms' borrowing capacity is limited. Overall, firms take longer to innovate (Panel D), and therefore aggregate innovation in this industry falls when r decreases (Panel C). Conversely, the saving channel is much weaker for the tangible industry, and the collateral channel stronger. The latter channel dominates, and lower r stimulates innovation and thus reduces the average age of innovating firms. These results yield a testable prediction: a decline in the interest rate negatively affects the innovation of young intangible firms much more than that of young tangible firms.

One caveat of this result is the following: if intangible technologies damage the innovation possibilities of firms, why do firms adopt them? In reality, the emergence of more intangible technologies observed in the data is also accompanied with higher productivity, which presumably explains why such technologies were adopted in the first place.

To show that our predictions are robust to this feature, in Figure 4 we consider simulations in which we estimate different steady states with same interest rate $r = 3\%$, but different intangible intensity μ, while allowing total factor productivity z to increase in μ according to the following relation:

$$z_t = [1 + (\mu - 0.2)\eta], \tag{31}$$

where the parameter η measures the productivity gains of more intangible technologies. We vary the intangible share from $\mu = 0.2$ (the average share for US firms at the beginning of our

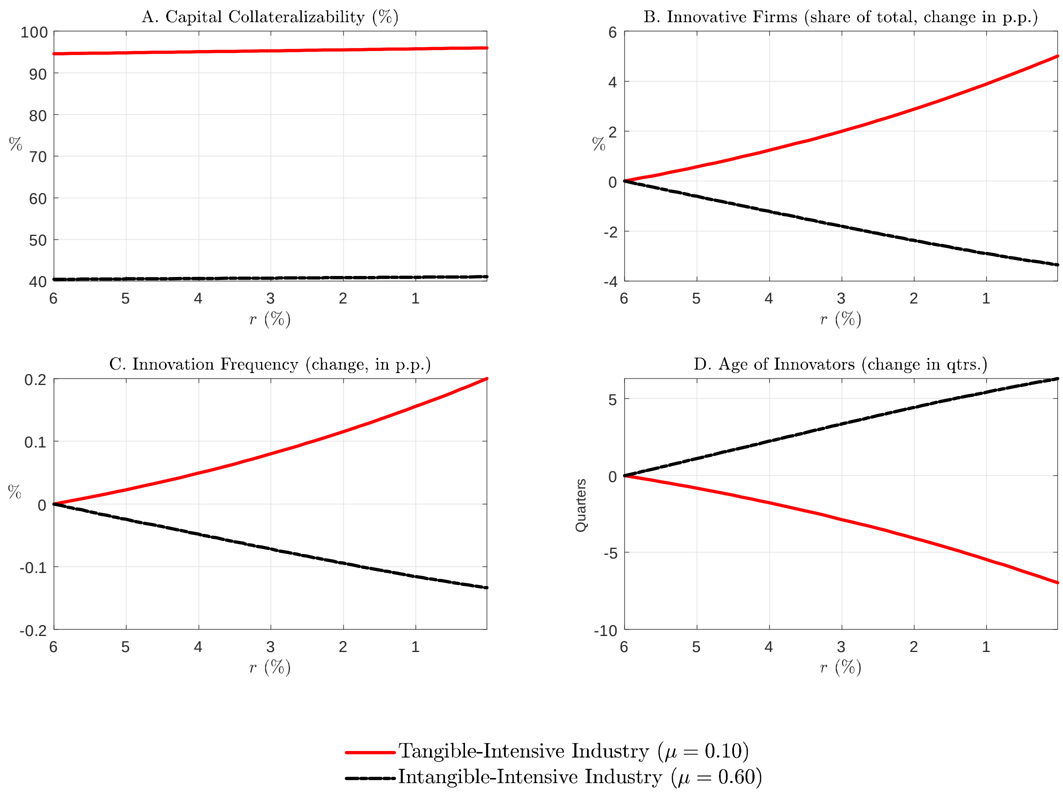


Figure 3: Simulation of Industry Equilibria: comparative statics for different values of r ($\mu = 0.10$ in a tangibles industry)

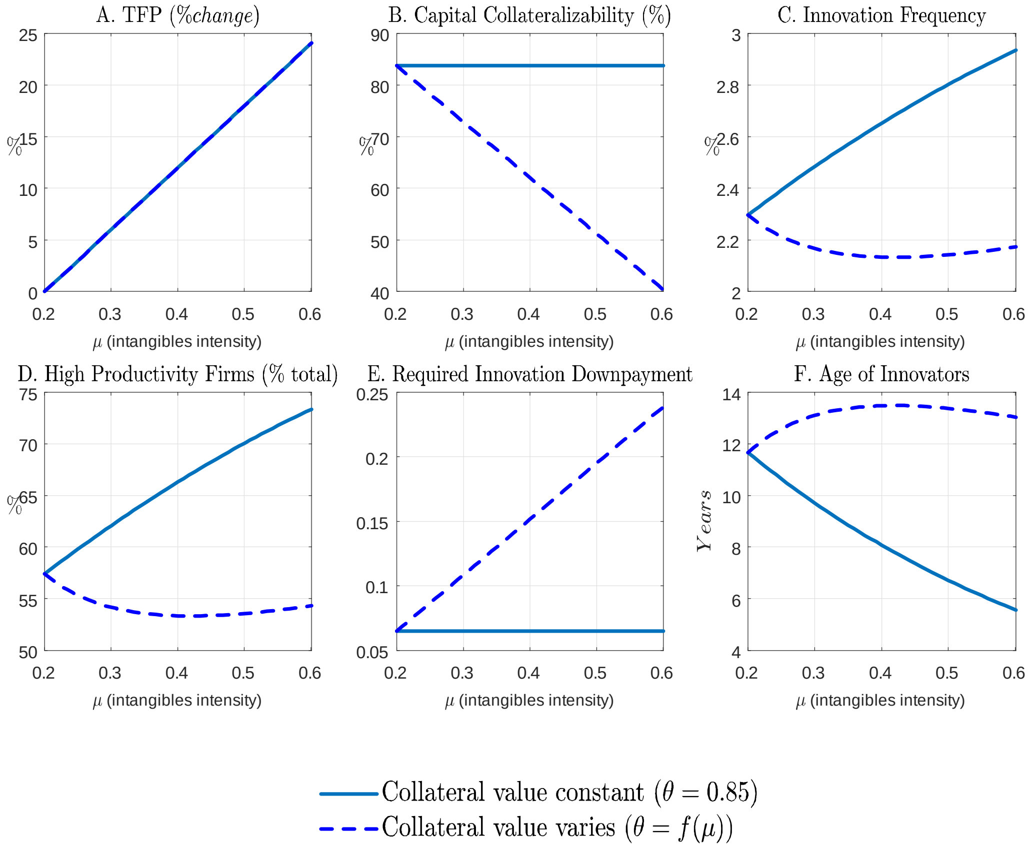


Figure 4: Simulation of Industry Equilibria: comparative statics for different values of intangible capital intensity

sample, in 1980) to $\mu = 0.6$ (the average share at the end of our sample, in 2018). We choose a value of $\eta = 0.6$, and therefore the rise of intangibles generates a 24% increase in productivity across the different steady states.

According to Equation (12), the overall collateral value of capital θ falls from 0.85 to 0.40 as μ increases from 0.2 to 0.6. In order to isolate the effect of this collateral channel, the solid lines in Figure 4 repeat the same exercise while keeping constant θ at its benchmark value of 0.85. To sum up, each line in the figure shows a sequence of steady states that differ in their value of μ, ranging from 0.2 to 0.6, and in their value of z, as it is a function of μ according to Equation (31). As is clear from panel B, the solid lines keep the parameter θ constant, while the discontinuous lines allow θ to fall as μ increases according to equation (12). All other parameters are kept constant at their benchmark value.

The solid lines show that, thanks to higher productivity, firms in industries that use a higher share of intangible capital are able to accumulate wealth faster and therefore innovate when they are younger (Panel F). This increases average innovation frequency in the industry (Panel C) as well as the share of High productivity firms (Panel D).

As mentioned before, the dashed lines represent simulations identical to the solid lines, except that the collateral value of capital decreases in μ according to Equation (12) (see Panel B). Therefore, the dashed lines illustrate a trade-off between the higher productivity of more intangible technologies, which increases profits and relaxes financial frictions, and their lower collateralizability, which tightens firms' borrowing constraints significantly and hurts firms' ability to finance an innovation. For the calibrated parameters, the negative effect of lower collateral value dominates. As a result, when μ is higher, firms need more years to accumulate enough internal funds to innovate. In equilibrium, the average age of innovators decreases rather than increasing.[11] Summing up, Figure 4 confirms that the rise of intangible technologies dampens the innovation frequency of young firms also when these technologies are substantially more productive than the tangible ones. Therefore, one additional testable prediction is that young firms innovate less on average the larger is the share of intangible capital μ.

4.6 Data

The sample we use to test our predictions consists of U.S. firms covered by Compustat at a quarterly frequency between 1980 and 2018, excluding utilities (SIC codes 4900–4949) and financials (SIC codes 6000–6999). We remove observations with negative revenues, missing information on total assets, or a value of total assets under $10 million. Our main firm-level variables of interest are tangible and intangible capital, age, and innovation decisions.

We define intangible capital as the sum of knowledge capital and organizational capital.[12] Following Falato et al. (2018), we measure the former by capitalizing R&D expenses and the latter by capitalizing selling, general and administrative (SG&A) expenses weighted by 0.2.[13] The expenditures are capitalized by applying the perpetual inventory method with an annual depreciation rate of 15% for R&D and 20% for SG&A. Our measure of tangible capital is net property, plant, and equipment. For robustness and consistency, we check that our results hold when using an alternative measure of tangible capital built in a similar way as our measure of intangible capital; by capitalizing capital expenditures, using an annual depreciation rate of 10%.

Firm age is taken from two sources. One source is Worldscope. Using Worldscope, we compute firm age as the age since foundation, unless the foundation year is missing, in which case the date of incorporation is taken into account. Next, we improve this data by using the information of firm foundation year from Loughran and Ritter (2004) (LR). Ritter updated this dataset in 2018, and provides the original incorporation for most IPOs since 1975. Their coverage is smaller than Worldscope, but they conduct a careful data construction process that slightly improves the accuracy of Worldscope. Whenever a firm is covered both by Worldscope and by LR, we take the firm age according to LR. For those firms not covered by LR, we take the value from Worldscope. For the majority of firms, Worldscope and LR provide the same firm

[11] However, intangible technologies are still optimal relative to tangible technologies. Firms innovate later because of financial frictions but after innovating they benefit from their higher productivity.

