Cash Holdings, Competition, and Innovation

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Abstract

We examine theoretically and empirically the determinants of innovating firms' cash holdings. Our model highlights an important strategic role that cash plays in affecting the development and implementation of innovation in the presence of expected competition in post-innovation product markets. Firms' equilibrium cash holdings are shown to depend on the intensity of expected competition in output markets and on the degree of innovation efficiency in firms' industries. The signs and magnitudes of these relations depend crucially on the degree of financial constraints that a firm faces. Our empirical evidence on the determinants of cash holdings of innovating U.S. public companies, demonstrates that expected competition intensity and innovation efficiency are associated with firms' observed cash-to-assets ratios in ways consistent with the model's predictions. We conclude that strategic considerations play an important role in shaping cash holdings policies of innovating firms.

Key words: Cash holdings, Strategic interactions; Innovation

JEL Codes: G32, L13

1 Introduction

In this paper we examine theoretically and empirically the determinants of innovative firms' cash holdings. Understanding the drivers of cash policy of companies that engage in innovation is important. Innovation is one of the crucial determinants of growth (e.g., Klette and Kortum (2004), Kogan, Papanikolaou, Seru, and Stoffman (2012)), and Acemoglu, Akcigit, Bloom, and Kerr (2013), and internal cash holdings are of a paramount importance in financing innovation (e.g., Himmelberg and Petersen (1994), Hall and Lerner (2009), and Brown and Petersen (2011)).

Consistent with cash being important for executing innovation, innovative firms' cash holdings are large relative to those of "old-economy" firms. In 2012, the mean cash-to-assets ratio of firms belonging to the top quintile of R&D-to-assets ratio approached 45%, while the mean cash-to-assets ratio of firms that did not report R&D expenditures was about 17%. Both large and small innovative firms hoard more cash than their old-economy counterparts. While large cash holdings of market leaders in the high-tech and biotech sectors are often discussed in popular press,[1] small innovative firms also hold more cash than their traditional counterparts.[2] However, not all innovative firms choose to hold large amounts of cash. We report that during the period 1976–2006, for a quarter of firms that file patents in a given year, cash constitutes less than 2.6% of assets in that year. In this paper we try to understand which unique characteristics of innovative firms affect their cash holdings choices and in which ways.

There are two characteristics of innovative firms that make their cash holdings decisions different from those of traditional firms. The first one is the need to finance innovation and its future implementation. While the "precautionary savings" motive for holding cash is present for all firms because of the possibility of a future need for liquidity, arising, for example, from operating losses or from uncertain future expenditures (e.g., Gamba and Triantis (2008) and Bolton, Chen, and Wang (2011)),[3] it is crucial for firms that engage in innovation. Because of the relatively high degree of information asymmetry between these firms and outsiders, innovating firms may face a larger wedge between the costs of external and internal finance (e.g., Akerlof (1970), Leland

[1] E.g., The Economist (November 3, 2012). At the end of 2012, General Electric, Microsoft, Google, Cisco, and Apple held over 300 billion dollars of cash in total.

[2] E.g., Opler, Pinkowitz, Stulz, and Williamson (1999) and Bates, Kahle, and Stulz (2009) report that cash holdings are positively correlated with R&D expenditures, controlling for various other determinants of cash holdings, including firm size.

[3] This idea dates back to Keynes (1936), who emphasizes the potential costs of obtaining external financing and of converting illiquid assets into cash. Consistent with this argument, Opler, Pinkowitz, Stulz, and Williamson (1999) and Han and Qiu (2007) find a positive relation between firms' cash holdings and their cash flow volatility; Denis and Sibilkov (2010) report a positive relation between cash holdings and investment, especially for financially constrained firms; and Frésard (2010) shows a positive relation between cash holdings and market share gains.

and Pyle (1977), and Myers and Majluf (1984)). As a result, internal cash holdings may have an important impact on the likelihood of developing and implementing innovations.

Kamien and Schwartz (1978) formalize this argument and demonstrate theoretically the increased marginal benefits of cash for firms engaging in large innovations. Schroth and Szalay (2010) show theoretically and empirically that firms that hold more cash are more likely to win patent races than those with lower cash holdings. Himmelberg and Petersen (1994) and Brown and Petersen (2011) examine empirically the relation between firms' R&D investments and their cash holdings and conclude that "because of capital market imperfections, the flow of internal finance is the principal determinant of the rate at which small, high-tech firms acquire technology through R&D." Hall and Lerner (2009) conclude that "large established firms [also] appear to prefer internal funds for financing R&D investments.[4]

The second reason for a special importance of cash holdings for innovative firms is strategic. Innovation does not happen in isolation. There is a large theoretical industrial organization literature modeling strategic interactions among innovative firms (e.g., Scherer (1967), Dasgupta and Stiglitz (1980), Reinganum (1982), Harris and Vickers (1987), Aghion and Griffith (2005) among many others). Such strategic interactions are also found in empirical studies of innovative industries (e.g., Cockburn and Henderson (1994) for the case of pharmaceuticals and Lerner (1997) for the case of disk drives). Importantly, firms interact strategically not only when they develop their innovations but also in the ensuing output markets. In other words, the innovation game is typically not a "winner takes all" one (e.g., Cockburn and Henderson (1994)). In many instances, innovations by multiple firms result in imperfectly substitutable products, which capture substantial market shares.[5] Thus, considering interaction among innovating firms in future output markets is crucial for understanding their cash holdings choices.

Surprisingly, despite the seemingly high importance of strategic considerations for innovating firms, the literature examining strategic choices of cash by such firms is limited. Our model is one of the first to illustrate the strategic and precautionary motives for holding cash, their interactions, and their special importance for innovative firms.[6]

We analyze firms' choices of cash holdings using a static model with two stages – innovation

[4]See Passov (2003) for anecdotal examples of the perverse effects of insufficient cash holdings on innovation development and implementation.

[5]Strategic interactions in output markets among successful innovators are most transparent in the pharmaceutical industry. For example, the market for erectile dysfunction drugs has been dominated for a number of years by two players – Pfizer, which holds the patent for Viagra (sildenafil citrate), and Eli Lilly, the holder of the patent for Cialis (tadalafil), each accounting for 40–45% of the global market in recent years.

[6]A notable exception is the contemporaneous work by Ma, Mello, and Wu (2013).

development and its implementation – that incorporates strategic interactions among firms in both stages. In the first stage, firms decide on the level of their R&D investment, which affects the likelihood of successful innovation. Successful firms then decide on their cash holdings (or, alternatively, payout) policies. In the second stage, firms that produce successful and viable innovations decide whether to implement them using cash holdings and, potentially, external funds. Firms that implement their innovations then obtain output market profits that depend on the resulting output market structure.

The precautionary motive for holding cash is of the first order importance in our model. The reason is that firms may be financially constrained in the innovation implementation stage, in which case they have to rely on internal resources to implement their innovations. Because of the possibility of not having access to external funds, a firm with relatively high cash holdings is more likely to be able to finance its innovation implementation than a firm with relatively low cash holdings.

Cash plays a strategic role in both stages of the game. In the second stage, a successful implementation by a firm reduces expected profits of a rival firm and, as a consequence, it reduces the rival's incentive to implement its innovation. Thus, high cash holdings reduce a rival's likelihood of innovation implementation, indirectly benefiting the firm. The strategic effect of cash also propagates to the first stage of the game. Because of a lower likelihood of innovation implementation, a rival firm reduces its optimal R&D investment, further increasing the firm value.

Our model results in two important empirical implications. First, due to the strategic effect of cash, firms' optimal cash holdings depend on the intensity of expected product markets competition. Importantly, the magnitude and sign of this relation depends crucially on the degree of financial constraints that a firm faces. For relatively financially constrained firms, the proportion of cash in firm value is increasing in the intensity of future product market competition. For relatively unconstrained firms, on the other hand, equilibrium cash holdings are decreasing in the intensity of competition.

The intuition is as follows. There are two effects in play. The first one is precautionary: the more fierce the competition in the output market for innovation outcomes, the lower the expected marginal benefit of investing in future innovation implementation and the lower the optimal cash holdings. The second effect is strategic: higher cash holdings raise the likelihood of future innovation implementation and deter the rival from investing in developing and implementing its own innovation. Importantly, the strategic effect is only present when a firm is likely to be financially constrained, i.e. to rely exclusively on internal resources while implementing innovation. As a result, for relatively unconstrained firms, the precautionary effect dominates the strategic one, resulting in an overall negative relation between expected output market competition intensity and cash holdings. For relatively constrained firms, the strategic effect dominates, leading to a positive relation between cash holdings and competition intensity.

The second important implication of the model is that innovation efficiency, i.e. the ease of obtaining viable innovation, also affects optimal cash holdings in a non-trivial way. For relatively unconstrained firms, cash holdings increase in innovation efficiency, while the relation is reversed for relatively constrained ones. Higher innovation efficiency is associated with higher firm values. It also increases the likelihood of implementing innovation and the marginal benefit of cash. Importantly, the marginal benefit of cash holdings is decreasing in the level of cash. Thus, for relatively constrained firms, whose equilibrium cash holdings are high, an increase in innovation efficiency results in a modest increase in optimal cash holdings, leading to a negative relation between innovation efficiency and the proportion of cash in firm value. For relatively unconstrained forms, whose equilibrium cash holdings are low, an increase in innovation efficiency has a large impact on optimal cash holdings, resulting in a positive relation between cash holdings as a proportion of firm value and innovation efficiency.

Our paper belongs to a broad literature that examines the effects of interaction among firms in output markets on firms' financial policies.[7] In the context of cash holdings of innovative firms, our paper belongs to a small set of contemporaneous working papers that focus on the impact of industry structure and strategic considerations on firms' optimal cash holdings.

The paper most closely related to our work is Ma, Mello, and Wu (2013). Similar to us, they examine the joint determination of cash holdings and R&D investment by innovative firms. Different from us, they focus on the "winner's advantage", as opposed to oligopolistic competition following innovation by multiple firms. In Ma, Mello, and Wu (2013)'s model, cash facilitates faster innovation implementation, deterring competitors from developing and implementing their innovations. While this strategic reason for holding cash is broadly similar to the one in our model, the implications of the two models are very different. First, unlike Ma, Mello, and Wu (2013), we focus on the intensity of competitive interaction among firms in future output markets (e.g., future products' similarity/substitutability). Second, we show that the effect of expected competitive interaction on equilibrium cash holdings depends crucially on the degree of financial

[7]See, for example, Telser (1966) and Bolton and Scharfstein (1990) for the case of cash holdings; Brander and Lewis (1986), Maksimovic (1988), and Showalter (1995) among others for the case of capital structure; Hackbarth and Miao (2012) and Bernile, Lyandres, and Zhdanov (2012) for the case of mergers and acquisitions; and Chod and Lyandres (2011) for the case of initial public offerings.

constraints. Third, we show that financial constraints are instrumental also in the relation between innovation efficiency and optimal cash holdings, while in Ma, Mello, and Wu (2013), optimal cash holdings are increasing in R&D efficiency regardless of the degree of financial constraints.

Another related contemporaneous paper is the one by Morellec, Nikolov, and Zucchi (2013), who examine the effects of competition on optimal cash holdings. There are many important distinctions between our model and the one in Morellec, Nikolov, and Zucchi (2013). First, they abstract from strategic considerations by focusing on competitive rather than concentrated industries. Second, we focus on future expected competition among innovating firms, as opposed to current current competition in product markets. Finally, while our model focuses specifically on innovating firms (i.e. firms that engage in multi-stage innovation development and implementation activities), the model of Morellec, Nikolov, and Zucchi (2013) describes optimal cash management decisions of any firm that operates in a competitive environment.

In the second part of the paper we test our model's empirical predictions using data obtained from the NBER Patent Citations Data Project. We use this dataset to construct a sample of innovating firms, to identify industries in which firms innovate, and to define measures of the intensity of future expected competition in output markets and of innovation efficiency. We then examine empirical relations between firms' cash holdings on one hand and proxies for the costs of external funds, intensity of output market competition, and innovation efficiency on the other hand.

Our empirical results provide strong support for the model's predictions and, more generally, for the strategic role of cash for innovating firms. First, the intensity of expected product market competition is positively related to observed cash holdings of relatively financially constrained firms and it is negatively related to cash holdings of relatively unconstrained firms. Second, innovation efficiency is positively associated with cash holdings of relatively unconstrained firms, while it is negatively related to cash holdings of relatively constrained firms. Importantly, we obtain these results while controlling for known determinants of cash holdings identified in the literature (e.g., Opler, Pinkowitz, Stulz, and Williamson (1999)), and in particular for the degree of current (as opposed to future) competition, as in Morellec, Nikolov, and Zucchi (2013) and for the importance of winner's advantage, as in Ma, Mello, and Wu (2013). Overall, our empirical analysis shows that cash serves an important strategic role for firms that compete in innovation development and implementation.