[12] Falato et al. (2018) also consider informational capital. However, they state that their results do not depend on its inclusion. As informational capital can be measured only at the industry level but not at the firm level using Compustat data, we choose not to include this type of capital.

[13] A portion of SG&A expenses captures expenditures that increase the value of intangible capital items such as brand names and knowledge capital. Part of SG&A expenditures, however, does not affect the value of intangible capital, so Falato et al. (2018) and Corrado, Hulten, and Sichel (2009) assume that the portion relevant to intangible capital is around 0.2.

age. Our results are robust, however, to only considering the age data from LR. We construct a dummy $young_{i,t}$ that takes value 1 if the firm is 10 years old or younger, and 0 otherwise. We find that 12% of all firm year observations belong to young firms, roughly equally distributed among tangible and intangible sectors. An exception is the dotcom bubble period of 1995-2000, during which there was a surge in the stock market entry of young firms in more intangible sectors. However, eliminating this period from our analysis does not significantly change the results presented below.

In order to obtain information on innovation activities and the value of innovations, we use the patenting information provided by Kogan, Papanikolau, Seru, and Stoffman (2017), which includes the number of granted patents for each firm-year observation, the average number of citations of patents, and the market value of patents (computed as the stock market response to patents granted).

Finally, we measure changes in interest rates in a variety of ways. First, we use a measure of the real short term interest rate, computed as the nominal 3-Month Treasury Bill rate minus the 12-month ahead inflation expectation given by the Surveys of Consumers of the University of Michigan. In the model, the causality goes from exogenous changes in the interest rates to the accumulation of financial assets for given investment opportunities, while in reality real interest rate changes might reflect changes in investment opportunities that affect innovation decisions directly. To deal with this concern, we use the monetary policy shocks identified by Karadi and Jarocinski (2019). These authors follow a well-established literature that uses high-frequency financial market surprises around key monetary policy announcements to identify unexpected variations in monetary policy. The innovative aspect of Jarocinski and Karadi's (2019) approach is that they are able to separately identify exogenous monetary policy shocks from shocks about new information from the Central Bank regarding the state of the economy. These monetary policy shocks are therefore orthogonal to shocks to firms investment opportunities.

4.7 Empirical evidence

In this section, we verify empirically the two predictions of the model:

Prediction 1: Relative to the whole industry, young firms innovate less on average the larger is the share of intangible capital μ

Prediction 2: A decline in the interest rate negatively affects the innovation of young intangible firms relative to that of young tangible firms.

We test these predictions by estimating regressions on both simulated and real-world data. We also consider an empirical analysis of the dynamics, persistence, and magnitude of our proposed channels using local projections analysis. Furthermore, in a preliminary analysis of the data, we verify and confirm a positive correlation between intangible capital and cash holdings. More precisely, we find that over time, as firms use more intangible capital, they have less collateral available to secure the financing of innovation expenses, and that the decreasing trend in collateral is accompanied by an increasing trend in cash holdings for innovating firms. See Appendix C for details.

Dep. Variable: Innovation Dummy				
	Data Regressions			
	(1) Real interest rate level	(2) FFR HFI surprises	(3) Jarocinski-Karadi (2019)	(4) ***Simulated Regression***
Young (dummy)	0.01	-0.01	-0.01	-0.04***
	(0.89)	(-0.47)	(-0.36)	(0.00)
Intangibility	-0.06***	-0.08***	-0.07***	0.01***
	(-3.39)	(-4.36)	(-4.28)	(0.00)
Young*Intangibility	-0.12***	-0.09***	-0.10***	-0.02***
	(-4.69)	(-3.98)	(-4.57)	(0.00)
r	-0.00	2.34	-1.23	0.00***
	(-0.17)	(0.60)	(-0.83)	(0.00)
*r**Intangibility	-0.00	0.02	0.03	-0.00***
	(-0.89)	(0.80)	(1.05)	(0.00)
*r**Young	-0.01***	-0.08**	-0.10**	-0.00***
	(-3.05)	(-2.15)	(-2.00)	(0.00)
*r**Young*Intangibility	0.01	0.15**	0.24***	0.01***
	(1.34)	(2.30)	(2.94)	(0.00)
Observations	199,589	176,346	186,734	1,200,000
R-squared	0.01	0.01	0.01	0.02
Number of gvkey	4,237	4,225	4,230	3,000

Robust t-statistics in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Figure 5: Regression results using *innovation* as the measure of innovation

4.7.1 Regression Results

We estimate the following model:

$$\begin{aligned} Inn_{i,t} &= \alpha_i + \omega_t + \beta_1 young_{i,t} + \beta_2 int\_share_{s,t} \\ &+\beta_3(int\_share_{s,t} * young_{i,t}) + \beta_4 \left(r_t * young_{i,t}\right) \\ &+\beta_5 \left(r_t * int\_share_{s,t}\right) + \beta_6 (r_t * int\_share_{s,t} * young_{i,t}) + \varepsilon_{i,t} \end{aligned} \tag{32}$$

where: $Inn_{i,t}$ is a *dummy* equal 1 if firm i innovated in year t, 0 otherwise. $young_{i,t}$ is a dummy equal to 1 if firm age ≤ 10 in year t, 0 otherwise. We also tried different specifications with $young_{i,t}$ defined as firms up to 15 years old. Results are confirmed qualitatively even though they are quantitatively less strong. $int\_share_{s,t}$ is the share of intangible assets over total assets in 2-digit sic sector s in year t. r_t is the real interest rate. Finally, we control for firm fixed effects α_i and time effects ω_t. Prediction 1 is confirmed if the coefficient of β_3 is negative. Prediction 2 is confirmed if the coefficient β_6 is positive.

Table 5 reports the regressions results. Columns 1-3 consider the three alternative measures of interest rates shocks described above. Column 4 reports the coefficient estimated from a regression on simulated data. These are produced by simulating 3,000 firms, of which 1,500 tangibles firms and 1,500 intangibles firms for 5,000 periods. Tangibles (intangibles) firms are defined as having an intangibility share of $\mu = 0.2$ ($\mu = 0.60$) and a collateral value of capital of

Dep. Variable: Radical Innovation Dummy				
	Data Regressions			
	(1) Real interest rate level	(2) FFR HFI surprises	(3) Jarocinski-Karadi (2019)	(4) ***Simulated Regression***
Young (dummy)	0.01*	0.00	0.00	-0.04***
	(1.71)	(0.60)	(0.48)	(0.00)
Intangibility	0.00	-0.01	-0.00	0.01***
	(0.51)	(-0.64)	(-0.19)	(0.00)
Young*Intangibility	-0.02**	0.00	-0.00	-0.02***
	(-2.33)	(0.32)	(-0.04)	(0.00)
r	-0.01***	8.54***	-3.20***	0.00***
	(-4.00)	(3.32)	(-3.36)	(0.00)
*r**Intangibility	0.01***	0.02	0.01	-0.00***
	(5.55)	(1.55)	(1.33)	(0.00)
*r**Young	-0.00*	-0.01	-0.01	-0.00***
	(-1.85)	(-0.83)	(-0.44)	(0.00)
*r**Young*Intangibility	0.01**	0.08**	0.07*	0.01***
	(2.22)	(2.50)	(1.95)	(0.00)
Observations	199,589	176,346	186,734	1,200,000
R-squared	0.03	0.03	0.03	0.02
Number of gvkey	4,237	4,225	4,230	3,000

Robust t-statistics in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Figure 6: Regression results using *radical innovation* as the measure of innovation

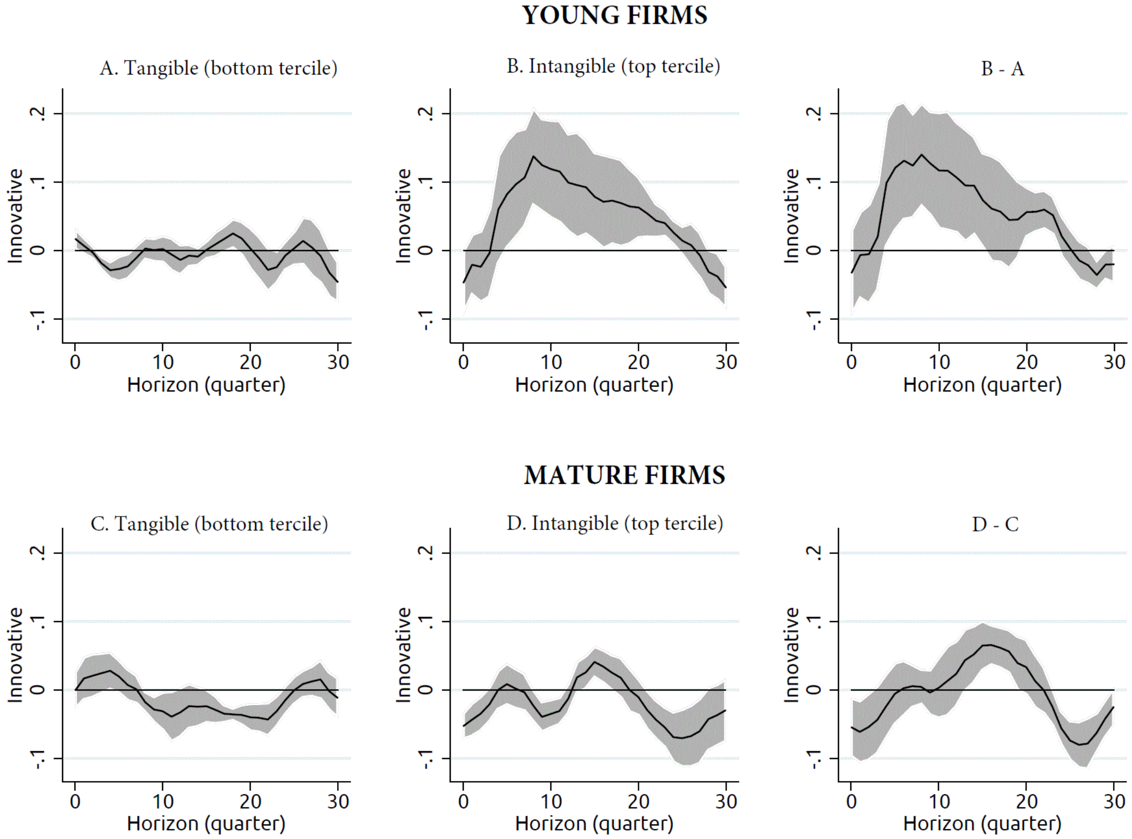
$\theta = 0.85$ ($\theta = 0.40$). We generate a random path of the interest rate, r_t, common to all firms, as well as idiosyncratic paths for the innovation shocks and the exit shocks. We discard the first 1,000 quarters of the simulation to avoid the influence of initial conditions. All variables are defined as in the empirical exercise.