The remainder of the paper is organized as follows. In the next section we present our model of strategic cash holdings in the context of competition in innovation. In Section 3 we discuss our data and empirical methods, and present the results of empirical tests of the model's predictions. Section 4 summarizes and concludes. Appendix 1 presents analytical proofs of the model's results. in Appendix 2 we present an alternative model, with somewhat different timing of events, and demonstrate that all the results are robust to the timing of the choice of R&D investments. Appendix 3 provides detailed definitions of the variables used in the empirical tests. Appendix 4 contains robustness tests of the main empirical results.

2 Model

2.1 Setup and assumptions

Assume that there are two firms in an industry, i and j.[8] Each firm can invest in research and development (R&D) of an innovative product. Each firm that succeeds in R&D is subject to an exogenous "project viability" shock. Following a positive realization of this shock, the firm can (but does not have to) invest in an implementation of its innovation using internal and possibly external resources. Given the uncertainties involved in innovation development and implementation, a firm that has implemented its innovation may either become a monopolist in the output market or it may compete in the output market with another firm that has successfully implemented its innovation. The game has two stages. In each stage, firms make decisions simultaneously and non–cooperatively.

2.1.1 First stage – R&D investment and of cash holdings choice

In the first stage of the game, firms choose two quantities. The first one is the level of investment in R&D, RD_i for firm i. Larger RD_i translates into higher likelihood of innovation success by firm i. The second choice variable is the amount of cash holdings, C_i for firm i, that is not used for R&D but that can be used to finance the implementation of innovation in the second stage. Cash holdings that are not used for R&D investment in the first stage earn a gross internal accumulation rate of r between the first and second stages. Thus, if a firm chooses to have cash holdings of C_i in the second (innovation implementation) stage, it needs to raise C_i/r in the first stage.

In terms of the timing of R&D investment and cash holdings decisions, we examine two versions of the model. In the first version, cash holdings to be used in the second stage of the game are chosen only by firms that succeeded in the development of their innovations. In the second version, cash holdings and investment in R&D are chosen simultaneously. The sequence of events in the

[8]The model is generalizable to the case of N firms and to endogenously determined industry structure. We focus on the two–firm case to simplify the discussion of the intuition behind the results.

first version of the model may be well suited for firms with established cash flows that make their payout decisions (and resulting cash holdings choices) as a function of their innovation successes and future needs of cash for innovation implementation. This version of the model is very tractable analytically and results in closed–form solutions and comparative statics of firms' optimal cash holdings.

The sequence of events in the second version of the model may be better suited to describe start–up firms that may only raise cash infrequently and may need to decide on the amount of cash to raise prior to being able to fully observe the outcomes of their innovation efforts. The setup of this version allows us to obtain closed–form solutions up to a system of first–order conditions, which we solve numerically. The advantage of the second version is that it allows us to examine the interaction between simultaneous R&D and cash holdings choices. We present analytical results of the first version of the model in this section and numerical results of the second version in Appendix B. Importantly, all the qualitative comparative statics and empirical predictions are consistent across the two versions of the model.

2.1.2 Second stage – implementation of innovation

In the beginning of the game's second stage, each firm that has succeeded in first–stage innovation observes realizations of three independent shocks. The first one is the "innovation viability" shock. In particular, we assume that an initial successful innovation becomes viable (i.e. can be implemented practically) with the likelihood of δ. In what follows, we refer to δ as the degree of innovation efficiency in an industry.[9]

The second shock relates to the required investment in the implementation of innovation. In particular, if firm i's innovation is viable, then it can be implemented by paying an investment cost of an exogenously determined size I_i. We assume that I_i is stochastic, has c.d.f. $F(I_i)$, is bounded between $\underline{I}$ and $\overline{I}$, and is independent across the two firms. To simplify the algebra, we assume that I_i is distributed uniformly in [0, 1].

Third, each firm realizes a shock to its ability to obtain external financing that may be required for implementation of its innovation. In particular, we assume that with probability α_i, firm i is shut out of capital markets and can only invest up to its cash holdings, C_i, in the implementation of its innovation. With probability $1-\alpha_i$, firm i can obtain unlimited external funds to supplement

[9] Innovation efficiency, δ, could be common to both firms or be firm-specific, δ_i for firm i. All of the model's comparative statics with respect to δ in the common-δ case are qualitatively similar to the comparative statics with respect to δ_i in the firm-specific-δ case. We elaborate on the reasons for this below. To simplify the algebra, we present the common-δ case here.

its cash holdings if necessary, i.e. it may choose to raise $I_i - C_i > 0$. To make the model analytically tractable, we assume that financing shocks are independent across firms.[10] In what follows, we refer to α_i as firm i's degree of financial constraints.[11]

After observing the investment and financing shocks, a firm with viable innovation decides whether to implement it. Firms that have obtained viable innovations and implemented them produce and realize product market profits. Given the uncertainties inherent in innovation development and implementation, the structure of the output market is not known ex–ante. In this case, the number of firms that have successfully implemented their innovations is either zero, or one, or two. If only one firm has implemented its innovation, it obtains monopolistic profit, $\pi_M > 0$. If both firms have implemented their innovations, each of them realizes duopolistic profit, $\pi_D(\gamma) > 0$, where γ is the degree of intensity of output market competition (i.e., product heterogeneity/substitutability). We do not need to assume a specific form of product market competition. The only assumptions that we make is that the duopolistic profit is lower than the monopolistic one, $\pi_D(\gamma) < \pi_M$, and that the duopolistic profit is decreasing in the intensity of output market competition, $\pi'_D(\gamma) < 0$.[12] Without loss of generality, we normalize the monopolistic profit to one: $\pi_M = 1$. In what follows, we use π_D instead of $\pi_D(\gamma)$ to simplify the notation.

To generate a meaningful cash holdings decision, we assume that the gross discount rate between the first and the second stage, R, is higher than the internal accumulation rate of cash between the two stages, $R < r$.[13] We also assume that firms' owners are risk–neutral and maximize their expected values in each stage of the game. The structure of the game is summarized in Figure 1.

2.2 Solution

We solve the model by backwards induction, starting from the second stage.

[10] Numerical analysis demonstrates that the independence assumption does not drive any of the qualitative results.

[11] An alternative way of modeling financial constraints is to assume that if the required investment, I_i exceeds firm i's cash holdings, C_i, the firm has to raise the difference externally and to pay proportional issuance cost $\alpha_i(I_i - C_i)$. All of the results hold under this alternative specification.

[12] These assumptions are consistent with any type of competition in heterogenous products. Imposing more structure on profits and micro-founding π_M and $\pi_D(\gamma)$ does not add anything to the intuition behind the results of the two–firm model. In the numerical illustrations of the model's comparative statics and in solutions of the alternative model in the Appendix, we impose more structure on the form of competition. None of the qualitative results depend on the assumed type of competition.

[13] This assumption may be justified by a carry cost of liquid assets (e.g., Opler, Pinkowitz, Stulz, and Williamson (1999), Morellec, Nikolov, and Zucchi (2013)).

2.2.1 Second stage – implementation of innovation

If firm i has access to external finance and is not limited by its cash holdings, it would invest to implement its innovation as long as the expected product market profit, $\mathbb{E}\pi_i$, exceeds the cost of investment, I_i. In other words, the unconstrained investment threshold of firm i is

$$I_{i,un} = \mathbb{E}\pi_i = \omega_j \pi_D + (1 - \omega_j)\pi_M, \tag{1}$$

where ω_j is the likelihood that firm i's competitor (firm j) implements its innovation. If firm i does not have access to external finance, then it would invest in innovation as long as the required investment is lower than the lowest of the cash on hands and expected output market profit. Thus, the constrained investment threshold is

$$I_{i,co} = \min[\mathbb{E}\pi_i, C_i]. \tag{2}$$

In equilibrium, firms would never choose cash holdings that exceed their expected output market profits. The reason is that if C_i were higher than $\mathbb{E}\pi_i$, some cash (i.e. $C_i - \mathbb{E}\pi_i > 0$) would never be used for implementation of innovation, resulting in a reduction in firm value equal to $\frac{(C_i - \mathbb{E}\pi_i)(R-r)}{R}$. Hence, in equilibrium we have $I_{i,co} = C_i$.

The probability that firm j implements its innovation, ω_j, is

$$\omega_j = \delta\left[(1-\alpha_j)F(I_{j,un}) + \alpha_j F(C_j)\right] = \delta[(1-\alpha_j)I_{j,un} + \alpha_j C_j], \tag{3}$$

where $F(I_{j,un}) = I_{j,un}$ and $F(C_j) = C_j$ are the probabilities of firm j implementing its first–stage innovation conditional on it being viable (i.e., the probabilities that the realization of the investment shock is lower than the unconstrained investment threshold or than cash holdings, in the unconstrained and constrained cases respectively). Firm j's likelihood of innovation implementation is affected by several variables: (i) the probability of firm j's innovation being viable (δ); (ii) the likelihood of firm j being shut out of the external finance market (α_j); (iii) its unconstrained innovation threshold, $I_{j,un}$, which depends on its expected product market profit; (iv) cash available to firm j when external funds are unavailable (C_j).

We can derive firms i and j's equilibrium unconstrained investment thresholds solving a system of two equations in two unknowns. The system obtains by plugging ω_j in Equation (3) into Equation (1) and a symmetric expression for ω_i into a similar equation for firm j's unconstrained investment implementation threshold. The solution of this system of equations delivers the following optimal unconstrained implementation threshold for firm i conditional on both firms' cash holdings:

$$I_{i,un}^{*} = \frac{1-\delta(1-\alpha_j)(1-\pi_D) + C_i\delta^2\alpha_i(1-\alpha_j)(1-\pi_D)^2 - C_j\delta\alpha_j(1-\pi_D)}{1-\delta^2(1-\alpha_i)(1-\alpha_j)(1-\pi_D)^2}, \tag{4}$$

and a similar threshold for firm j.

The investment implementation threshold in Equation (4) allows us to study the roles that a firm's own and its rival's cash holdings have on the likelihood of implementing a firm's innovation in the unconstrained case. Lemma 1 summarizes the implications of Equation (4).

Lemma 1 *Firm i's equilibrium unconstrained implementation threshold, $I_{i,un}^{*}$, is increasing in its own cash holdings, C_i, and is decreasing in its rival's cash holdings, C_j.*

The negative relation between a firm's innovation implementation threshold and its competitor's cash holdings is the first manifestation of the *strategic effect of cash*. The reason for this negative relation is that firm j's cash holdings increase the likelihood that it would implement its innovation in the constrained state, which raises the overall unconditional likelihood that firm j would implement its innovation and reduces firm i's expected product market profit as a result.

The strategic effect of firm j's cash is stronger the higher the degree of innovation efficiency, δ, the higher the degree of firm j's financial constraints, α_j, and the lower the duopoly profit, π_D (i.e. the larger the product substitutability across the two firms). The intuition is as follows. Rival's cash has a larger negative effect on a firm's expected profit when the likelihood of innovation being viable is high (since cash holdings are only useful when innovation is viable), when the rival is financially constrained (since cash is only important when a firm is shut out of external capital markets), and when the difference between monopolistic and duopolistic profits is large (since strategic considerations are only important when firms' actions have a material impact on their rivals' values).

The positive effect of a firm own's cash holdings on its unconstrained implementation threshold is indirect. Firm i's cash holdings have a negative impact on firm j's expected likelihood of implementing its innovation, leading to higher firm i's expected product market profit and a higher innovation implementation threshold in the unconstrained state.

2.2.2 First stage – cash holdings choice

Following successful first–stage innovation, firm i maximizes its value, V_i, with respect to cash that it raises at the end of the first stage:

$$
\begin{aligned}
\max_{C_i} V_i &= -C_i/r + \frac{1}{R}\left[C_i + \delta\left(\alpha_i \int_{\underline{I}}^{C_i} f(I_i)\left(\mathbb{E}_i(\pi) - I_i\right) dI_i + (1-\alpha_i)\int_{\underline{I}}^{I^*_{i,un}} f(I_i)\left(\mathbb{E}_i(\pi) - I_i\right) dI_i\right)\right] \\
&= -C_i/r + \frac{1}{R}\left[C_i + \delta\left(\alpha_i C_i\left(I^*_{i,un} - C_i/2\right) + \frac{1}{2}(1-\alpha_i)(I^*_{i,un})^2\right)\right]. \qquad (5)
\end{aligned}
$$

Following successful innovation, firm i raises C_i/r, which is carried over as C_i to the second stage. The firm's innovation is viable with probability δ, which pre-multiplies the expression for expected product market profit net of implementation cost. If the firm is shut out of the external capital markets (which happens with probability α_i), under the uniform distribution assumption, its likelihood of implementing innovation conditional on it being viable equals C_i, and the expected product market profit conditional on implementing the innovation is $(I^*_{i,un} - C_i/2)$. Similarly, if the firm has access to external funds, its likelihood of implementing innovation conditional on viability is $I^*_{i,un}$ and its expected profit conditional on implementing the innovation is $I^*_{i,un}/2$.