The coefficient of $int\_share_{s,t} * young_{i,t}$ is negative and significant both in the model and in the data, confirming Prediction 1. It implies that a larger intangible share is associated to lower probability to innovate when young than when old. The magnitude of the coefficient is smaller in the simulated data than in the empirical estimations. As shown in Panel F of Figure 4, the negative effect of intangible intensity on the innovation of young firms in the model is relatively small because we assume a large value of η, so a large productivity gain of intangible technologies. As argued above, assuming a lower value of η would probably be more realistic and imply a larger (in absolute value) coefficient of $int\_share_{s,t} * young_{i,t}$.

The coefficient of $r_t * int\_share_{s,t} * young_{i,t}$ is positive both in the model and in the empirical data that use exogenous measure of interest rate shocks (columns 2 and 3). It implies that a decline in the interest rate reduces even more the innovation frequency of young intangible firms, relative to young tangible firms, thus confirming Prediction 2.

Table 6 replicates the same analysis using as dependent variable a dummy equal to one if the firm performed one of the largest 10% innovations, and zero otherwise. This measure of innovation, which we used for calibration purposes, is in theory more consistent with the model,

Figure 7: Local Projections



which focuses on large innovation projects. However is also observed much less frequently, and as a results there are much fewer observations of young innovating firms. Results are therefore more noisy, and empirical estimated parameters are sometimes not significant. Nonetheless, the predictions are largely confirmed. The coefficient of $r_t * int\_share_{s,t} * young_{i,t}$ is positive both in the model and in all the three empirical specifications, while the coefficient of $int\_share_{s,t} * young_{i,t}$ is negative and significant in one empirical specification and not significant in the two other ones.

4.7.2 Timing and Persistence of the Effects: Local Projections Analysis

In this section, we provide additional evidence supporting the prediction that young intangible firms are more likely to react less negatively (or more positively) to rate increases than older or more tangible firms (Prediction 2). To be able to study the dynamics, persistence, and magnitude of our proposed channel, we use local projection techniques to examine the impact of an interest rate shock on the innovation decisions of firms at different time horizons. We follow Jorda et al. (2017) and Cloyne et al. (2018) and estimate impulse response functions on firm-level panel data using monetary policy shocks structurally identified in a separate estimation process. Our specification is

$$Inn_{i,t+h} = \gamma_i^h + \sum_{g=1}^{4} I_{i,g} \left(\alpha_g^h + \beta_g^h \Delta r_t\right) + \mathbf{controls}_{i,t} \left(\eta^h + \lambda^h \Delta r_t\right) + \epsilon_{i,t+h}, \tag{33}$$

where the dependent variable $Inn_{i,t}$ is the innovation dummy defined earlier. We study the response of the innovation status up to a horizon of $h = 10$ quarters. Firm fixed effects are captured by γ_i^h, and g indicates one of the 4 buckets of firms determined by age and intangibles intensity: $g = \{young - intangible, young - tangibles, old - intangible, old - tangible\}$. $I_{i,g}$ is an indicator function that takes value 1 if firm i is in group g. The monetary surprise in quarter t, Δr_t, is calculated by adding up the monthly monetary policy shocks obtained from Jarocinski and Karadi (2019). We also introduce quarter fixed effects to control for seasonality, Driscoll and Kraay standard errors, and double clustering of standard errors at quarter and industry level.[14] Firms in the sample are required to be active for at least eight years after the monetary policy shock occurs.

Figure 7 shows the estimation results, which are consistent with the regression results shown above and with the predictions of the model. Tangible firms slightly reduce innovation frequency in response to a positive interest rate shock, especially mature ones, while intangible firms, especially the young ones, increase innovation in response to the same shock. The third panel computes the difference in the responses of intangibles and tangibles firms. The difference is significantly positive, especially for young firms. These opposite responses between tangible and intangible firms are consistent with the industry simulations (see Panel D of Figure 3), and confirm Prediction 2.

4.7.3 Robustness checks

One concern with our results is that in the model only financially constrained firms innovate, and therefore we do not analyse the implications of changes in the interest rate for the innovation decisions of unconstrained firms. Lower rates could make innovation more attractive by reducing the opportunity cost of the innovation, and in particular by increasing the net present value of its future revenues if the innovation is successful. Such a channel, which would operate in the absence of financial frictions, might be stronger for tangibles innovations, if their value is more sensitive to interest rate changes. This could for example happen if the innovations of tangible firms have longer duration than the innovations of intangible firms.

We dispel this concern in two ways. First, the above mechanism would predict a differential effect of interest rates on tangible and intangible innovations irrespective of firms age. Conversely, our evidence that the reduced sensitivity of intangible investment to interest rates is significantly stronger for young firms (shown to have worse access to external funds than older firms) is consistent with financial frictions playing an important role in this effect. Second, for the above alternative mechanism to generate our findings, it would have to be that lower rates increase more the value of the innovations of young tangible than of young intangible

[14] Driscoll and Kraay (1998) introduce a covariance matrix estimator which produces standard errors that are robust to heteroscedasticity and to very general forms of spatial and temporal dependence of the residuals.

firms, and we directly test for this possibility in our dataset. More precisely, in Appendix D we run a regression similar to Equation (32) but with the value of innovations over total assets as dependent variable. The alternative hypothesis described above implies that the coefficient of the triple interaction ($r_t * int\_share_{s,t} * young_{i,t}$) should be positive. However we find it to be generally negative and not significant. Thus we find no evidence in favour of this alternative explanation.

5 Model with multiple investment opportunities

In Section 3, we demonstrated that the relation between interest rates and investment depends on the degree of capital tangibility. In Section 4 we derived, and tested empirically, an application of this general insight, focusing on innovation decisions.

In this section we prove that this main insight also applies to a more general investment model which relaxes three restrictive assumptions we maintained in the two previous sections: First, that firms can invest only once. Second, that only firms facing financial frictions have investment opportunities. Third, that firms with investment opportunities are always net savers. In reality, firms perform large investment project repeatedly during their lifetimes, and they are often net borrowers. Furthermore, many of them are arguably financially unconstrained, and how their investment decisions react to interest rate changes is important for the aggregate implications of the model. We use this model to show that in equilibrium the various channels described before matter for the allocation of resources across constrained and unconstrained firms, for the mean and dispersion of the marginal product of capital, and for the sensitivity of aggregate investment to the interest rate. One caveat of the analysis is that, in order to keep the model tractable despite these extensions, in this section we do not allow for the possibility to invest in innovation to improve productivity.

5.1 Technology and Firm Dynamics

As in the previous sections, we consider a production sector where firms operate a technology that uses tangible capital, intangible capital and labor as inputs. However, we introduce heterogeneity of firms in their access to external finance. Following Kiyotaki and Moore (1997 and 2012) and Del Negro et al. (2017), we assume that there are two types of firms: one type faces financial imperfections, and is financially constrained in equilibrium, while the other type does not face financial frictions. We call firms of the first type "constrained", and firms of the second type "unconstrained".[15]

[15] Another approach would be instead to assume that all firms face the same frictions but that the presence of persistent idiosyncratic shocks and/or decreasing returns to scale implies that some firms—typically the younger ones—are endogenously more productive and financially constrained, and other firms—typically the older ones—are less productive and financially unconstrained thanks to past accumulated savings (e.g. Buera, Kaboski and Shin, 2011; Kahn and Thomas, 2013). All of the results derived here could be generalized in a more complicated model following the latter approach.

5.1.1 Constrained Firms

There is a continuum of mass 1 of constrained firms. These face financial frictions and therefore are analogous to the firms considered in the previous sections. The production function is a Cobb-Douglas in labor and capital

$$y_{c,t} = z_{c,t} e_{c,t}^{1-\xi} \left(l_{c,t}^{1-\alpha} k_{c,t}^{\alpha} \right)^{\xi},$$

where $0 < \alpha \leq 1$ and $0 < \xi < 1$. The subscript "c" is for "constrained". Labor $l_{c,t}$ is provided by the household sector, who can supply it to both constrained and unconstrained firms. The only difference with the previous section is that we add entrepreneurial labor input $e_{c,t}$, which is provided by a continuum of specialized entrepreneurs of mass 1, who can only provide labor to constrained firms. This additional assumption allows us to simplify aggregation and obtain a closed form solution of the model.[16]

As in the previous section, the term $k_{c,t}$ is a composite of tangible and intangible capital according to equations 9-12. The budget constraint, collateral constraint and dividend constraint for constrained firms, are also similar to those derived in the previous section:

$$d_{c,t} = \pi_{c,t} + (1 + r_t) a_{c,t} - a_{c,t+1} - (k_{c,t+1} - (1 - \delta) k_{c,t}), \tag{34}$$

$$a_{c,t+1} \geq -\theta \frac{(1 - \delta) k_{c,t+1}}{1 + r_{t+1}}, \tag{35}$$

$$d_{c,t} \geq 0. \tag{36}$$

$$\pi_{c,t} \equiv y_{c,t} - w_{c,t}^{e} e_{c,t} - w_{c,t} l_{c,t} \tag{37}$$

Where $\pi_{c,t}$ denotes current profits. $w_{c,t}^{e}$ is the wage paid to the entrepreneur, and $w_{c,t}$ the wage paid to a worker. A negative value of $a_{c,t+1}$ indicates net borrowing, and θ is a function of θ^T and θ^I, as defined in Equation (12). $k_{c,t+1}$ units of capital purchased in period t have a residual value of $(1 - \delta) k_{c,t+1}$ in period $t+1$, and guarantee a debt repayment of $\theta(1 - \delta) k_{c,t+1}$. Therefore the maximum face value of debt $-(1 + r_{t+1}) a_{c,t+1}$ has to be smaller or equal than $\theta(1 - \delta) k_{c,t+1}$, which yields Equation (35).

Every period, with probability γ firms can invest to expand fixed capital k_t. This can be interpreted as the opportunity to invest in a large expansion or innovation project. Otherwise, with probability $1 - \gamma$, they can only produce with their existing depreciated capital.[17]

Finally, as in the previous section, after producing, the firm's technology becomes obsolete with probability ψ. In this case, the firm liquidates all of its capital, pays out as dividends all

[16] The reason is that adding entrepreneurial labour ensures that the production function is constant returns to scale, and this implies, as it will be shown below, that all constrained firms chose the same optimal ratio between inputs. Eliminating specialized entrepreneurial labour would not affect any of the results, but would complicate the analysis because we would not be able to solve the model analytically.

[17] An alternative approach, to introduce lumpy investment decisions is to add nonconvex adjustment costs (e.g. see Gourio and Kashyap, 2007, among others). For the purpose of this paper, our assumption of exogenous investment opportunities has similar implications, but is much more tractable and allows for a closed-form solution.

of its savings, including the liquidation value of capital, and exits. Exiting firms are replaced with newborn ones, with initial endowment W_0.[18]

Optimization

Firms choose their investment and savings in order to maximize the net present value of their dividends. Since the value function optimization problem is similar to the one in the previous chapter, we define it in Appendix E, and we focus here on the most relevant features only. Investing in one unit of capital has a opportunity cost of r_{t+1} (the lost return on saving) plus the depreciation of capital δ, and has a marginal return of $\alpha\xi z_{c,t} e_{c,t}^{1-\xi} l_{c,t}^{\xi(1-\alpha)} k_{c,t}^{\alpha\xi-1}$. It follows that a constrained firm faces a binding borrowing limit (35) in equilibrium if the marginal return on capital is higher than the user cost:

$$\frac{\partial y_{c,t+1}}{\partial k_{c,t+1}} = \alpha\xi z_{c,t} e_{c,t}^{1-\xi} l_{c,t}^{\xi(1-\alpha)} k_{c,t}^{\alpha\xi-1} > r_{t+1} + \delta. \tag{38}$$

We claim $-$ and check later in our calibrated simulations $-$ that, in equilibrium, the above condition is satisfied. The implication of (38) for investing firms is that the borrowing constraint (35) is binding, and that firms choose not to pay dividends, so the equity constraint (36) is also binding. Making $d_{c,t} = 0$ in budget constraint (34), using (34) to substitute for $a_{c,t+1}$ in (35), assuming (35) is binding, and solving for $k_{c,t+1}$, we obtain their level of investment:

$$(k_{c,t+1} \mid \text{invest}) = \frac{\pi_{c,t} + (1 + r_t)a_{c,t} + (1 - \delta)k_{c,t}}{1 - \frac{\theta}{1+r_{t+1}}}. \tag{39}$$

This has the same interpretation of equation (17) in the previous section. The right-hand side of equation (39) is the maximum feasible investment for a firm. The numerator is the total wealth available to invest determined by current profits $\pi_{c,t}$, the net financial position from the previous period $(1 + r_t)a_{c,t}$, and the residual value of capital $(1 - \delta)k_{c,t}$. The denominator is the downpayment to buy one unit of capital. Investing firms in equilibrium borrow as much as possible, and

$$(a_{c,t+1} \mid \text{invest}) = -\frac{\theta}{1 + r_{t+1}} k_{c,t+1} < 0. \tag{40}$$

The implication of assumption (38) for non-investing firms is that they will not sell any of their capital, and, for these firms, the law of motion of capital is

$$(k_{c,t+1} \mid \text{not invest}) = (1 - \delta)k_{c,t}. \tag{41}$$

Non-investing firms always retain all earnings and select $d_{c,t} = 0$ because they face a positive probability of being financially constrained in the future, and hence the value of cash inside the firm is always higher than its opportunity cost (see Appendix E for a formal proof). Substituting $d_{c,t} = 0$ and (41) in (34):

$$(a_{c,t+1} \mid \text{not invest}) = \pi_{c,t} + (1 + r_t)a_{c,t}. \tag{42}$$

[18] We assume that newly created firms do not produce in period 0, and use their wealth W_0 to invest. this is why their initial endowment is defined as W_0 and not as a_0, because a_t denotes in general savings from period $t-1$, that generate $(1 + r_t)a_t$ resources in period t. The relation between W and a is derived in Appendix 4.

Equations (40) and (42) determine the wealth dynamics of firms. A firm that invested in period $t-1$ but is not investing in period t has debt equal to $-a_{c,t} = \frac{\theta}{1+r_t}k_{c,t}$. It uses current profits $\pi_{c,t}$ to pay the interest rate on debt $-r_t a_{c,t}$ and to reduce the debt itself. As long as the firm is not investing, the debt $-a_{c,t}$ decreases until the firm becomes a net saver and has $a_{c,t} > 0$. At this point, wealth accumulation is driven both by profits $\pi_{c,t}$ and by interest on savings $r_t a_{c,t}$, until the firm has an investment opportunity and its accumulated wealth $(1+r_t)a_{c,t}$ is used to purchase capital (see equation (39)). This discussion clarifies that a lower interest rate r_t helps the non-investing firm repay existing debt, and we call this effect the "*Net debtor channel*", but it slows down the accumulation of savings after the firm has repaid the debt (the savings channel already analyzed before).

5.1.2 Unconstrained Firms

There is a continuum of mass 1 of identical unconstrained firms. Their production function has the same functional form of the production function of constrained firms:

$$y_{u,t} = z_{u,t} e_{u,t}^{1-\xi} \left(l_{u,t}^{1-\alpha} k_{u,t}^{\alpha} \right)^{\xi}, \tag{43}$$

Where $e_{u,t}$ is the input provided by a mass 1 of entrepreneurs specialized in operating unconstrained firms. They finance capital with equity from the household sector and pay out all profits as dividends d_t^u to households every period:

$$d_{u,t} = \pi_{u,t} - \left(k_{u,t+1} - (1-\delta) k_{u,t} \right), \tag{44}$$

$$\pi_{u,t} \equiv y_{u,t} - w_{u,t}^e e_{u,t} - w_{u,t} l_{c,t} \tag{45}$$

These unconstrained firms are able to issue equity, and so $d_{u,t}$ is allowed to be negative. As for the constrained firms, these firms are also able to invest with probability γ, The first order conditions for $e_{u,t}$ and $l_{u,t}$, as well as the first order conditions for $k_{u,t}$ for investing firms, are reported in Appendix E.

5.1.3 Aggregation of the Firm Sector

We assume that all firms employ the same homogeneous labor provided by households, which is in fixed aggregate supply $N = 1$:

$$L_{c,t} + L_{u,t} = 1, \tag{46}$$

Therefore, the wage paid to households is equalized across sectors:

$$w_{u,t} = w_{c,t} \equiv w_t. \tag{47}$$

Furthermore, there is a measure 1 of entrepreneurial labor specialized in operating each type of firm:

$$E_{c,t} = E_{u,t} = 1 \tag{48}$$

Given that firms operate a CRS production function, within the constrained and unconstrained groups all firms employ inputs in the same optimal ratio, and we can thus aggregate factors of production within each group. We denote aggregate factor values with upper case letters. Equations (81-87) in Appendix E determine in equilibrium the values of $\mathbf{Y}_{c,t}, \mathbf{Y}_{c,t}, L_{u,t}, K_{u,t}, w_t, w^e_{u,t}$ and $w^e_{c,t}$ given $K_{c,t}$.

5.2 Households and entrepreneurial Sectors

We consider a representative household, a representative productive entrepreneur and a representative unproductive entrepreneur. Each supplies inelastically one unit of labor and consumes. Consumption and savings are chosen to maximize:

$$V^j_t \left(B^j_t\right) = \max_{C^j_t, B^j_{t+1}} u\left(C^j_t\right) + \beta V_{t+1}\left(B^j_{t+1}\right) \tag{49}$$

subject to

$$C^j_t = D^j_t + W^j_t - (1 + r_t)B^j_t + B^j_{t+1} \tag{50}$$

where $j \in \{e_c, e_u, h\}$ indicates the type of agent. C^j_t is aggregate consumption, D^j_t, W^j_t are dividends and wages, where $W^{e_c}_t = w^e_{c,t}$, $W^{e_u}_t = w^u_{u,t}$ and $W^h_t = w_t$, and B^j_t are aggregate borrowing (or savings if negative). The first order condition is the usual consumption Euler equation:

$$u'\left(C^j_t\right) = \beta(1 + r_{t+1})u'\left(C^j_{t+1}\right)$$

5.3 Steady State

In the steady state household consumption is constant, implying $r = \frac{1}{\beta}$. Furthermore, unconstrained firms distribute all their profits as dividends and do not hold any financial assets, so that the market clearing conditions for asset holdings implies that total household debt is equal to the asset holdings of the constrained firms A:

$$B^{e_c}_{t+1} + B^{e_u}_{t+1} + B^h_{t+1} = A$$

The remaining steady state equilibrium conditions are described in Appendix E. Here we focus on the aggregate capital stock K_c and the aggregate wealth A of the constrained firms. K_c can be shown to be equal to (see Appendix E for details):

$$K_c = \frac{\gamma\left[(1-\psi)\left(\Pi_c + (1+r)A\right) + \psi W_0\right]}{\left(1 - \frac{\theta}{1+r}\right)\left[\delta + \psi\left(1-\delta\right)\right] - \frac{\theta}{1+r}\gamma(1-\delta)(1-\psi)}, \tag{51}$$

where Π_c is the aggregate profits of constrained firms:

$$\Pi_c \equiv z_c \left[K_c^{\alpha} L_c^{(1-\alpha)}\right]^{\xi} - w_c^e - w(1 - L_u). \tag{52}$$

Equation 51 has an intuitive explanation. The numerator is the aggregate amount of liquid resources of the measure γ of investing firms. For the fraction $(1-\psi)$ of already operating firms, liquid resources are profits Π_c plus net savings $(1+r)A$. For the fraction ψ of new firms they are the initial endowment W_0. The denominator is the downpayment necessary to support one unit of capital in the steady state. It requires the replacement of the depreciated capital and the lost capital of exiting firms (a fraction $\delta+\psi(1-\delta)$) and can benefit from using existing capital held by the investing firms as collateral (fraction $\gamma(1-\delta)(1-\psi)$). Furthermore, aggregate asset holdings of the constrained firms A can be shown to be equal to:

$$A = \frac{1}{1-(1-\psi)(1+r)} \left\{(1-\psi)\Pi_c + \psi W_0 - [\psi + \delta(1-\psi)] K_c\right\}. \tag{53}$$

A is equal to the net earnings of the constrained firms, multiplied by a factor $\frac{1}{1-(1-\psi)(1+r)}$, which measures the expected accumulated value of saving each period one unit of wealth at the rate r until the firm exits from the market. The net earnings are the endowment of the new firms ψW_0 plus the net earnings of continuing firms $(1-\psi)\Pi_c$, minus the term $[\psi + \delta(1-\psi)] K$, which is total expenditures to replace the depreciated capital of continuing firms $\delta(1-\psi)K$, and the capital liquidated by exiting firms ψK.

5.3.1 Discussion

In this section, we briefly discuss a key feature of the equilibrium described above, namely the relation between capital tangibility and the net financial position of constrained firms. Consider the effect of a shift toward more intangible technologies (higher μ) that reduces θ (see Equation 12). This reduces the borrowing capacity of the constrained firms by increasing the required downpayment $\left(1-\frac{\theta}{1+r}\right)$ in the denominator of (51). It follows that their aggregate capital K_c is lower for given liquid resources in the numerator.