Differentiating firm i's value function in Equation (5) with respect to C_i delivers firm i's optimal cash holdings reaction function to firm j's cash holdings:

$$
C_i^*(C_j) = \frac{r + r\alpha_i\delta - R\left(1 - (1-\alpha_i)\Phi_i\right) - r\Phi_i - r\alpha_i(1-\alpha_j)\delta^2(1-\pi_D)\pi_D}{r\alpha_i\delta(1-\Phi_i)} - \frac{C_j\alpha_j\delta(1-\pi_D)}{1-\Phi_i}, \quad (6)
$$

where $\Phi_i = (1-\alpha_j)\,\delta^2\,(1-\pi_D)^2$. Differentiating Equation (6) with respect to firm j's cash holdings leads to the second manifestation of the strategic effect of cash:

Lemma 2 *Firm i's reaction function in cash holdings, $C_i^*(C_j)$, is downward sloping, $C_i^{*'}(C_j) < 0$.*

The reason for the negative effect of firm's rival's cash holdings on the firm's optimal cash holdings is intuitive. The higher the rival's cash holdings, the higher the likelihood that the rival would implement its innovation in the constrained state, in which the rival's access to external capital is restricted. Higher implementation probability in the constrained state leads to higher rival's overall unconditional implementation likelihood, and to lower firm's expected product market profit, leading to lower marginal benefit of holding cash and lower resulting optimal cash holdings. Using the two firms' optimal cash holdings reaction functions, we can derive the following expressions for the equilibrium choices of cash holdings and the unconstrained equilibrium implementation threshold:

$$
\begin{aligned}
C_i^{EQ} &= \frac{(r-R)(1-\delta(1-\alpha_i)\pi_D) + \delta\left(r - R(1-\alpha_i)\right)}{r\delta\alpha_i\left(1+\delta\left(1-\pi_D\right)\right)}, \qquad (7)\\
I_{i,un}^{EQ} &= \frac{R(1-\pi_D) + r\pi_D}{r\left(1+\delta\left(1-\pi_D\right)\right)}. \qquad (8)
\end{aligned}
$$

Similar expressions hold for firm j.

Two remarks are in order regarding the expressions in Equations (7) and (8). First, the equilibrium unconstrained implementation threshold is always higher than equilibrium cash holdings: $(I_{i,un}^{EQ} - C_i^{EQ} = \frac{R-r}{\delta r \alpha_i} > 0)$. The reason is that at $C_i^{EQ} = I_{i,un}^{EQ}$ the marginal benefit of increasing C_i by one unit equals the marginal benefit of increasing $I_{i,un}$ by one unit, while the marginal cost of holding cash is higher, since the internal accumulation rate, r, is lower than the inter-period discount rate, R. Given that the marginal benefit of cash is decreasing in the level of cash, it has to be that in equilibrium $C_i^{EQ} < I_{i,un}^{EQ}$.

Second, we need to impose a restriction on the relation between the discount rate, R, and the internal accumulation rate, r, that ensures positive cash holdings in equilibrium:

$$R < r\left(1 + \frac{\delta\alpha_i}{1 + \delta(1-\alpha_i)\,(1-\pi_D)}\right). \tag{9}$$

The intuition for this restriction is that if R is substantially higher than r then the marginal cost of holding even the first unit of cash outweighs its marginal benefit. The largest admissible wedge between the discount rate and the internal accumulation rate is increasing in innovation efficiency, δ (the marginal benefit of cash is increasing in the likelihood of an innovation being viable), and in the likelihood of being financially constrained, α_i (the marginal benefit of cash is increasing in the likelihood of a firm being shut out of external capital markets).

Another way to write the condition in Equation (9) is in terms of a restriction on the degree of financial constraints:

$$\alpha_i > 1 - \frac{r(1+\delta) - R}{\delta(1-(R-r)\pi_D)}. \tag{10}$$

The intuition is that for given discount rate, R, and internal accumulation rate, r, we need a high enough probability of a negative financing shock in order for the benefit of holding cash to outweigh its cost. In what follows, since we are interested in the determinants of innovating firms' (positive) cash holdings, we assume that conditions Equation (9) and/or Equation (10) are satisfied.

The equilibrium value of firm i conditional on successful innovation is

$$V_i^{EQ} = \frac{\frac{(R-r)^2(1-\alpha_i)}{\alpha_i} + \frac{(r(1+\delta)-R)^2}{(1+\delta(1-\pi_D))^2}}{2\delta r^2 R}. \tag{11}$$

We derive Equation (11) by incorporating Equations (7) and (8) in the value function in Equation (5). A similar expression obtains for firm j.

In the next section, we analyze the effects of financing constraints, α_i, intensity of output market competition, γ, and innovation efficiency, δ, on firms' equilibrium choices of cash holdings.

Since changes in α_i, γ, and δ affect firm value even when cash holdings are held constant, in what follows we normalize a firm's equilibrium cash holdings in Equation (7) by the sum of its equilibrium value pre-cash, V_i^{EQ}, and its equilibrium cash holdings, C_i^{EQ}/r:

$$\widetilde{C}_i^{EQ} = \frac{C_i^{EQ}/r}{V_i^{EQ} + C_i^{EQ}/r}. \tag{12}$$

Because of symmetry, we only present the comparative statics of firm i's normalized equilibrium cash holdings.[14]

2.3 Comparative statics

To examine the relation between firms' cash holdings and financial constraints, in Proposition 1 we study how firm i's equilibrium cash-to-value ratio is affected by its likelihood of being shut out of the financial markets, α_i.

Proposition 1 *Firm i's equilibrium cash-to-value ratio,* $\widetilde{C}_i^{EQ}$*, is increasing in the likelihood of the firm not having access to external finance,* α_i*.*

The positive relation between equilibrium cash holdings and financial constraints is quite intuitive and is a consistent with the precautionary motive for holding cash. The more likely it is that a firm would not have access to external finance in the implementation stage, the more likely the firm is to inefficiently reject a positive NPV project when it is financially constrained. In other words, the marginal benefit of holding cash increases in the degree of financial constraints. Thus, the optimal level of cash, C_i^{EQ}, is increasing in α_i. V_i^{EQ}, on the other hand, is decreasing in α_i, as more severe financial constraints reduce the likelihood of implementing the firm's innovation. As a result, the cash-to-value ratio is increasing in the degree of financial constraints.

The next proposition illustrates the relation between the intensity of output market competition, γ, and optimal cash holdings.

Proposition 2 *Firm i's equilibrium cash-to-value ratio,* $\widetilde{C}_i^{EQ}$*, is decreasing in the intensity of output market competition,* γ*, for* $\alpha_i < \overline{\alpha}$*, and it is increasing in* γ *for* $\alpha_i > \overline{\alpha}$*, where* $\overline{\alpha} = 1 - \frac{(r-R+r\delta)^2}{\delta^2(R+r\pi_D-R\pi_D)^2}$.

[14] Since $\frac{C_i^{EQ}/r}{V_i^{EQ}+C_i^{EQ}/r} = \frac{C_i^{EQ}/r}{V_i^{EQ}} \Big/ \left(1+\frac{C_i^{EQ}/r}{V_i^{EQ}}\right)$, $\frac{C_i^{EQ}/r}{V_i^{EQ}+C_i^{EQ}/r}$ is monotonically increasing in $\frac{C_i^{EQ}/r}{V_i^{EQ}}$. Thus, all the qualitative results hold for a definition of cash-to-value ratio in which value excludes cash, $\widetilde{C}_i^{EQ} = \frac{C_i^{EQ}/r}{V_i^{EQ}}$.

Abstracting from the two manifestations of the strategic effect of cash holdings, discussed in Lemma 1 and Lemma 2, it follows from Equation (5) that the marginal benefit of holding cash is $\delta\alpha_i\left(\mathbb{E}\pi_i - C_i\right)/R$. An increase in γ leads to a reduction in π_D, and as a consequence, in the expected profit, $\mathbb{E}\pi_i$. Since the marginal cost of holding cash is independent of γ, optimal cash holdings are decreasing in γ, reaching zero when the marginal cost of holding cash equals the marginal benefit of holding cash (i.e., when $\mathbb{E}\pi_i = \frac{R-r}{\delta\alpha_i}$). Abstracting from the strategic effect of cash holdings, the negative elasticity of equilibrium cash holdings with respect to γ is larger in absolute terms than the negative elasticity of firm value with respect to γ. Thus, in the absence of the strategic effect of cash, the relation between the intensity of output market competition, γ, and equilibrium cash-to-value ratio, $\widetilde{C}_i^{EQ}$ would be negative.

However, in the presence of a sufficiently strong strategic effect of cash, this relation reverses. As follows from Equation (4), the strength of the strategic effect is proportional to the degree of financial constraints and to the difference between the output market profits in the monopolistic and duopolistic scenarios. The reason is that cash can only deter a rival's investment in innovation implementation if cash is useful (i.e., in situations in which access to external capital is restricted) and if the implementation of a firm's innovation has a material impact on the rival's expected profit. Thus, the higher the α_i, the less steep the negative relation between the intensity of product market competition and equilibrium cash holdings. For substantially high α_i the relation between γ and $\widetilde{C}_i^{EQ}$ changes sign and becomes positive.

We illustrate the relation between the intensity of competition, γ, and firm's equilibrium cash-to-value ratio in Figure 2. For purposes of graphical illustration, we assume a specific form of product market competition.[15] In particular, we assume Bertrand competition in heterogenous goods with substitutability parameter γ, linear demand for the firms' products, $D(\eta_i, \eta_j) = a - b\eta_i + c\eta_j$, where η_i and η_j are firm i's and its rival's output market prices, and zero marginal costs. In a standard model of a representative consumer with quadratic utility $U(q_i, q_j) = \mu \sum_{i=1}^{k} q_i - \frac{1}{2}\left(\sum_{i=1}^{k} q_i^2 + 2\gamma \sum_{j \neq i} q_i q_j\right)$, where q_i and q_j are quantities consumed of products produced by firms i and j, the resulting coefficients of the demand function are $a = \frac{\mu}{1+\gamma}$, $b = \frac{1}{(1+\gamma)(1-\gamma)}$, and $c = \frac{\gamma}{(1+\gamma)(1-\gamma)}$ (e.g., Vives(2000)). The resulting duopoly profit can be expressed as a fraction of the monopoly profit:

$$\pi_D = \pi_M \frac{8(2-\gamma^2)}{(4+\gamma-\gamma^2)^2}. \tag{13}$$

[15] The intensity of output market competition affects the duopoly profit, π_D. The nature and type of product market competition, as well as the functional form of the relation between γ and π_D have no impact on the signs of derivatives and the resulting comparative statics as long as π_D is decreasing in γ.

The other parameters are as follows: $r = 1.03$, $R = 1.10$, $\alpha_j = 0.4$, $\delta = 0.6$. We vary the competition intensity parameter, γ, between 0 and 0.9, and examine two separate scenarios. In the first one, depicted in Panel A of Figure 2, firm i is relatively financially unconstrained, $\alpha_i = 0.15$. In the second scenario, depicted in Panel B of Figure 2, firm i is relatively financially constrained, $\alpha_i = 0.8$.

In both Panels A and B, the solid line represents equilibrium cash holdings, C_i^{EQ}/r, the dashed line represents equilibrium firm value, V_i^{EQ}, and the dashed-dotted line represents equilibrium cash-to-value ratio, $\widetilde{C}_i^{EQ}$. Not surprisingly, equilibrium firm value is decreasing in the intensity of output market competition, as more intense competition is associated with lower expected output market profit. In addition, abstracting from the strategic effect of cash, the marginal benefit of holding cash is decreasing in expected output market profit, leading to a negative relation between equilibrium cash holdings and the intensity of competition.

Importantly, the cash-to-value ratio is decreasing in γ in the low financial constraints case, depicted in Panel A, and it is increasing in γ in the high financial constraints case, illustrated in Panel B. The reason is that the strategic effect of cash is increasing in the degree of financial constraints and in the difference between the monopolistic and duopolistic profits, i.e. in γ. This strategic effect of cash is relatively unimportant when financial constraints are low, and it is relatively important in the high financial constraints case. In fact, when financial constraints are severe enough, as in Panel B, the strategic role of cash is sufficiently important and it reverses the negative relation between equilibrium cash-to-value ratio and the intensity of product market competition.