The reduction in aggregate capital K_c affects net aggregate financial wealth A in Equation (53). More specifically, the multiplicative factor $\frac{1}{1-(1-\psi)(1+r)}$ in Equation (53) is always positive. Moreover, since the endowment of new firms ψW_0 is small, the sign of the term in square brackets is determined by the difference between a positive term $(1-\psi)\Pi_c$, concave in K_c (see the definition 52) and a linear negative term $-[\psi + \delta(1-\psi)] K_c$. When capital is tangible and θ is large, K_c is also large because its required downpayment is small, and in Equation (53) the negative term dominates, making A negative. In other words tangible constrained firms are, on aggregate, net borrowers, and lower interest rate benefit them via the Net debtor channel. Conversely, in an intangible (low θ) economy, K_c is lower and the positive concave term dominates making A positive, implying that a lower interest rate penalizes these firms via the Saving channel. Note also that when A is positive, a reduction in the interest rate reduces investment both through a reduction in the return on savings rA_f and through a reduction in the multiplicative factor $\frac{1}{1-(1-\psi)(1+r)}$.

5.4 Calibration

Our benchmark calibration is illustrated in Table 3. Whenever possible, we maintained the same parameters used for the previous model and described in Section 4.4. These include α, η, θ^T, θ^I, δ, μ, and also β, which matches the same real interest rate r chosen before.

The parameters that are new or have a slightly different interpretation in this model are ψ, γ, W_0, z_c and z_u. One important element of this exercise is that we want to generate results for realistic levels of financial frictions. Therefore, we normalize z_u to 1, and we calibrate z_c and ψ to jointly match the share of output produced by constrained firms, and the average intensity of financial frictions in the economy.

In the model, unconstrained firms have access to frictionless financing. Therefore, we match their share with the share of output produced by the Compustat firms with best credit ratings. The share of output produced by AAA and AA rated firms is around 15%. Adding also A rated firms gives a value of 45%. We choose an intermediate value of 30%. This implies a share of output produced by firms facing some form of financial imperfections equal to 70%. Regarding the average intensity of financial frictions, Gilchrist Sim and Zakrajsek (2013) document the bond spreads of the cross-section of US firms, and report the average spreads for the 10th percentile. We interpret the firms with 10% lowest spreads as within our group of unconstrained firms defined above, and we consider the difference in spread between them and all the other firms, obtaining an average spread of 2.5%. In the model, we compute the spread of constrained firms Δ^c as the interest rate premium that the firms would be willing to pay over r to access additional credit, which is given by: :

$$\Delta^c = \alpha\xi z_c L_c^{\xi(1-\alpha)} K_c^{\alpha\xi-1} - (r+\delta)$$

Since such spread is 0 for unconstrained firms, to obtain an average spread equal to 2.5% it must be that $\Delta^c * 0.7 = 2.5\%$, which implies that $\Delta^c = 3.6\%$. The quarterly probability to receive an investment opportunity γ is set to 0.1. This value is a bit low compared to empirical studies of tangible capital. For example Doms and Dunne (1998) document that around half of the plants in their sample perform a capital adjustment of at least 37% in a given year. However, Chiavari and Goraya (2020) document that intangible capital is considerably lumpier than tangible capital. Nonetheless, selecting a higher value of γ would not significantly change our results. The initial endowment of newborn firms W_0 is equal to 0.3, and is a parameter not calibrated to match a specific moment due to a lack of a clear empirical counterpart. It corresponds to 2% of average firm annual output. Our results show very little sensitivity to variations in our choice of W_0 in the range $0.1\% - 20\%$.

One caveat of this calibration strategy is that by targeting 70% of output produced by firms facing some type of financing imperfection, we might overestimate aggregate financial frictions. It is plausible to assume that most firms in the data do not have a frictionless access to finance, but for many of these firms, frictions take the form of a interest rate premium rather than a

Table 3: Parameter Values

Parameter	Symbol	Value	Source/Target
TFP (Low-productivity tangibles firms)	z_u	1	
TFP (Low-productivity tangibles firms)	z_c	1.5	Productivity dispersion in Syverson (2004)
Probability of innovation opp. (quarterly)	γ	0.01	Capital reallocation estimates (David, 2014; Eisfeldt and Rampirin, 2006)
Exit probability (quarterly)	Ψ	0.01	Capital reallocation estimates (David, 2014; Eisfeldt and Rampirin, 2006)
Initial endowment of firms	W_0	0.3	
Rate of time preference (annual)	β	0.97	

quantity borrowing constraint as in the model. Another caveat is that we impose the same depreciation rate δ for both types of capital. We do so to simplify the model, but it is well known that in reality most types of intangible capital depreciate faster than tangible capital. Therefore, in a robustness section we verify that the results are robust to lowering the fraction of output produced by constrained firms and to assuming a higher depreciation rate of intangible capital than of tangible capital.

5.5 Simulation Results

5.5.1 Benchmark exercise

We perform a comparative static analysis similar to the one shown in Figure 3 in the previous section, namely we compare the effects of a reduction in r in a "tangibles" and an "intangibles" economy. Figure 8 analyses the tangibles economy first, and therefore the parameters are the benchmark ones except that we set $\mu = 0.2$, so tangible capital is 80% of total capital. The lines represent different simulations for different values of the real interest rate r (displayed in the the top left graph), ranging from 6% (when $\beta = 0.94$) to 0% (when $\beta = 1$) in annualized terms. All other parameters are kept constant at their benchmark value. The savings channel, which generates a positive relation between r and capital, is weak in this economy, because the corporate sector as a whole is a net borrower (Panel C). Even though some investing firms are net savers (those firms that receive an investment opportunity after many periods from the previous investment opportunity), many firms are instead net borrowers, and benefit from the reduction in r. However, the saving channel is still dampening the sensitivity of aggregate capital to r, and dominates on average. As a result, as the interest rate falls from 6% to 0%, the capital in constrained firms falls slightly, by 3% (Panel D). Conversely, capital in unconstrained firms expands strongly, by up to 300% (Panel E), driving up aggregate output (Panel I). The differential effect of r on capital is shown clearly at the bottom of the figure. While the sensitivity of K to r is slightly positive for constrained firms (PANEL J), the average sensitivity across all firms is negative (Panel K), driven by the fact that lower r stimulates the investment of unconstrained firms. Interestingly, the expansion of unconstrained firms reduces their marginal productivity of capital, and increases the dispersion in MPK across all firms (Panel G), thus slightly increasing the misallocation of resources.

Figure 9, presents the same simulations shown above, and compares them with the simulation of an intangibles-intensive economy ($\mu = 60\%$), represented by the red discontinuous lines. Because intangible firms borrow less when they have an investment opportunity, overall the constrained firms are net savers (PANEL C). Thus the saving channel is much stronger in this economy, and implies a sharp reduction in capital in constrained firms as r falls (PANEL D). This significantly reduces the output expansion caused by lower rates (Panel I). The larger misallocation between constrained and unconstrained firms is documented also by the sharper increase in MPK dispersion relative to the Tangibles Economy (Panel G). Finally, Panel J shows that aggregate K held by constrained firms responds positively and very strongly to r, implying that the overall sensitivity of K to r is less negative than in the tangible economy for most values of r (PANEL K), roughly those in the in the 1.75%-6% interval. For very low values of r, the amount of capital held by constrained productive firms drops so much that the sensitivity of unconstrained firms dominates when computing the aggregate response of K to r.

5.5.2 Robustness checks

In this section we provide two robustness checks of the above results. First, in Figure 10 we change the calibration so to reduce the fraction of constrained firms from 70% to 35%.[19] The results shown below in Figure 10 are qualitatively similar to those shown before. We still find that, compared to the tangibles economy, the intangibles economy has a much stronger contraction in the capital of constrained firms as r falls, and a larger increase in MPK dispersion. However, the aggregate implications of this increased misallocation are smaller, and the sensitivity of aggregate capital to r is almost identical in the two economies.

Second, in Figure 11 we both reduce to 35% the fraction of output produced by constrained firms, and we select different depreciation rates for tangible and intangible capital. More precisely, we choose the realistic values computed by Falato et al. (2018): yearly depreciation rates δ are equal to 10% and 19% for tangible and intangible capital, respectively. Interestingly, the simulations in Figure 11 show larger differences between the behavior of tangible and intangible economies as r falls, closer to the results in the benchmark simulations in Figure 9. and thus confirm our main findings both qualitatively and quantitatively. The intuition is simple. A higher depreciation rate dampens the sensitivity of unconstrained firms to r, and therefore increases the importance of the constrained firms in determining the behavior of aggregate capital and output, even when their share of output is relatively small.

5.6 Empirical evidence

The simulation results shown above confirm the main results obtained with the simpler models analyzed in the previous sections, and generate new insights. In particular, we show that an increase in intangible intensity is related to the corporate sector transitioning from being net borrower to net saver, which is consistent with the empirical evidence (Falato et al, 2018). Moreover, we derive two additional testable predictions:

[19] Notice that we still match the overall intensity of frictions as measured by the average spread of 2.5%, therefore the spread between constrained and unconstrained firms is 2.5%/0.35=7.1%.

Figure 8: Simulation with benchmark parameters, tangible economy

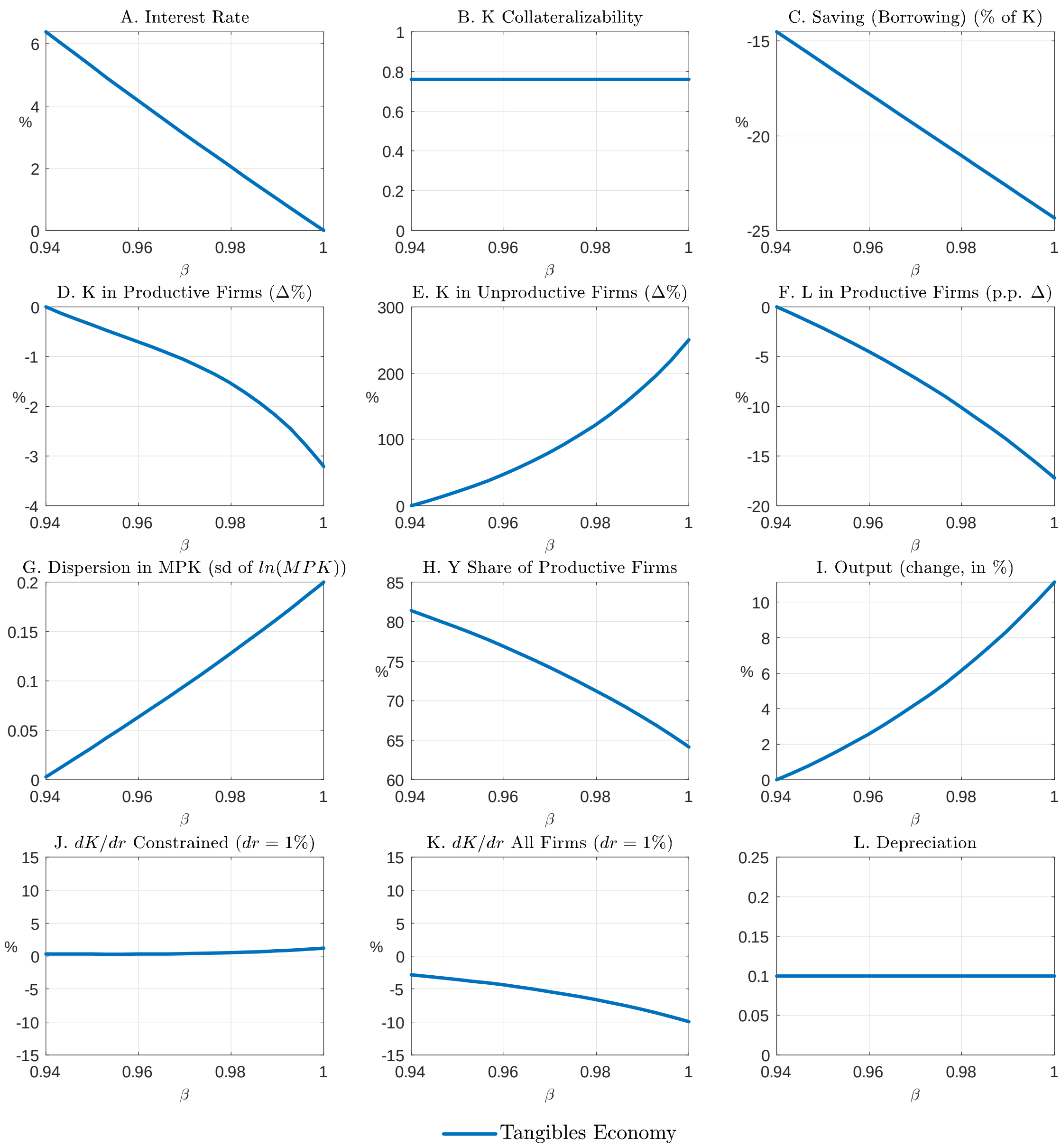


Figure 9: Simulation with benchmark parameters, both tangibles and intangibles economy

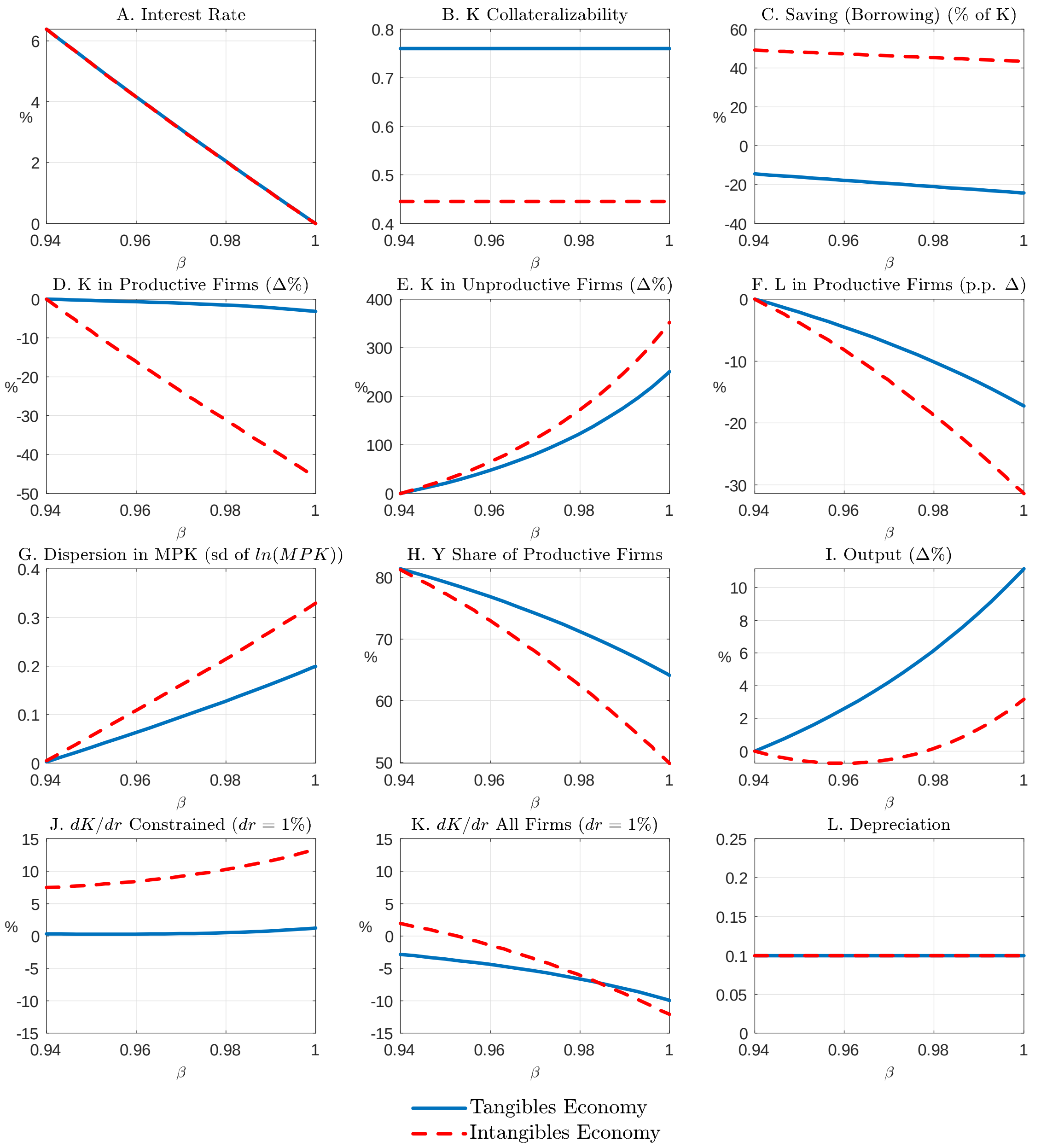


Figure 10: Alternative simulation results with lower share of output from constrained firms

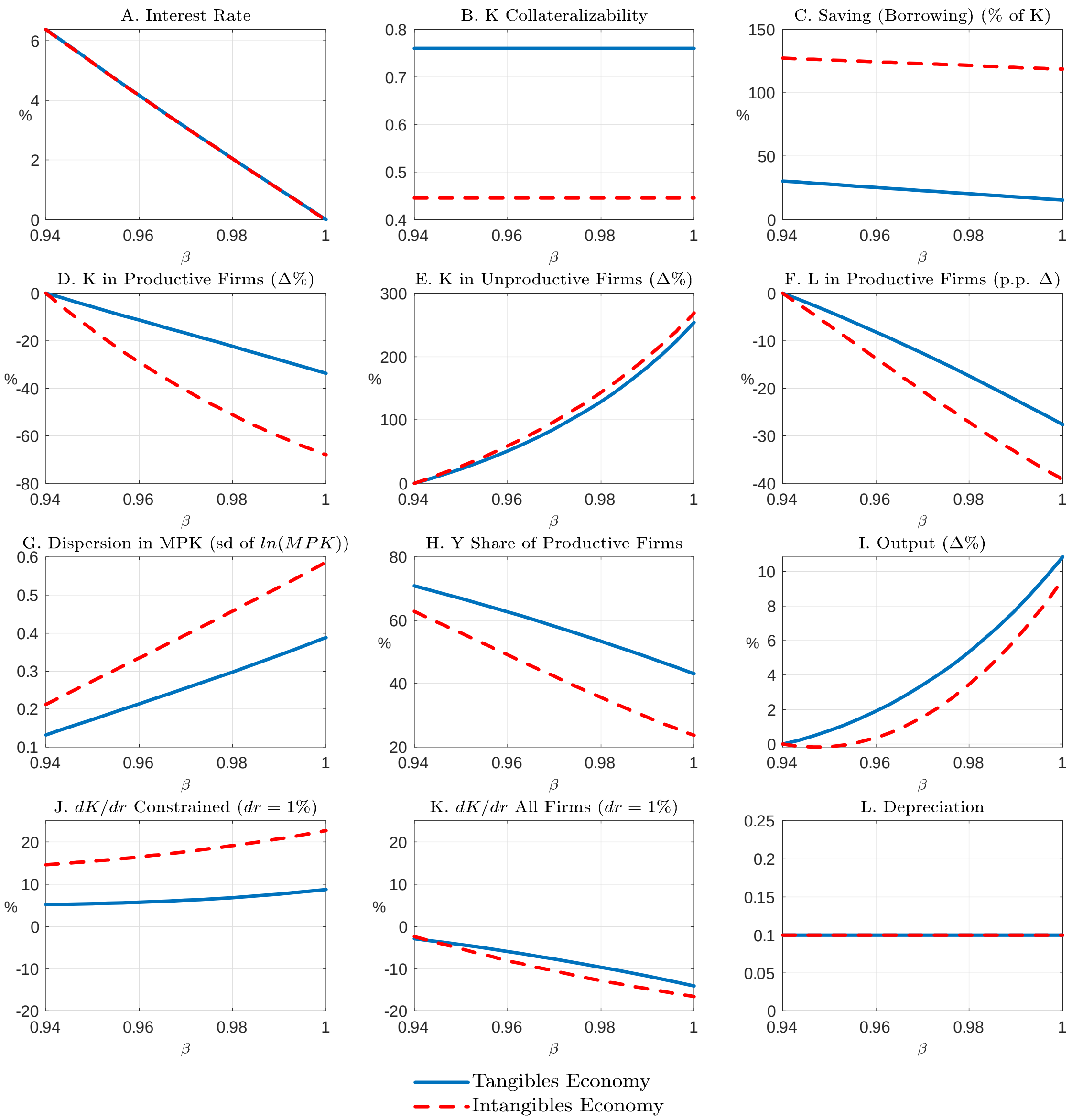
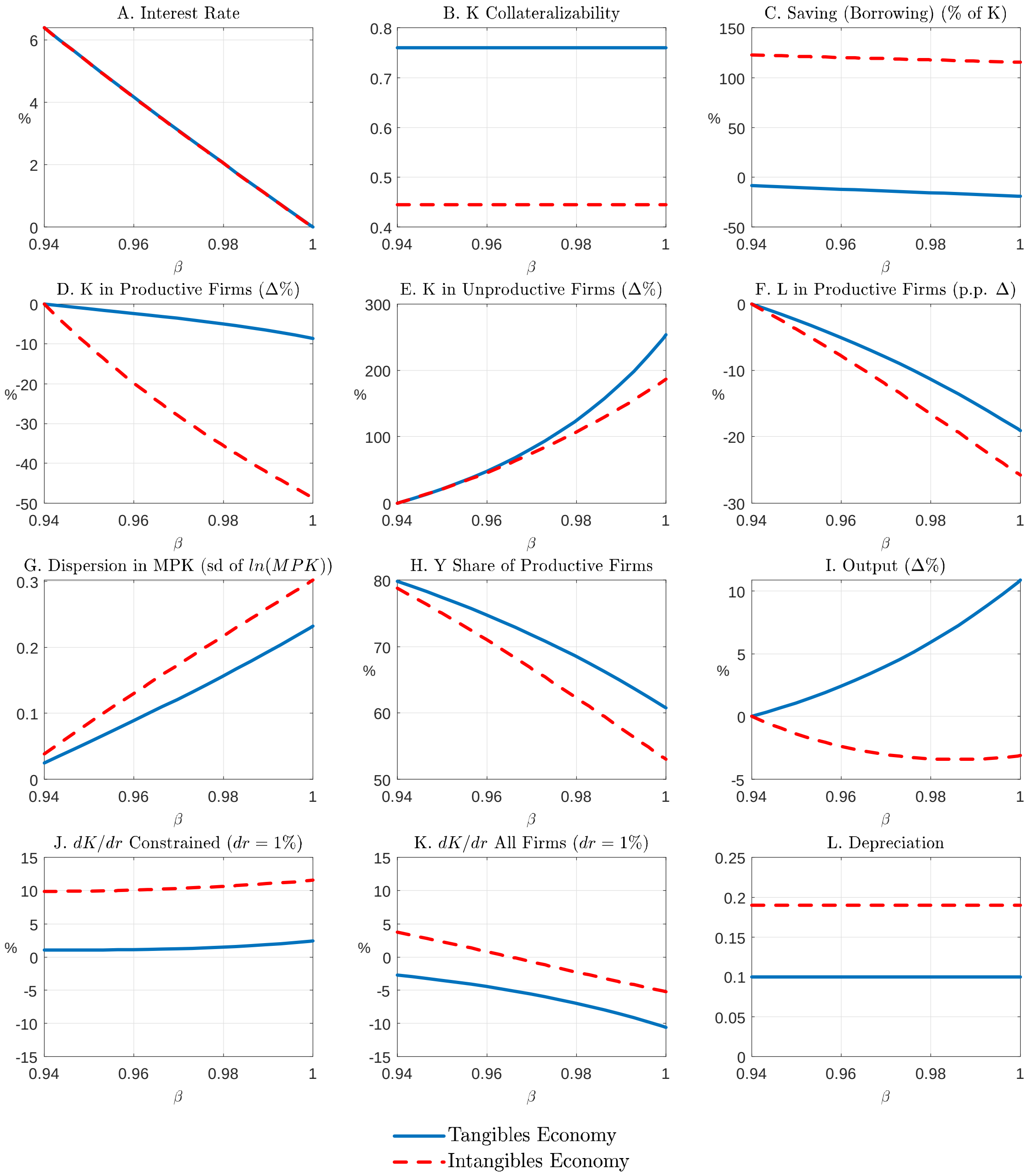