Next, we examine the relation between innovation efficiency, δ, and firms' cash holdings:

Proposition 3 *Firm i's equilibrium cash-to-value ratio, $\widetilde{C}_i^{EQ}$, is increasing in innovation efficiency, δ, for $\alpha_i < \overline{\alpha}$, and it is decreasing in δ for $\alpha_i > \overline{\alpha}$, where $\overline{\alpha} = 1 - \frac{(r-R+r\delta)^2}{\delta^2(R+r\pi_D-R\pi_D)^2}$.*

The intuition for the result in Proposition 3 is as follows. Keeping cash holdings and the unconstrained implementation threshold constant, firm value in Equation (5) is linear in innovation efficiency. The marginal benefit of cash holdings, $\delta\alpha_i(I_{i,un}^* - C_i)/R$, is linearly increasing in δ and in α_i, and it is decreasing in C_i. The marginal cost of cash holdings, $\frac{(R-r)}{R}$ is independent of C_i, α_i, and δ. Thus, the relation between optimal cash holdings, C_i^{EQ}/r, and innovation efficiency, δ, is increasing and concave. For relatively low α_i, optimal cash holdings are low, and they are more sensitive to changes in δ than firm value is. For relatively high α_i, optimal cash holdings are high, and they are less sensitive to changes in δ than firm value is. This leads to a positive relation between $\widetilde{C}_i^{EQ}$ and δ for relatively low α_i and to a negative relation for relatively high α_i.

Importantly, our assumption that δ is common to the two firms, as opposed to being firm-specific, δ_i for firm i, does not drive the result in Proposition 3. The reason is that if δ is common to both firms, a change in δ has a direct effect that is identical to the one of a change in δ_i in the firm-specific-δ case, and an indirect effect (due to the change in competitor's δ). The magnitude of the indirect effect is always smaller than that of the direct effect, leading to similar directional predictions across the two cases.

The relation between equilibrium cash-to-value ratio and innovation efficiency is presented in Figure 3. Panel A in Figure 3 presents the case of low financial constraints, $\alpha_i = 0.15$, while Panel B depicts the relatively constrained case, $\alpha_i = 0.8$. The other parameters are the same as in Figure 2, with the exception of γ, which we assume to equal 0.5, resulting in $\pi_D(\gamma) = 0.775$. In Figure 3, we vary δ between 0.6 and 1.

Similar to Figure 2, the solid line represents equilibrium cash holdings, C_i^*/r, the dashed line represents equilibrium firm value, V_i^*, and the dashed–dotted line represents equilibrium cash-to-value ratio, $\widetilde{C}_i^{EQ}$. Both equilibrium cash holdings and firm value are increasing in innovation efficiency, δ. Higher δ leads to higher likelihood of viable innovation, raising firm value. In addition, it increases the marginal benefit of holding cash, since the likelihood of having to use cash for innovation implementation increases as well. However, the sign of the relation between cash-to-value ratio and innovation efficiency depends on the degree of financial constraints. When financial constrains are low (Panel A), equilibrium cash holdings are low and they are very sensitive to innovation efficiency, more so than firm value is, resulting in a positive relation between cash-to-value ratio and innovation efficiency for relatively constrained firms. When financial constraints are high (Panel B), optimal cash holdings are high and they are less sensitive to changes in innovation efficiency. The result is a negative relation between cash-to-value ratio and innovation efficiency for constrained firms.

Next, we summarize the empirical predictions following from Propositions 1–3.

2.4 Summary of empirical predictions

The comparative statics discussed in the previous subsection concern the effects of financing costs, intensity of output market competition (i.e. product substitutability), and innovation efficiency on firms' equilibrium choices of cash holdings. In what follows, "cash holdings" refer to equilibrium normalized cash holdings in the model. Since the model is too stylized to be calibrated, we do not have a threshold in the data that corresponds to $\overline{\alpha} = 1 - \frac{(r-R+r\delta)^2}{\delta^2(R+r\pi_D-R\pi_D)^2}$ in Propositions 2 and 3. Thus, the empirical predictions concern the relative magnitudes of the effects of the intensity of output market competition and of the degree of innovation efficiency on optimal cash holdings of constrained and unconstrained firms.

Prediction 1. Firms' cash holdings are expected to be increasing in the degree of financial constraints.

Prediction 2. The relation between the intensity of output market competition and cash holdings is expected to be less positive (more negative) for firms facing relatively low costs of external financing than for firms facing relatively high external financing costs.

Prediction 3. The relation between innovation efficiency and cash holdings is expected to be more positive (less negative) for firms facing relatively low costs of external financing than for firms facing relatively high external financing costs.

In the next section, we test these predictions empirically employing data on patent grants and citations, which we use in order to identify a sample of innovative firms and to develop proxies for the intensity of output market competition and for innovation efficiency.

3 Empirical tests

3.1 Data, empirical specification, variables, and summary statistics

In this section, we describe the data sources, the empirical specifications that we adopt to test the model's predictions, and the summary statistics.

3.1.1 Data sources

We employ two data sources in our empirical tests. The first one is the NBER Patent Citations Data Project,[16] which we use to construct a sample of innovating firms, to identify industries in which firms innovate, and to develop measures of expected product market competition (PMC) intensity and of innovation efficiency. The second one is the CRSP/Compustat Merged Database, which provides information on various accounting variables that we employ in our analysis.

The NBER Patent Data Project contains data on all utility patents granted by the U.S. Patent and Trademark Office between 1976 and 2006. For each patent, the dataset contains an assigned GVKEY, which we use to match patent data to Compustat, the date when the patent was granted, the patent's technology field – defined according to one of the 36 two–digit technological

[16] https://sites.google.com/site/patentdataproject/Home

subcategories developed by Hall, Jaffe, and Trajtenberg (2001) – and the number of times a patent has been cited. Naturally, our analysis includes only firms that were awarded at least one utility patent. Restrictions on Compustat data availability result in a final sample of $33,097$ firm-years with patent grants.

3.1.2 Empirical specification

The empirical predictions summarized at the end of the previous section concern determinants of firms' cash holdings, in particular the degree of financial constraints that a firm faces, and industry-level expected product market competition (PMC) intensity and innovation efficiency. Our empirical specifications relate proxies for these factors to cash holdings, while incorporating the fact that the magnitudes and signs of the relations between cash holdings and some of their determinants may crucially depend on the severity of a firm's financing constraints.

Our basic empirical specification takes the following form:

$$Cash_{i,t} = \beta_0 + \beta_1 \mathbf{X_{i,t}} + \phi D_t + \varepsilon_{i,t}, \tag{14}$$

The dependent variable, $Cash_{i,t}$, is a measure of cash holdings; $\mathbf{X_{i,t}}$ is a vector of explanatory variables similar to those used in past empirical studies of the determinants of cash holdings (e.g., Opler, Pinkowitz, Stulz, and Williamson (1999), Han and Qiu (2007), Bates, Kahle, and Stulz (2009), Morellec, Nikolov, and Zucchi (2013), and Ma, Mello, and Wu (2013)); D_t is a vector of year dummies, and $\varepsilon_{i,t}$ is an i.i.d. normally distributed error term.

Importantly, in the empirical specification in Equation (14), following the large cash holdings literature (e.g., Opler, Pinkowitz, Stulz, and Williamson (1999), Han and Qiu (2007), and Bates, Kahle, and Stulz (2009) among many others), cash holdings are defined as the ratio of cash and marketable securities (Compustat item `CHE`) and book value of assets (item `AT`). In the model, however, we normalize cash holdings by the firm's market value. In order to ensure that this disconnect between the theoretical definition of cash holdings and its accepted empirical counterpart is not responsible for our empirical results, we repeat all the tests while using the ratio of cash to the sum of market value of equity and book value of debt as the dependent variable and find results similar to those obtained using the main specification. These results are reported and discussed in Appendix D. We provide a precise description of independent variables below.

The model's specific empirical predictions are cross-sectional in nature. Thus, the regression in (14) is estimated using year fixed effects. While estimating Equation (14), we cluster standard errors at the industry level because innovation efficiency and intensity of competition are industry-wide regressors (e.g., Cameron and Miller (2014)).

3.1.3 Measures of financial constraints, innovation efficiency, and intensity of competition

Measures of financial constraints

A firm's cost of external financing is generally unobservable, forcing us to rely on proxy variables. One of the most important determinants of the cost of external funds relative to that of internally-generated funds is the degree of information asymmetry between a firm and the capital market (e.g. Leland and Pyle (1977) and Myers and Majluf (1984)). The cost of external funds relative to that of internal ones is expected to increase monotonically in the extent of information asymmetry. To measure the severity of a firm's financial constraints, we rely on three different proxies for the degree of information asymmetry.

The investment-cash flow sensitivity literature (e.g., Gilchrist and Himmelberg (1995) and Erickson and Whited (2000)) and the cash holdings literature (e.g., Han and Qiu (2007)) suggest that firm size is inversely related to the extent of information asymmetry. In addition, older, more established firms are likely to be characterized by a lower degree of information asymmetry and lower costs of external financing than younger firms. For these reasons, we use the size–age index (SA Index) proposed by Hadlock and Pierce (2010) as our first measure of firm-level financing constraints.[17]

Whited and Wu (2006) use a structural model of financing and investment to derive an index of firms' financing constraints via GMM estimation of an investment Euler equation. We use WW index which is based on a linear combination of cash flow, sales growth, long-term debt, size, dividend policy, and a firm's three-digit industry sales growth as our second measure of firm-level financing constraints.[18]

Finally, following Fazzari, Hubbard, and Petersen (1988), Cleary (1999), and Han and Qiu (2007) among others, our third proxy for the cost of external financing is an indicator variable that equals one if the firm paid dividends (item `DV`> 0) or repurchased shares (item `PRSTKL`> 0) in a given year and equals zero otherwise.[19]

[17] Hadlock and Pierce (2010) index is computed as $SA_{i,t} = -0.737 * SIZE_{i,t} + 0.043 * SIZE^2_{i,t} - 0.04 * AGE_{i,t}$, where $SIZE_{i,t}$ is the log of the book value of assets adjusted for inflation using the GDP deflator and $AGE_{i,t}$ is the difference between year t and the first year firm i has appeared in Compustat, capped at 37.

[18] $WW_{i,t} = -0.091 * CF_{i,t} - 0.062 * DIVPOS_{i,t} + 0.021 * TLTD_{i,t} - 0.044 * LNTA_{i,t} + 0.102 * ISG_{i,t} - 0.035 * SG_{i,t}$, where CF is the ratio of cash flows (item `IB` plus item `DP`) to total assets (item `AT`), $DIVPOS$ is an indicator that takes the value of one if a firm pays cash dividends (item `DVC` plus item `DVP`), $TLTD$ is the ratio of the long term debt (item `DLTT`) to total assets (item `AT`), $LNTA$ is the log of the book value of assets adjusted for inflation using the GDP deflator , ISG is the firm's 3-digit industry sales growth, SG is firm sales growth, both derived from item `SALE`.

[19] Another popular measure of financial constraints used in past literature is the availability of debt ratings (e.g.,

Measures of innovation efficiency

Following Hall, Jaffe, and Trajtenberg (2005), Schroth and Szalay (2010), Hirshleifer, Hsu, and Li (2013), and Bena and Li (2014) among others, our first measure of innovation efficiency is based on the number of citations that patents generate per dollar of R&D spending. In particular, for each firm-year, we compute the number of citations to firm's patents granted in that year and divide this measure by a measure of the firm's expenditures on R&D required to generate these patents. We use the number of citations to patents as a measure of R&D outcome, since Hall, Jaffe, and Trajtenberg (2005) find that it is important to account for the "quality of innovation", measured by the number of citations per patent, as well as for the "quantity of innovation", measured by the number of patents per million dollars of R&D expenditure.

We measure the number of citations to each patent following Bena and Li (2014). First, we consider only patents granted in year t that have an application year that precedes the granting year by at most three years (variable *Pat*). Then for each patent, we evaluate the total number of citations that a patent receives within three years from the granting year (variable *Cit*). To measure the firm's expenditures on R&D we follow Hirshleifer, Hsu, and Li (2013) and build a measure of firm-level capital stock in year t (*R&D Stock*) by summing the depreciated capital expenditures from year $t-4$ to year t. Following Hall, Jaffe, and Trajtenberg (2005), we set the rate of depreciation to 15%. If the value for capital expenditures is missing, we set it to zero.[20] Our first measure of firm i's innovation efficiency in year t, is, thus, estimated as

$$\delta_{i,t}^{CIT} = \log\left(1 + \frac{\sum_{j\in(i,t)} Cit_{j,i,t}}{R\&Dstock_{i,t-3}}\right), \tag{15}$$

where $Cit_{j,i,t}$ is the number of citations generated by patent j filed by firm i in year t, and $R\&Dstock_{i,t-3}$ is firm i's estimated R&D stock in year $t-3$.

Given that some of the firms in our sample are awarded patents that do not receive any citations within a three year window, we also adopt a second measure of R&D efficiency using the number of patents granted to firm i in year t

$$\delta_{i,t}^{PAT} = \log\left(1 + \frac{Pat_{i,t}}{R\&Dstock_{i,t-3}}\right), \tag{16}$$

Gilchrist and Himmelberg (1995)). We do not use this measure in our tests, as debt of our sample firms is seldom rated.