Figure 11: Alternative simulation results with lower share of output from constrained firms and different depreciation rates of tangible and intangible capital.



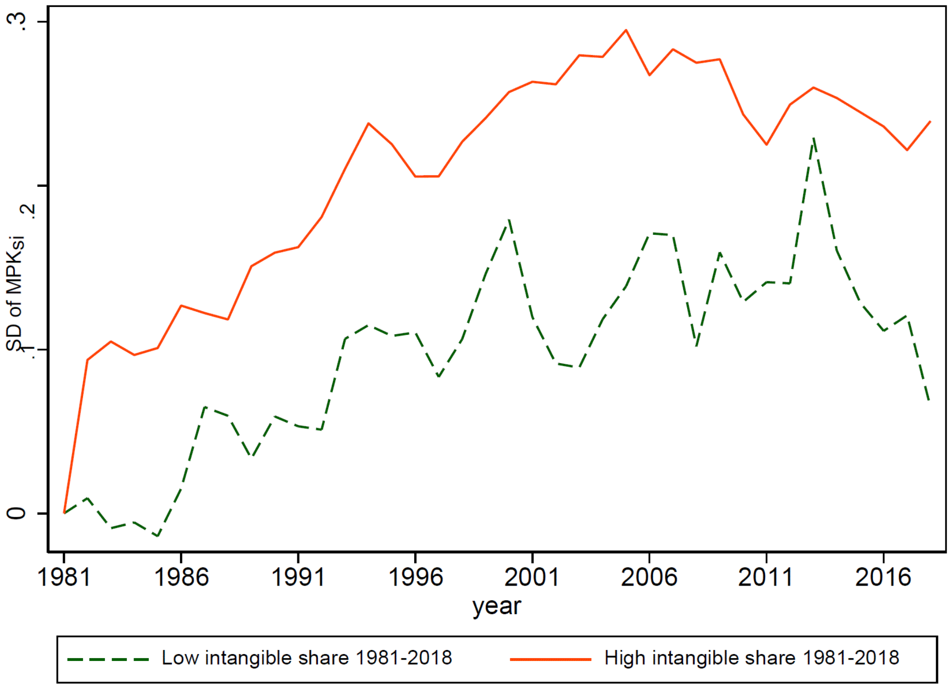


Figure 12: Dispersion of the Marginal Product of Capital in Tangibles and Intangibles Industries

Prediction 3: lower interest rates are related to a larger MPK dispersion in intangible industries than in tangible industries.

Prediction 4: The sensitivity of capital to r is more negative in tangible than in intangible industries.

Below we provide some empirical evidence related to these predictions.

5.6.1 Productivity Dispersion

In order to investigate the relation between the rise in intangibles and dispersion in the marginal product of capital, we use the data described in Section 4.6. We consider sectors at the 2-digit Standard Industrial Classification (SIC) level and drop those with less than 500 firm-year observations over the sample period. We measure output by sales and total capital by the sum of capitalized tangible and intangible capital as described in Section 4.6. To control for outliers, we drop firms in the 1st and 99th percentiles of the distribution of capital productivity. Capital productivity mpk_{sit} of firm i in industry s in period t is measured as the log difference between firm output and the total capital stock, and productivity dispersion is computed as the standard deviation of mpk_{sit} in each industry s each period t. This measure of productivity dispersion is the same one used in the model simulations shown in Figures 8-11.

Figure 12 plots the dispersion of capital productivity in 2-digit SIC industries. The red line displays the sales-weighted mean of the dispersion measure across high-intangible industries, defined as the industries in the top 50% of the distribution of the industry-wide ratio of intangible capital to total capital averaged across years.[20] The green line displays the complementary

[20]The sectors with high shares of intangible capital are: Chemicals and Allied Products; Industrial and Com-

sample of low-intangible industries. The figure shows that capital productivity dispersion has increased in intangibles sectors during recent decades, much more than in tangibles sectors, consistent with prediction 3.[21]

5.6.2 Local Projections Analysis

In this section we provide evidence on how changes in interest rates affect aggregate investment of public firms in the United States. Our simulations imply not only that the sensitivity of capital to the interest rate is more negative for tangible than intangible capital, but also that it declines for both groups as r falls. Since in our sample (1990-2018) we observe a gradual decrease in r and in the share of intangibles, it should be that the sensitivity of capital to r has become less negative over time. To verify it, we again estimate the dynamic causal effects of interest rate changes using a panel local projection technique, similar to the one used in Section 4.7.2. Our specification is

$$\ln K_{i,t+h} - \ln K_{i,t-1} = \gamma_i^h + \beta_g^h \Delta r_t + \mathbf{controls}_{i,t}\eta^h + \epsilon_{i,t+h}, \tag{54}$$

where $K_{i,t+h}$ is the stock of tangible and intangible capital of firm i at the end of quarter $t+h$. The coefficient β_g^h thus captures, approximately, the percent change in the capital stock between right before the policy shock occurs and horizon $t+h$, or roughly the cumulative net investment divided by the initial capital stock. We study the response of investment up to a horizon of $h = 20$ quarters. The methodology used is otherwise analogous to the one described in Section 4.7.2. To test if corporate investment responds more strongly to interest rate shocks in the early part of the sample, we estimate Equation (54) separately considering only monetary policy shocks occurring in the period 1990-2000 and only those occurring in 2001-2019.

The results are in Figure 13. Consistent with our prediction, investment is less negatively correlated with monetary policy in the later part of the sample. In fact, monetary policy rate increases are strongly contractionary in the 1990s, while they are moderately expansionary after 2000. Our model attributes this pattern to the large growth in the average usage of intangible capital between the 1990s and the post-2000 period.[22] Nonetheless, it is certainly possible that other developments happened during the same period, which could explain these findings, such as for example a change in the nature and magnitude of monetary policy shocks. Therefore, we provide a more direct test of Prediction 4 in Figures 14 and 15. Namely, we test whether surprise increases in the monetary policy rate are less contractionary (or even expansionary) for