[20] We get almost identical results if we (1) evaluate the firm-level R&D capital stock using a perpetual inventory method approach as suggested by Hall, Jaffe, and Trajtenberg (2005); (2) use the value of R&D expenditure in a given year; (3) sum the past five years values of R&D expenditure, while setting the depreciation rate to 20% as in Hirshleifer, Hsu, and Li (2013); (4) sum the past five years values of R&D expenditure, while setting the depreciation rate to zero.

where $Pat_{i,t}$ is the total number of patents awarded to firm i in year t.

Finally, we compute an industry-wide aggregate measure of innovation efficiency by averaging $\delta^{CIT}_{i,t}$ and $\delta^{PAT}_{i,t}$ within two-digit SIC industries:

$$\delta^{CIT}_{n,t} = \sum_{i \in n} \frac{\delta^{CIT}_{i,t}}{N}, \tag{17}$$

$$\delta^{PAT}_{n,t} = \sum_{i \in n} \frac{\delta^{PAT}_{i,t}}{N}, \tag{18}$$

where N is the number of firms in two-digit SIC industry n. These two industry-wide measures of innovation efficiency are assigned to all firms in the industry. To simplify notation, in what follows, we use δ^{CIT} and δ^{PAT} instead of $\delta^{CIT}_{n,t}$ and $\delta^{PAT}_{n,t}$ respectively.

Measures of product market competition intensity

Our measures of firm-level intensity of expected output market competition is based on the idea that competition is increasing in product substitutability (e.g., Syverson (2004) and Goettler and Gordon (2014)). Since our focus is on firms' innovation activities, we are interested in the substitutability of future products that would result from current innovation. This substitutability of future products is likely to be positively related to how close firms' R&D activities are. For example, products of two firms that develop all of their patents in the same set of patent classes are likely to be more substitutable than products of two firms that have little overlap in patent classes. Thus, we depart from accepted measures of *current* product market competition, such as those used in Morellec, Nikolov, and Zucchi (2013) and focus on measures of *future* expected product market competition, based on firms' current innovation activities.

To measure how close a firm's R&D activity is to the one of its competitors, we follow Bena and Li (2014) and adopt a firm-level measure of technological overlap based on Jaffe (1986). For each firm i in year t, we capture the scope of innovation in a vector $S_{i,t} = [S_{i,t,1}, ..., S_{i,t,k}, ...S_{i,t,K}]$, where $k = 1, ..., K = 36$ is the number of two–digit technological subcategories. $S_{i,t,k}$ is the ratio of the number of awarded patents in class k in year t over the total number of patents awarded in year t. Then we calculate the quantity $\delta^{PAT}_{i,j,t}$, defined as the pairwise technological proximity of firm i with all the firms $j \neq i$ that belong to the same industry – defined using two-digits SIC codes – in year t:

$$\gamma^{PAT}_{i,j,t} = \frac{S_{i,t} S'_{j,t}}{\sqrt{S_{i,t} S'_{i,t}} \sqrt{S_{j,t} S'_{j,t}}} \in [0, 1].$$

If $\gamma_{i,j,t}^{PAT}$ equals 1, then there is perfect technological overlap between firm i and firm j. On the other hand, if $\gamma_{i,j,t}^{PAT}$ equals 0, then there is no technological overlap between the two firms. Our first measure of the intensity of product market competition is based on firm-level technological overlap, and is given for firm i in year t by the average value of $\gamma_{i,j,t}^{PAT}$:

$$\gamma_{i,t}^{PAT} = \frac{\sum_{j \neq i}^{N} \gamma_{i,j,t}^{PAT}}{N-1},$$

where N is the total number of firms in firm i's industry in year t.

We also adopt an additional measure of PMC intensity, based on a firm-level measure of citations similarity. For each firm i in year t, we construct a vector $C_{i,t} = [C_{i,t,1}, ..., C_{i,t,k}, ...C_{i,t,K}]$, where $k = 1, ..., K = 36$ is the number of the two–digit technological subcategories. $C_{i,t,k}$ is the ratio of the number of citations to patents awarded in class k in year t over the total number of citations to patents awarded in year t. Then we calculate the quantity $\gamma_{i,j,t}^{CIT}$, defined as the pairwise similarity of firm i with each firm $j \neq i$ that belong to the same industry – defined using two-digit SIC codes – in year t:

$$\gamma_{i,j,t}^{CIT} = \sum_{k=1}^{K} \min[C_{i,t,k}, C_{j,t,k}] \in [0, 1].$$

If $\gamma_{i,j,t}^{CIT}$ equals 1, then firm i and firm j have the exact same proportions of citations across the 36 two-digit technological subcategories. On the other hand, if $\gamma_{i,j,t}^{CIT}$ equals 0, then the two firms do not share any citations in two-digit technological subcategory. Our second measure of the intensity of future expected PMC is based on citation similarity, and is given for firm i in year t by the average value of $\gamma_{i,j,t}^{CIT}$:

$$\gamma_{i,t}^{CIT} = \frac{\sum_{j \neq i}^{N} \gamma_{i,j,t}^{CIT}}{N-1},$$

Finally, we compute industry-wide measures of expected product market competition intensity, which for industry n equals

$$\gamma_{n,t}^{CIT} \equiv \gamma_{CIT} = \sum_{i \in n} \frac{\delta_{i,t}^{CIT}}{N}, \tag{19}$$

$$\gamma_{n,t}^{PAT} \equiv \gamma_{PAT} = \sum_{i \in n} \frac{\delta_{i,t}^{PAT}}{N}. \tag{20}$$

3.1.4 Control variables in cash holdings regressions

The literature on the determinants of cash holdings has identified a set of key variables that help explain a firm's cash hoarding behavior. We follow Bates, Kahle, and Stulz (2009) and include in our cash holdings analysis the following variables: Industry-level cash flow volatility, which may increase the precautionary savings motive; Market-to-book ratio to control for future investment opportunities; Size because there are economies of scale to raising cash; Cash flows, since firms with higher cash flows are likely to require lower precautionary cash holdings; Net working capital, since it can be considered a substitute for cash; Capital expenditures plus acquisitions, since these investments create assets that can be used as collateral, reducing the need for precautionary cash; Leverage, both because firms may use cash to reduce leverage and because cash can serve as a hedge for highly levered firms; R&D expenditures because firms with low tangibility have a larger precautionary savings motive. In addition, we follow recent studies of Ma, Mello, and Wu (2013) and Morellec, Nikolov, and Zucchi (2013) and include the following two industry-level variables: Herfindahl index that proxies for current (as opposed to future) competition and market share skewness that proxies for the winner's advantage. Appendix C provides detailed definitions of all the variables used in the empirical analysis.

3.1.5 Summary statistics

Table 1 summarizes the U.S. patent data used in the empirical analysis. The average (median) number of patents that firms in our sample are granted annually is 26 (3). The distribution of patent grants is highly right-skewed and its standard deviation is large (105). The same is true for the distribution of citations: the mean (median) number of citations in the subsequent three years to patents granted to a firm in a given year is 60 (5) and the standard deviation of the number of citations is 308. A typical firm files patents in multiple technology classes: the mean (median) number of classes in which firms are granted patents in a given year is 4 (2).[21]

Table 2 reports summary statistics for the accounting-based variables used in the empirical analysis. The mean cash-to-assets ratio of a firm in our sample is 0.17, and the median cash-to-assets ratio is 0.08, higher than the respective values in Opler, Pinkowitz, Stulz, and Williamson (1999) and in Almeida, Campello, and Weisbach (2004). Given that ours is a sample of R&D-intensive firms, this is consistent with the evidence mentioned in the introduction that innovating firms tend to hold more cash on average. The industry-level cash flows' coefficient of variation has an average value of 2.01 with a standard deviation of 1.23. The mean (median) market-to-book ratio is 2.07 (1.42), which is somewhat higher than the mean and median market-to-book ratios of Compustat firms, consistent with firms in our sample deriving a relatively large part of their value from growth options.

[21]The majority of patents are filed within one patent class: the average (median) proportion of patents filed in the class in which the highest number of subsequent citations is received is 0.61 (0.58).

The average firm in our sample has size – measured using the total book value of assets adjusted for inflation (using 1984 dollars as the base) – of $\$1,962M$ and generates no cash flows, while the median firm has $182M$ in assets and generates cash flows equal to 7% of total assets. The net working capital – evaluated net of cash holdings – of the average (median) firm is 0.13 (0.14). The mean (median) investment-to-asset ratio, which is computed net of sales of property, plant and equipment and gross of acquisitions, is 0.06 (0.05). The mean (median) book leverage is 0.23 (0.20), somewhat lower than typical in capital structure studies (e.g., Frank and Goyal (2009)) and consistent with the negative relation between growth options and optimal leverage (e.g., Rajan and Zingales (1995) and Barclay, Morellec, and Smith (2006)). R&D expenditures over sales takes an average value of 15. Such a high value is driven by R&D-intensive firms that have a very small value of total sales. More than 50% of firms in our sample have a R&D expenditures over sales ratio lower than 0.013.

The last three quantities in Table 2 summarize our firm-level measures of financing constraints. Around 64% of firms in our sample pay a dividend or repurchase shares in a given year. The average value of the SA–index is -3.31, while the average value of the WW–index is -0.29. These two measures are positively associated with the degree of financial constraints.[22]

Table 3 reports industry-level measures of product market competition (PMC) intensity, γ^{CIT} and γ^{PAT} (Panel A), and innovation efficiency, δ^{CIT} and δ^{PAT} (Panel B), computed as averages of firm-level values across two-digit SIC industries. A typical industry in our sample has an average value of citations overlap, γ^{CIT}, of 0.18 (0.15) and an average (median) value of patents overlap, γ^{PAT}, of 0.23 (0.18). The mean (median) number of citations generated per $1M$ of R&D spending, δ^{CIT}, is 0.43 (0.42), while the median number of patens generated per $1M$ of R&D, δ^{CIT}, is 0.35 (0.30). Our two measures of intensity of output market competition are highly positively correlated., as are the two measures of innovation efficiency.[23]

In Panel C of Table 3 we report summary statistics of two industry-level variables that were shown in recent studies to be related to cash holdings. The first one is HHI, the two-digit SIC industry Herfindahl–Hirschman index in year t, used as a proxy for the intensity of current (as opposed to future, expected) product market competition (e.g., Morellec, Nikolov, and Zucchi (2013)). The second one is *Winner advantage*, the skewness of market share within an industry, following Ma, Mello, and Wu (2013), who use market share skewness as a measure of winner's

[22]The correlation coefficient between the latter two variables is 0.81, a value almost identical to the 0.80 reported in Hadlock and Pierce (2010).

[23]The correlation coefficient between γ^{CIT} and γ^{PAT} equals 0.79 and it is statistically significant at the 1% level. The correlation between δ^{CIT} and δ^{PAT} is 0.75 and is significant at the 1% level.

advantage in an industry, i.e. the importance of being the first to implement an innovation, and show that it is positively related to firms' cash holdings.

3.2 Determinants of cash holdings

In this section we test the model's predictions by examining the relation between proxies for the external financing costs, α, intensity of product market competition, γ, and innovation efficiency, δ, and firms' cash-to-assets ratios. In these tests we account for the fact that the model predicts a monotonically positive relation between cash holdings and financial constraints, while the signs and magnitudes of the relations between cash holdings on one hand and intensity of PMC and innovation efficiency on the other hand depend on the degree of financial constraints.

3.2.1 Financial constraints and cash holdings

We begin by Testing Prediction 1 of the model, that cash holdings are increasing in the degree of financial constraints. Table 4 reports the results of regressions in which we estimate the relation between cash holdings and variables that were found in past studies to be related to cash holdings, as in Equation (14), while augmenting the regressions by our three measures of financial constraints. In column 1, we use the SA index-based measure of financial constraints, in column 2 we use the WW index-based measure, while in column 3 we use the dividend and repurchases dummy. To ease the interpretation of the results, in the first two columns we define dummy variables that equal one if SA index (WW index) is above its annual median.[24]

There is a positive relation between all three measures of financial constraints and cash holdings, which is statistically and economically significant. Firms with SA index above median (i.e. relatively constrained ones) have 6.7 percentage points higher cash-to-assets ratios than firms with SA index below median (relatively unconstrained firms), ceteris paribus. Similarly, relatively constrained firms according to WW index have 5.1 percentage points higher cash holdings than relatively unconstrained firms. Finally, firms that pay dividends or repurchase shares have cash holdings that are on average 6.3 percentage points lower than non-dividend-paying and non-repurchasing firms. These numbers are large in comparison with mean cash-to-assets ratio (17%) and its standard deviation (21%). This result is consistent with the literature that explores the effects of financing constraints on cash holdings policies at the firm level (e.g., Almeida, Campello, and Weisbach (2004) and Han and Qiu (2007)) and validates our model's prediction on the role of financing constrains (Prediction 1).

[24] Piecewise-linear regressions with finer partitions of the sample based on financial constraints measures show monotonically increasing relations between measures of financial constraints and cash holdings.

The coefficients on control variables are generally consistent with past studies and intuition. Similar to Bates, Kahle, and Stulz (2009), the coefficients on size, cash flows, net working capital, investment, and leverage are negative, while the coefficients on the market-to-book ratio and industry-level cash flow variability are positive. Differently from Bates, Kahle, and Stulz (2009), in our sample there is no significant association between R&D expenditures over sales and cash holdings. The coefficient on the industry Herfindahl index is negative and significantly different from zero. This result is consistent with the findings of Morellec, Nikolov, and Zucchi (2013). The coefficient on industry-level market share skewness is significantly positive, similar to Ma, Mello, and Wu (2013).

3.2.2 Intensity of product market competition and cash holdings

Our model predicts that the effect of the intensity of product market competition on a firm's cash holdings policy depends crucially on the firm's degree of financial constraints. To explore the role of financial constraints, we split the sample into subsamples of firms with relatively low estimated external financing costs and subsamples of firms with relatively high financing costs and estimate the relation between PMC intensity and firms' cash holdings within these subsamples. Table 5 reports the results of this analysis.

As in Table 4, we use three different proxies for financial constraints. When the proxy is the SA index or WW index (columns 1–3 and 4–6 respectively), firms are classified as not financially constrained (NFC) if they belong to the bottom 30% of the annual SA index (WW index) distribution and as financially constrained (FC) if they belong to the top 30% of the annual SA index (WW index). When the proxy is the dividend and repurchases dummy (columns 7 and 8), firms are classified as financially constrained if the dummy is zero, otherwise they are considered to be not financially constrained.

We estimate two equations for each proxy for the intensity of product market competition within each subsample in columns 1-8. In the first equation, we do not add any control variables to test for the significance of the relation between the proxy for the intensity of PMC and cash holdings:

$$Cash_{i,t} = \beta_0 + \beta_\gamma \gamma_{n,t} + \phi D_t + \varepsilon_{i,t}, \tag{21}$$

where $\gamma_{n,t}$ is one of the two industry-level product market competition intensity measures, γ^{CIT} and γ^{PAT}. In the second equation, we examine whether the relation between the proxy for the intensity of PMC and cash holdings is robust to the addition of the control variables in Equation (14): industry-level cash flow volatility, market-to-book ratio, size, cash flows, net working capital,

capital expenditures plus acquisitions, leverage, R&D expenditures, industry Herfindahl index, and market share skewness:

$$Cash_{i,t} = \beta_0 + \beta_\gamma \gamma_{n,t} + \beta_\mathbf{1} \mathbf{X_{i,t}} + \phi D_t + \varepsilon_{i,t}, \tag{22}$$

To save space, Table 5 reports only the estimated coefficients on the proxy of interest, β_γ.

According to Prediction 2, the relation between the intensity of product market competition and cash holdings is expected to be less positive (more negative) for firms facing relatively low costs of external financing than for firms facing relatively high external financing costs.

Panels A and B in Table 5 report the results when we measure industry-level PMC intensity using citations-based similarity, γ^{CIT}. Consistent with the model's prediction, the unconditional relation between PMC intensity and cash holdings is increasing in the severity of financing constraints (Panel A). This conclusion holds across the three different subsample formation criteria that we adopt. The difference in estimated coefficients on PMC intensity between the most constrained and least constrained subsamples ($\Delta\beta_\gamma$) is always significantly different from zero, as follows from the Wald chi-square statistics.[25] When we add the set of control variables (Panel B), the magnitude of the coefficient on PMC intensity becomes smaller within financially constrained subsamples, however the coefficients remain statistically significant across all three subsample formation criteria. As in Panel A, the difference in estimated coefficients on PMC intensity between the most constrained and least constrained subsamples is always significantly different from zero. Panels C and D report the results when we measure industry-level PMC using patents-based similarity, γ^{PAT}. The results are consistent with the ones reported in Panels A and B, showing that the effect of PMC intensity on cash holdings does not depend on the particular proxy for the intensity of PMC.

The economic significance of the results in Table 5 is substantial. For example, increasing the measure of PMC intensity by one standard deviation (0.084 and 0.122 for γ^{CIT} and γ^{PAT} respectively) is associated with an increase in the the cash-to-assets ratios of relatively constrained firms by 2.5–4.5 percentage points, and with a reduction in the cash-to-assets ratios of relatively unconstrained firms of 1–1.3 percentage points, ceteris paribus.

To summarize, the results in Table 5 strongly support our model's prediction regarding the relation between product market competition intensity and cash holdings. The sign and magnitude of the effect of the intensity of product market competition on observed cash holdings depend crucially on the costs of external financing that firms face. For relatively financially constrained

[25] All the Wald chi-square statistics are derived while clustering errors at the industry level.

firms, this relation is positive and generally economically and statistically significant. For relatively financially unconstrained firms, the relation is significantly smaller, as predicted by the model, and negative and statistically different from zero in most specifications.

3.2.3 Innovation efficiency and cash holdings

Prediction 3 states that the relation between innovation efficiency and cash holdings is expected to be more positive (less negative) for firms facing relatively low costs of external financing than for firms facing relatively high external financing costs. Similar to specifications in Table 5, we estimate subsample regressions, in which the dependent variable is cash holdings, while the main independent variable is $\delta_{n,t}$, which takes the value of one of our two measures of innovation efficiency, δ^{CIT} and δ^{PAT}:

$$Cash_{i,t} = \beta_0 + \beta_\delta \delta_{n,t} + \phi D_t + \varepsilon_{i,t}, \tag{23}$$

$$Cash_{i,t} = \beta_0 + \beta_\delta \delta_{n,t} + \beta_{\mathbf{1}} \mathbf{X_{i,t}} + \phi D_t + \varepsilon_{i,t}. \tag{24}$$

Table 6 reports the results of our empirical tests of Prediction 3. The layout of Table 6 is similar to that of Table 5. Panels A and B in Table 6 report the results for citations-based measure of innovation efficiency, δ^{CIT}. Consistent with the model's prediction, the relation between innovation efficiency and cash holdings is positive and significant within samples of firms that face low levels of financial constraints, whereas it is negative within subsamples of relatively financially constrained firms. This is true across the three different subsample formation criteria. However, the difference between the coefficients on δ^{CIT} between the constrained and unconstrained subsamples are statistically insignificant in two cases out of three.

The results of the model augmented by control variables (Panel B) support the model's prediction: the coefficient on δ^{CIT} is positive and significant within all three unconstrained subsamples, while it is significantly negative within all three constrained subsamples. The difference between the coefficients within the constrained and unconstrained subsamples, $\Delta\beta_\delta$, is positive and significant across all three different subsample formation criteria. The results are also economically sizable: an increase in one standard deviation of δ^{CIT} (0.204 from Table 3) is associated with a 0.5–0.8 percentage points increase in cash-to-assets ratios for relatively unconstrained firms, and with a decrease of 1.3–2.2 percentage points in cash-to-assets ratios for relatively constrained firms.

Panels C and D in Table 6 report the results when we use a patent-based measure of industry-level innovation efficiency, δ^{PAT}. The difference between the coefficients on δ^{PAT} between constrained and unconstrained samples, in particular in Panel D, has the right sign and is statistically significant in two specifications out of three. Thus, the results using δ^{PAT} as a measure of innovation efficiency are broadly consistent with the results using δ^{CIT} and with the model's prediction according to which the effect of innovation efficiency on observed cash holdings depends crucially on the costs of external financing that firms face.

4 Conclusion

We develop a model of cash holdings by innovating firms. Firms compete by funding R&D expenditures that may result in technological innovations. Firms that succeed in developing their innovations obtain an option to implement them while using internal and, possibly, external funds.

Our model illustrates the strategic reason for hoarding cash by innovating firms. In the presence of financial constraints, modeled as a chance of being shut out of capital markets, a firm that has access to a larger pool of internal funds at the time of potential implementation of successful innovation commits to implement the innovation in more states of the world. This commitment lowers the payoff to the firm's competitors from both investing in R&D and from implementing successful innovations, indirectly benefiting the firm.

Our model leads to two important empirical implications. First, firms' cash holdings are expected to depend on the intensity of competition among innovators in future output markets. Importantly, the magnitude and sign of this relation is different for relatively financially constrained and unconstrained firms. For the former, the proportion of cash in firm value is increasing in the intensity of future product market competition. For the latter, cash holdings are decreasing in the intensity of competition. Second, innovation efficiency (R&D productivity) also affects optimal cash holdings in a non-trivial way. For relatively unconstrained firms, cash holdings increase in innovation efficiency, while the relation is reversed for relatively constrained ones.

We test our model's predictions using data obtained from the NBER Patent Data Project, which are instrumental in identifying firms' areas of technological innovation and in constructing measures of intensity of future output market competition and innovation efficiency. Consistent with the model's prediction, we find that the intensity of expected product market competition is positively related to relatively constrained firms' cash holdings, whereas it is negatively related to relatively unconstrained firms' cash holdings. Consistent with another prediction of the model, we document that innovation efficiency is positively related to cash holdings within subsamples of relatively financially unconstrained firms, while it is negatively related to cash holdings within subsamples of relatively constrained firms.

To summarize, we believe that our model and empirical results demonstrate some of the driving forces in innovating firms' cash holdings choices. In particular, our paper highlights the importance of strategic interactions among innovating firms in determining their cash holdings choices.

A Proofs

A.1 Proof of Lemma 1

The first derivative of $I^*_{i,un}$ in Equation (4) with respect to C_j equals

$$\frac{\partial I^*_{i,un}}{\partial C_j} = -\frac{\delta \alpha_j (1-\pi_D)}{1-\delta^2(1-\alpha_i)(1-\alpha_j)(1-\pi_D)^2}. \tag{25}$$

Since $\pi_D < 1$, the numerator of Equation (25) is positive. Since $\alpha_i < 1$, $\alpha_j < 1$, and $\delta < 1$, the denominator of Equation (25) is positive as well, then $\frac{\partial I^*_{i,un}}{\partial C_j} < 0$. The first derivative of Equation (4) with respect to C_i is

$$\frac{\partial I^*_{i,un}}{\partial C_i} = \frac{\delta^2 \alpha_i (1-\alpha_j)(1-\pi_D)^2}{1-\delta^2(1-\alpha_i)(1-\alpha_j(1-\pi_D)^2}. \tag{26}$$

Both the numerator and the denominator of Equation (26) are positive thus leading to $\frac{\partial I^*_{i,un}}{\partial C_j} > 0$.

A.2 Proof of Lemma 2

The first derivative of $C^*_i(C_j)$ in Equation (6) with respect to C_i equals

$$\frac{\partial C^*_i(C_j)}{\partial C_i} = -\frac{\alpha_j \delta (1-\pi_D)}{(1-\alpha_j)\,\delta^2\,(1-\pi_D)^2}. \tag{27}$$

Since $\alpha_j < 1$ and $\pi_D < 1$, $\frac{\partial C^*_i(C_j)}{\partial C_i} < 0$.

A.3 Proof of Proposition 1

The first derivative of $\frac{C^{EQ}_i}{V^{EQ}_i}$ with respect to α_i equals

$$\frac{2r(R-r)R\delta(r+r\delta-R)(-1+\delta(-1+\pi_D))^2(R(1-\pi_D)+r\pi_D)}{\Psi}, \tag{28}$$

where Ψ is a quadratic form and is positive.[26] The quadratic term $(-1+\delta(-1+\pi_D))^2$ is positive and by assumption ($R > r$ and $\pi_D < 1$) the terms $2r(R-r)R\delta$ and $(R(1-\pi_D)+r\pi_D)$ are also positive. Equation (9) implies that

$$r + r\delta - R = (1-\alpha_i)r\delta + (R-r)(1-\alpha_i)\delta^2\,(1-\pi_D) > 0. \tag{29}$$

It follows that the numerator of Equation (28) is positive: $\partial\left(\frac{C^{EQ}_i}{V^{EQ}_i}\right)/\partial\alpha_i > 0$. Since $\frac{C^{EQ}_i/r}{V^{EQ}_i + C^{EQ}_i/r}$ is monotonically increasing in $\frac{C^{EQ}_i}{V^{EQ}_i}$, it is also increasing in α_i.

[26] The expression for Ψ is available upon request.

A.4 Proof of Proposition 2

The first derivative of $\frac{C_i^{EQ}}{V_i^{EQ}}$ with respect to π_D is

$$\frac{2rR\alpha_i\delta(r-R+r\delta)(R^2(1+(-1+\alpha_i)\delta^2(-1+\pi_D)^2)}{\Psi} - \\ -\frac{2rR(1+\delta+(-1+\alpha_i)\delta^2(-1+\pi_D)\pi_D)+r^2(1+\delta(2+\delta+(-1+\alpha_i)\delta\pi_D{}^2)))}{\Psi} \tag{30}$$

The denominator of Equation (30) is a quadratic form and is positive. The numerator of Equation (30) is positive (negative) if $\alpha_i < \overline{\alpha}$ ($\alpha_i > \overline{\alpha}$), where $\overline{\alpha} = 1 - \frac{(r-R+r\delta)^2}{\delta^2(R+r\pi_D-R\pi_D)^2}$.