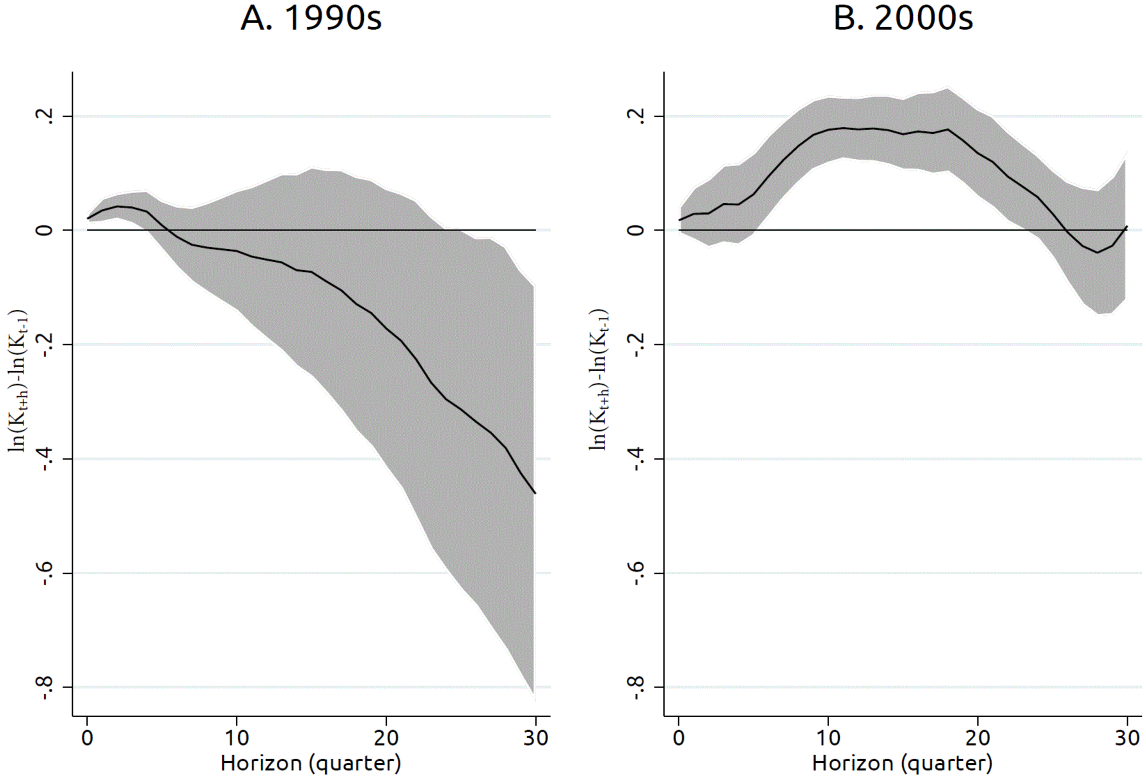
mercial Machinery and Computer Equipment; Electronic & Other Electrical Equipment & Components; Transportation Equipment; Measuring, Photographic, Medical, & Optical Goods, & Clocks; Miscellaneous Manufacturing Industries; Wholesale Trade - Durable Goods; Home Furniture, Furnishings and Equipment Stores; Miscellaneous Retail Business Services; and Engineering, Accounting, Research, and Management Services.

The sectors with low shares of intangible capital are: Oil and Gas Extraction; Food and Kindred Products; Paper and Allied Products; Rubber and Miscellaneous Plastic Products; Stone, Clay, Glass, and Concrete Products; Primary Metal Industries; Fabricated Metal Products; Wholesale Trade - Nondurable Goods; General Merchandise Stores; Food Stores; Apparel and Accessory Stores; and Eating and Drinking Places.

[21] In unreported results, we found similar trends also for labor productivity and TFP. Details are available from the authors.

[22] We check that outliers in the monetary policy shock series are not driving results by running a robustness analysis in which we drop the 9/11/2001 and the 2008-2009 shocks.

Figure 13: Local projection



intangibles than for tangible firms. We use a similar specification as in (33):

$$\ln K_{i,t+h} - \ln K_{i,t-1} = \gamma_i^h + \sum_{g=1}^{4} I_{i,g} \left(\alpha_g^h + \beta_g^h \Delta r_t\right) + \mathbf{controls}_{i,t} \left(\eta^h + \lambda^h \Delta r_t\right) + \epsilon_{i,t+h}, \quad (55)$$

In figure 14 we compare tangible and intangible firms, while in Figure 15 we also control for age. Therefore in this case g indicates one of the 4 buckets of firms determined by age and intangibles intensity: $g = \{young - intangible, young - tangibles, old - intangible, old - tangible\}$. $I_{i,g}$ is an indicator function that takes value 1 if firm i is in group g. Our coefficient of interest is β_g^h, which gives us the effect of intangible intensity on the interest rate sensitivity of investment in each of the 4 groups. We distinguish between young and old firms because we use age as an exogenous indicator correlated to the intensity of financial frictions. We study a horizon of 8 years and require firms to be active for at least that amount of time after the shock.

The results in Figure 14 confirm Prediction 4, by showing that Intangible firms have a less negative relation between investment and interest rate shocks than Tangible firms, with a difference that becomes statistically significant at longer horizons. Importantly, Figure 15 shows that this result is driven by the younger firms in the sample, which are likely to be the most affected by financial frictions.

Figure 14: Local Projections, Tangible versus Intangible firms

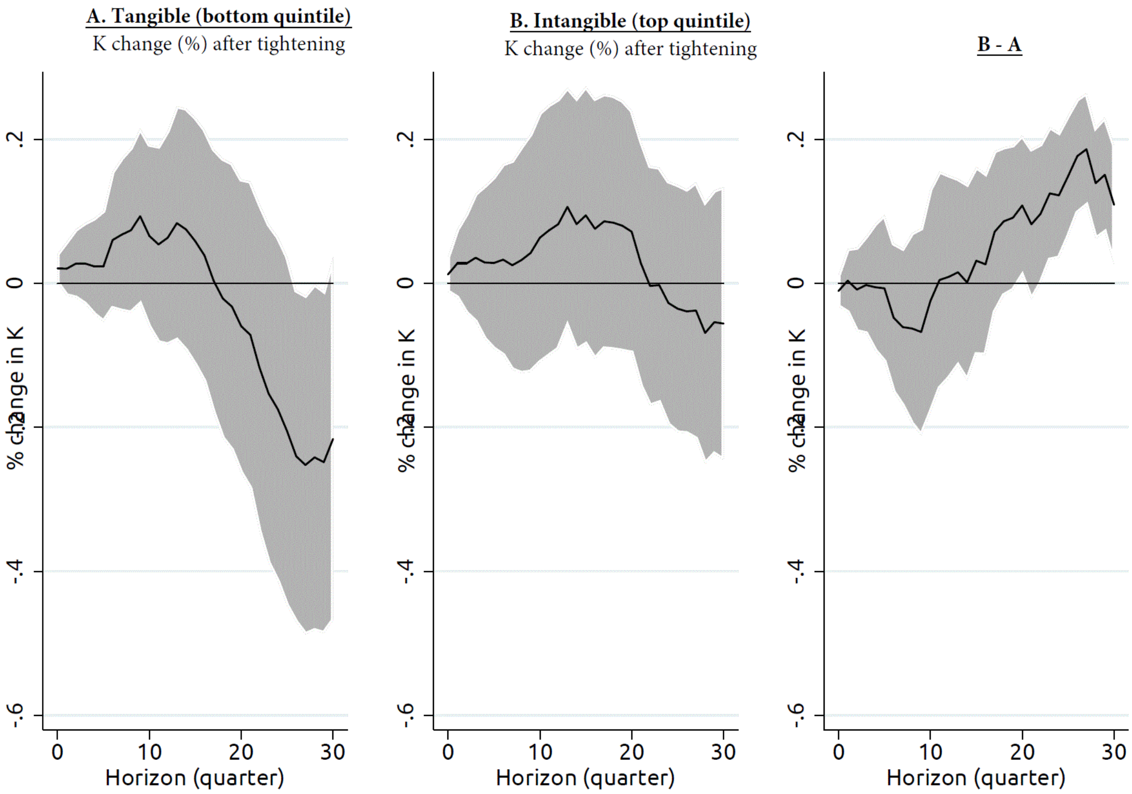
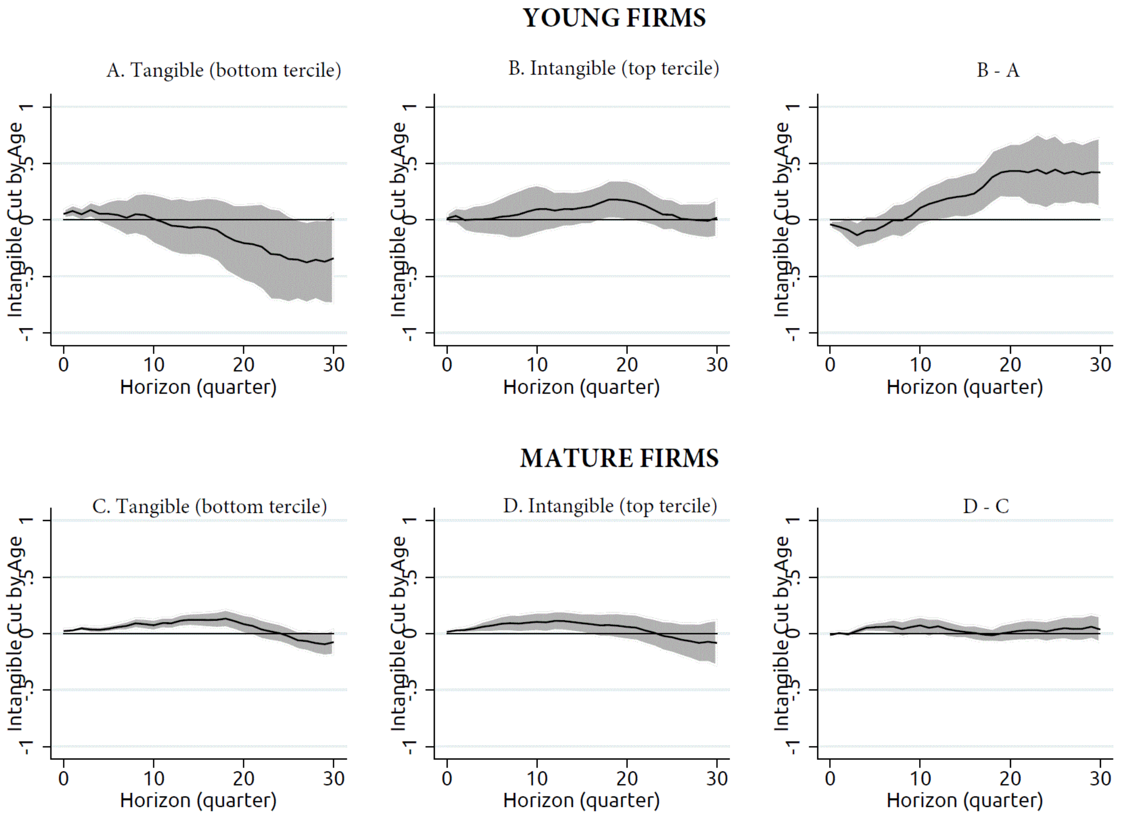


Figure 15: Local Projections, Tangible versus Intangible firms within different age groups



6 Conclusion

The widespread emergence of intangible technologies in recent decades and the associated changes in corporate financing patterns may have significantly affected the relationship between interest rates and corporate investment. In our theoretical framework, as in reality, a shift toward intangible capital in production is followed by a shift in the corporate sector toward a net saving position, because intangible capital has a low collateral value. We show that, as a result, firms' ability to purchase intangible capital is impaired by low interest rates because low rates slow down the accumulation of savings, and our empirical analysis strongly supports this prediction. Furthermore, we also present empirical evidence consistent with the misallocation implications of our model.

Our insights have relevant policy implications. On the one hand, the mechanisms described in this paper suggest that the rise in intangibles dampens the effectiveness of expansionary monetary policy shocks. On the other hand, the negative externality in households' and firms' excessive saving decisions might introduce a role for a fiscal policy that discourages such saving.

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