Since $\frac{\partial \pi_D}{\partial \gamma} < 0$ and $\frac{C_i^{EQ}/r}{V_i^{EQ}+C_i^{EQ}/r}$ is monotonically increasing in $\frac{C_i^{EQ}}{V_i^{EQ}}$, the derivative of $\frac{C_i^{EQ}/r}{V_i^{*}+C_i^{EQ}/r}$ w.r.t. γ is negative when $\alpha_i < \overline{\alpha}$ and positive when $\alpha_i > \overline{\alpha}$.

A.5 Proof of Proposition 3

The first derivative of $\frac{C_i^{EQ}}{V_i^{EQ}}$ with respect to δ is

$$-\frac{2rR\alpha_i(R+r\pi_D-R\pi_D)(R^2(1+(-1+\alpha_i)\delta^2(-1+\pi_D)^2)}{\Psi} + \\ +\frac{2rR(1+\delta+(-1+\alpha_i)\delta^2(-1+\pi_D)\pi_D)+r^2(1+\delta(2+\delta+(-1+\alpha_i)\delta\pi_D{}^2)))}{\Psi} \tag{31}$$

The denominator of Equation (30) is a quadratic form and is positive. The numerator of Equation (30) is negative (positive) if $\alpha_i < \overline{\alpha}$ ($\alpha_i > \overline{\alpha}$), where $\overline{\alpha} = 1 - \frac{(r-R+r\delta)^2}{\delta^2(R+r\pi_D-R\pi_D)^2}$.

Since $\frac{C_i^{EQ}/r}{V_i^{EQ}+C_i^{EQ}/r}$ is monotonically increasing in $\frac{C_i^{EQ}}{V_i^{EQ}}$, the derivative of $\frac{C_i^{EQ}/r}{V_i^{*}+C_i^{EQ}/r}$ w.r.t. δ is positive when $\alpha_i < \overline{\alpha}$ and negative when $\alpha_i > \overline{\alpha}$.

B Alternative model specification

In the baseline model in Section 2, we assume that firms choose cash holdings following successful innovations. In this section we examine an alternative specification, in which firms' cash holdings choices are made simultaneously with the choices of R&D investment. We assume that R&D investment, RD_i, translates into the likelihood of an initial innovation success of $p(RD_i)$, which has the following properties: $p'(RD_i) > 0$, $p''(RD_i) \leq 0$, $p(0) = 0$, $p(\infty) \longrightarrow 1$. In particular, we assume the following functional form for the probability of initial innovation success:

$$p_i = 1 - \exp(-RD_i). \tag{32}$$

In what follows, we examine a model whose setup and assumptions are identical to the ones in Section 2 except for the timing of the choice of cash flows. The timeline of the game is depicted in Figure 4.

Similar to the baseline model, we solve the modified model by backwards induction. In the second stage, each of the firms that have innovated successfully and have raised cash to be used in the implementation stage chooses whether to implement its innovation following realizations of the shocks to innovation viability, access to external funds, and required investment in innovation implementation.

The main difference between the second stage in the baseline model and the current one is as follows. In the baseline model, the industry structure is known: we examine the case in which two firms that have successfully innovated make their innovation implementation decisions while accounting for the optimal responses of their rival. In the current model, three realizations of the first-stage uncertainty are possible: 1) two firms have successfully innovated, 2) one of the firms has successfully innovated, 3) neither of the firms has successfully innovated.

When neither of the two firms has successfully innovated in the first stage, their second stage payoffs equal their discounted cash holdings, C_i/R for firm i. In case one firm (say firm i) has successfully innovated, its innovation implementation threshold conditional on its innovation being viable equals monopoly profits,

$$I_{i,un}^{alone} = \pi_M = 1, \tag{33}$$

where the superscript *alone* refers to only one firm making it to the second stage.

The solution of the second stage of the game in the case in which both firms have successfully innovated is very similar to the solution of the baseline model. The only difference is that now it is possible that firm i chooses cash holdings that are higher than expected second-stage product market profit, $C_i > \mathbb{E}\pi_i$. This is possible because each firm now chooses cash holdings while accounting for the possibility of being a monopolist in the output market, in which case the marginal benefit of cash is higher. Whether equilibrium cash holdings would exceed the unconstrained implementation threshold in the case in which both firms have successfully innovated depends on the marginal cost of cash holdings relative to their expected marginal benefit. If the marginal cost is very low (i.e. $r \to R$), firms would choose high levels of cash holdings and would be unconstrained in the second-stage duopoly case. On the other hand, if the marginal cost of cash holdings is high enough, firms would choose cash holdings lower than the unconstrained implementation threshold in the second–stage duopoly case.

In the case in which the marginal cost of cash holdings is sufficiently low, cash holdings play no strategic role, in the sense that a firm's level of cash holdings does not impact its rival's optimal choice of cash holdings, its level of investment in innovation, or the likelihood of implementing the innovation in the second stage. Since the strategic motive for holding cash is one of the focal points of our analysis and since we model innovative firms, which are likely to be relatively financially constrained, we concentrate on the case in which firms are constrained in the second-stage duopoly. We do that by choosing parameter values that ensure that both firms' equilibrium cash holdings choices are lower than expected second-stage profit, i.e. that $C_i^* < \mathbb{E}\pi_i$. Therefore, in the case in which both firms have successfully innovated in the first stage, the equilibrium unconstrained optimization threshold is given in Equation (4) for firm i and similarly for firm j. In what follows, we rename the unconstrained optimal investment implementation threshold for this case, $I_{i,un}^{both}$, where the superscript *both* refers to both firms having successfully innovated in the first stage, in which cash holdings play a strategic role.

In the first stage, the two firms choose their levels of R&D investment and cash holdings. In particular, firm i has the following objective function:

$$\begin{aligned}
\max_{RD_i,C_i} V_i &= -RD_i - C_i/r + \exp(-RD_i)C_i/R + \\
&+ (1-\exp(-RD_i))\exp(-RD_j)(C_i + \delta(\alpha_i \int_{\underline{I}}^{C_i} f(I_i)\,(\pi_M - I_i)\,dI_i + \\
&+ (1-\alpha_i)\int_{\underline{I}}^{I_{i,un}^{alone}} f(I_i)\,(\pi_M - I_i)\,dI_i))/R + \\
&+ (1-\exp(-RD_i))\,(1-\exp(-RD_j))\,(C_i + \delta(\alpha_i \int_{\underline{I}}^{C_i} f(I_i)\,(\mathbb{E}_i(\pi) - I_i)\,dI_i + \\
&+ (1-\alpha_i)\int_{\underline{I}}^{I_{i,un}^{both}} f(I_i)\,(\mathbb{E}_i(\pi) - I_i)\,dI_i))/R \qquad (34)
\end{aligned}$$

The first line in Equation (34) contains investment in R&D, cash raised in order to be potentially used for second-stage implementation of innovation, and the likelihood of firm i's innovation effort being unsuccessful multiplied by the discounted cash holdings. The second and third lines in Equation (34) refer to the case in which firm i is successful in initial innovation, while firm j is not. In this case, if firm i's innovation turns out viable and if it decides to implement it, it becomes a monopolist in the output market, and realizes profit $\pi_M = 1$. The fourth and fifth lines in Equation (34) refer to the case in which both firms have succeeded in their first-stage innovations and is similar to the value function in the baseline model in Section 2.

Differentiating firm i's value function in Equation (34) with respect to C_i and RD_i, equating the resulting two F.O.C.s, which are linear in C_i and RD_i, to zero, and solving for C_i and RD_i generates the reaction functions of firm i's cash holdings and R&D investment. The reaction functions are firm i's optimal choices of cash holdings and investment in innovation as functions of firm j's cash holdings and investment in innovation. We call these function $C_i^*(C_j, RD_j)$ and $RD_i^*(C_j, RD_j)$, respectively. It is easy to show that these reaction functions are downward-sloping.[27] The reason for the negative effect of firm j's cash holdings on firm i's optimal cash holdings is that firm j's higher cash holdings increase the likelihood of firm j implementing its innovation, which, in turn, reduces firm i's expected second-stage profit and the marginal benefit of holding cash, resulting in lower equilibrium cash holdings, $C_i^*(C_j, RD_j)$. This is one of the strategic benefits of holding cash, discussed in Section 2. (An additional strategic benefit of cash holdings, discussed in Section 2 and present here, is that firm j's cash holdings reduce firm i's unconstrained investment implementation threshold, $I_{i,un}^{both}$).

The downward-sloping $RD_i(C_j, RD_j)$ is a manifestation of the third strategic benefit of holding cash, that of reducing rival's investment in innovation. Because of the two strategic effects of cash holdings discussed above, higher C_j is associated with lower expected firm i's second-stage profit and resulting lower marginal benefit of investing in R&D in the first stage, and lower optimal investment in innovation. In the baseline model in Section 2 we have abstracted from this interaction between cash holdings and investment. With this interaction present, the strategic effect of cash holdings becomes even stronger.

Writing similar F.O.C.s of firm j for C_j and RD_j and solving the resulting system of four equations in four unknowns leads to firms' equilibrium choices: RD_i^{EQ}, RD_j^{EQ}, C_i^{EQ}, and C_j^{EQ}. In what follows, we re-examine the relations between firm i's cash-to-value ratio, $\widetilde{C_i^{EQ}} = \frac{C_i^{EQ}/r}{V_i^{EQ}+C_i^{EQ}/r}$, on one hand, and degree of financial constraints, α_i, intensity of output market competition, γ, and innovation efficiency, δ, on the other hand in the context of the current version of the model, in which cash holdings and R&D investment are chosen simultaneously.

Figure 5 illustrates the relation between the intensity of competition, γ, and firm's equilibrium cash-to-value ratio. The parameters are also identical to those used in the construction of Figure 2. We vary the competition intensity parameter, γ, between zero and one, and examine two separate scenarios: a relatively constrained one ($\alpha_i = 0.15$ in Figure 5A) and a relatively unconstrained one ($\alpha_i = 0.8$ in Figure 5B).

Similar to Figure 2, in both Figures 5A and 5B, the solid line represents equilibrium cash holdings, C_i^{EQ}/r, the dashed line represents equilibrium firm value, V_i^{EQ}, and the dashed-dotted line represents equilibrium cash-to-value ratio, $\widetilde{C_i^{EQ}}$. The shapes of the relations between C_i^{EQ}/r, V_i^{EQ}, and $\widetilde{C_i^{EQ}}$ on one hand, and γ on the other hand, are consistent with those in Figure 2: both equilibrium cash holdings and firm value are decreasing in the intensity of output market competition, while the effect of γ on $\widetilde{C_i^{EQ}}$ depends on the degree of financial constraints: it is

[27] A proof is available upon request.

negative in the low-α_i case, in which strategic considerations are relatively unimportant, and it is positive in the high-α_i case, in which strategic considerations dominate the relation.

In Figure 6, we depict the relation between innovation efficiency, δ, and firm i's equilibrium cash holdings for the case of low financial constraints, $\alpha_i = 0.15$ (in Figure 6A), and for the case of high financial constraints, $\alpha_i = 0.8$ (in Figure 6B). The parameter values are identical to those in Figure 3. Similar to the baseline model, the relation between cash-to-value ratio and innovation efficiency depends on the degree of financial constraints. When a firm is relatively unconstrained, its cash-to-value ratio is increasing in innovation efficiency, while the opposite is true for a relatively constrained firm. The reason is identical to the one discussed in the baseline model: the sensitivity of cash holdings to innovation efficiency is higher when equilibrium cash holdings are low (i.e. when α_i is low) than when cash holdings are high (i.e. when α_i is high).

Overall, the model in this Appendix, which is different from the baseline model in that it allows for complementarities between cash holdings and R&D investments and for the strategic effect of cash holdings on rival's R&D investment, results in similar qualitative relations between normalized cash holdings on one hand, and financial constraints, intensity of output market competition, and innovation efficiency, on the other hand, as the baseline model in Section 2. This finding is important as it demonstrates that the roles of these factors in determining optimal cash holdings of innovative firms are robust and insensitive to the timing of cash holdings choices.

C Definitions of Control Variables

We obtain accounting variables that we use in the empirical analysis from the CRSP/Compustat Merged Database. The literature on the determinants of cash holdings has identified a set of key variables that help explain a firm cash hoarding behavior. We follow Bates, Kahle, and Stulz (2009) and include in our cash holdings analysis the following variables:[28]

- *Cash* is the amount of cash and cash equivalents (item `CHE`).
- *Industry CFCV* is a measure of cash flow volatility. Following Han and Qiu (2007), we calculate the cash flow coefficient of variation (CFCV) at the firm level using the previous 16 quarters. A quarterly cash flow is defined as net income before extraordinary items (item `IBQ`) plus depreciation (item `DPQ`) in quarter j over the value of total assets (item `ATQ`) in

[28]All balance sheet and income statement items are scaled by the contemporaneous value of total assets (Compustat item `AT`), if not specified otherwise.

quarter $j-1$. *Industry CFCV* is the industry (two–digit SIC code) average value. We require at least five observations in each industry–year.

- *Market-to-book* is the ratio of the firm's market value over the firm's book value. We define the book value as the value of total assets (item `AT`) and the market value as the book value minus the book value of equity (item `CEQ`) plus the market value of equity (item `CSHO` × item `PRCC_F`).

- *Size* is the book value of assets (item `AT`) deflated using the Consumer Price Index (CPI).

- *Cash flow* is defined as earnings before depreciation (item `OIBDP`) net of interest (item `XINT`, set to zero when missing), dividends (item `DVC`), and taxes (item `TXT`).

- *Net working capital* is computed as the difference between working capital (item `WCAP`) and cash (item `CHE`).

- *Investment* is defined as investment in physical capital (item `CAPX`) net of sales of property, plant and equipment (item `SPPE`, set to zero when missing) plus acquisitions (item `AQC`, set to zero when missing).

- *Leverage* is the sum of long-term debt (item `DLTT`) and debt in current liabilities (item `DLC`) at time t.

- *R&D* is R&D expenditures (item `XRD`). This variable is set equal to zero when R&D expenditures values are missing. Following Bates, Kahle, and Stulz (2009), *R&D* is deflated by *Sales* (item `SALE`).

In addition, following recent studies of the determinants of cash holdings (Morellec, Nikolov, and Zucchi (2013) and Ma, Mello, and Wu (2013)), we include the following two control variables:

- *HHI* is the Herfindahl-Hirshman index of sales, computed as the sum of squared sales (item `SALE`) of all firms belonging to a two-digit SIC industry divided by squared industry sales.

- *Winner advantage* is the skewness of sales (item `SALE`) within a two-digit SIC industry.

D Regressions with Cash-to-Value Ratios

In this Appendix we re-examine the relations between cash holdings and measures of financial constraints, intensity of product market competition, and innovation efficiency, while replacing

Table 1: Patent Data

	Mean	Std. Dev.	25%	50%	75%	Min	Max	N
Patents	26.087	104.847	1	3	10	1	2,905	33,097
Citations	59.578	307.794	1	5	19	0	11,987	33,097
Classes	3.940	5.076	1	2	4	1	35	33,097

This table reports the mean, standard deviation, 25th percentile, 50th percentile, 75th percentile, minimum value, maximum value, and number of firm-year observations with non-zero patent grants. *Patents* is the number of patents granted to a firm in year t. We consider only patents that have an application year that precedes the granting year by at most three years. *Citations* is the total number of citations that a firm's patents granted in year t receive within three years from the granting year. *Classes* is the number of unique technology classes assigned to patents granted to a firm in year t.

the cash-to-assets ratio by the cash-to-value ratio. The latter is defined as the sum of the firm's market value of equity (the product of the number of shares outstanding (item `CSHO`) and price per share (item `PRCC_F`)) and the book value of debt (the sum of long-term debt (item `DLTT`) and debt in current liabilities (item `DLC`)). Cash-to-value is the quantity examined in the model in Section 2, thus the tests in this section are well aligned with the model.

The results in Tables 7, 8, and 9 are broadly consistent with those in Tables 4, 5, and 6, in which cash-to-assets ratio is used as the dependent variable. In particular, the coefficients on all three measures of financial constraints in Table 7 are negative and significant, consistent with financially constrained firms holding more cash. The coefficients on proxies for the intensity of PMC in Table 8 are significantly negative in all the non-constrained subsamples, while they are positive in all the constrained samples, and are significant in the majority of them. The results in Table 9 are somewhat stronger than in the corresponding Table 6: the spread between the coefficients on innovation efficiency measures tends to be larger when the dependent variable is cash-to-value ratio than when it is cash-to-assets ratio.

Overall, the results in this section demonstrate that our empirical findings are not due to the normalization of cash holdings by book assets, as is common in the empirical cash holdings literature, and that the relations between measures of cash holdings on one hand, and measures of financial constraints, intensity of expected Product market competition, and innovation efficiency on the other hand are robust to various definitions of cash holdings.

Table 2: Firm-Level Accounting Data

	Mean	Std. Dev.	25%	50%	75%	Min	Max	N
Cash	0.174	0.214	0.026	0.082	0.235	0.000	0.899	33,097
Industry CFCV	2.067	1.233	1.050	1.997	2.897	0.154	14.589	29,962
Market-to-book	2.116	2.090	1.059	1.408	2.208	0.643	14.029	30,252
Size	1,962	5,408	38	184	1,073	1	36,151	33,097
Cash flow	-0.007	0.265	0.015	0.066	0.103	-1.549	0.252	32,896
Net working capital	0.134	0.204	0.017	0.142	0.269	-0.738	0.543	32,564
Investment	0.065	0.062	0.028	0.050	0.082	-0.027	0.401	32,605
Leverage	0.226	0.204	0.065	0.198	0.322	0.000	1.119	33,042
R&D to sales	15.284	96.305	0.000	0.013	0.389	0.000	916.872	33,097
SA index	-3.311	0.949	-4.108	-3.354	-2.742	-4.627	1.091	32,509
WW index	-0.290	0.131	-0.385	-0.297	-0.205	-0.545	0.262	30,919
Dividend dummy	0.636	0.481	0.000	1.000	1.000	0.000	1.000	33,097

This table reports the mean, standard deviation, 25th percentile, 50th percentile, 75th percentile, minimum value, maximum value, and number of available observations for the accounting-based variables. All balance sheet and income statement items are scaled by the contemporaneous value of total assets (Compustat item `AT`), if not specified otherwise. *Cash* is the amount of cash and cash equivalents (item `CHE`). We calculate the cash flows coefficient of variation at the firm level using the previous 16 quarters. A quarterly cash flow is defined as net income before extraordinary items (item `IBQ`) plus depreciation (item `DPQ`) in quarter j over the value of total assets (item `ATQ`) in quarter $j-1$. *Industry CFCV* is the industry average value. *Market-to-book* is the ratio of the firm's market value over the firm's book value. We define the book value as the value of total assets (item `AT`) and the market value as the book value minus the book value of equity (item `CEQ`) plus the market value of equity (item `CSHO` $\times$ item `PRCC_F`). *Size* is the book value of assets (item `AT`) deflated using the Consumer Price Index (CPI) and reported in millions of 1984 dollars. *Cash flow* is defined as earnings before depreciation (item `OIBDP`) net of interest (item `XINT`, set to zero when missing), dividends (item `DVC`), and taxes (item `TXT`). *Net working capital* is computed as the difference between working capital (item `WCAP`) and cash (item `CHE`). *Investment* is defined as investment in physical capital (item `CAPX`) net of sales of property, plant and equipment (item `SPPE`, set to zero when missing) plus acquisitions (item `AQC`, set to zero when missing). *Leverage* is the sum of long-term debt (item `DLTT`) and debt in current liabilities (item `DLC`) at time t. *R&D to Sales* is the ratio of R&D expenditures (item `XRD`) to sales (item `SALE`). This variable is set equal to zero when R&D expenditures are missing. *SA index* is the firm–level financial constraints index proposed by Hadlock and Pierce (2010). *WW index* is the firm–level financial constraints index proposed by Whited and Wu (2010). *Dividend dummy* is a dummy variable that takes the value of one if the sum of dividends (item `DV`) and repurchases (item `PRSTKC`, set to zero when missing) is positive and zero otherwise. The data are at the annual frequency over the period 1976–2003 and all the variables are winsorized at the top and bottom 1%. Appendix C provides extended definitions of these accounting-based variables.

Table 3: Industry-Level Data

Panel A: Industry–level measures of intensity of competition

	Mean	Std. Dev.	25%	50%	75%	Min	Max	N
γ^{CIT}	0.183	0.084	0.121	0.155	0.223	0.000	0.900	33,005
γ^{PAT}	0.228	0.122	0.145	0.192	0.284	0.000	1.000	32,825

Panel B: Industry–level measures of innovation efficiency

	Mean	Std. Dev.	25%	50%	75%	Min	Max	N
δ^{CIT}	0.428	0.204	0.304	0.420	0.536	0.000	2.866	32,462
δ^{PAT}	0.350	0.224	0.192	0.295	0.446	0.006	2.530	32,462

Panel C: Industry–level control variables

	Mean	Std. Dev.	25%	50%	75%	Min	Max	N
HHI	0.251	0.207	0.116	0.180	0.321	0.043	1.000	33,036
Winner advantage	5.912	3.168	3.381	5.714	8.286	-0.707	14.833	32,717

This table reports the mean, standard deviation, 25% percentile, 50% percentile, 75% percentile, minimum value, maximum value, and number of available observations for industry-level measures of product market competition intensity (Panel A) and innovation efficiency (Panel B). Industries are defined using two–digit SIC codes. γ^{CIT} (γ^{PAT}) is the industry average of firm-level citations-based (patents-based) similarity. δ^{CIT} (δ^{PAT}) is the industry average citations-based (patents-based) efficiency measure. Panel C reports two industry-level variables that we use as controls. *HHI* is the industry Herfindahl Index. *Winner advantage* is the skewness of the market share within an industry. Section 3.1.3 provides extended definitions of the variables.

Table 4: Cash Holdings and Financial Constraints

	(1)	(2)	(3)
SA dummy	0.067***		
	(0.016)		
WW dummy		0.051***	
		(0.016)	
Dividend dummy			-0.063***
			(0.021)
Cash flow volatility	-0.001	-0.001	-0.002
	(0.005)	(0.005)	(0.005)
Market-to-book	0.016***	0.017***	0.015***
	(0.002)	(0.002)	(0.002)
Size	-0.011***	-0.012***	-0.015***
	(0.002)	(0.002)	(0.001)
Cash flow	-0.048**	-0.048*	-0.041*
	(0.023)	(0.024)	(0.022)
Net working capital	-0.364***	-0.377***	-0.368***
	(0.039)	(0.043)	(0.038)
Investment	-0.420***	-0.412***	-0.411***
	(0.082)	(0.082)	(0.078)
Leverage	-0.419***	-0.431***	-0.437***
	(0.025)	(0.027)	(0.027)
R&D to sales	-0.000	-0.000	-0.000
	(0.000)	(0.000)	(0.000)
HHI	-0.057***	-0.059***	-0.054***
	(0.019)	(0.019)	(0.018)
Winner advantage	0.006***	0.006***	0.005***
	(0.001)	(0.001)	(0.001)
Constant	0.294***	0.312***	0.404***
	(0.027)	(0.029)	(0.047)
Obs.	28,066	28,066	28,066
R^2–adj	0.490	0.483	0.490
Year FE	YES	YES	YES

This table reports the estimates of the following regression:

$$Cash_{i,t} = \beta_0 + \beta_\alpha \alpha_{i,t} + \beta_\mathbf{1} \mathbf{X_{i,t}} + \phi D_t + \varepsilon_{i,t},$$

where $Cash_{i,t}$ is cash-to-assets ratio, $\alpha_{i,t}$ is a measure of high financial constraints, $\mathbf{X_{i,t}}$ is a vector of variables that includes *Cash flow CV*, *Market-to-book*, *Size*, *Cash flow*, *Net working capital*, *Investment*, *Leverage*, *R&D to sales*, *HHI*, and *Winner advantage*, $D_{i,t}$ is a vector of year dummies, and $\varepsilon_{i,t}$ is an i.i.d. normally distributed error term. We use three measures of financial constraints: SA dummy that equals one if a firm's SA index is above annual median, WW dummy that equals one if a firm's WW index is above annual median, and dividend dummy that equals one if a firm paid dividends or repurchased shares in a given year. The quantity of interest is β_α, the regression coefficients on the firm-level measures of financial constraints. Appendix C reports detailed definitions of all of the variables included in the regression. *Obs.* is the number of firm-year observations and R^2–adj is the adjusted R-squared. The data are at the annual frequency over the period 1976–2003 and all accounting variables are winsorized at the top and bottom 1% to limit the influence of outliers. The 1%, 5%, and 10% significance levels are denoted with ***, **, and *, respectively. Standard errors clustered at the industry level are reported in parentheses.

Table 5: Cash Holdings and Industry Intensity of PMC

	SA index			WW index			Dividend dummy	
	NFC	Middle	FC	NFC	Middle	FC	NFC	FC
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Panel A: γ^{CIT}, Without control variables								
β_γ	-0.157***	0.100	0.661	-0.122	0.121	0.713	-0.166*	0.930**
	(0.040)	(0.221)	(0.455)	(0.082)	(0.240)	(0.444)	(0.085)	(0.355)
Obs	9,081	12,127	9,664	8,620	11,510	10,744	19,290	11,584
R^2–adj	0.092	0.119	0.185	0.035	0.126	0.166	0.060	0.157
$\Delta\beta_\gamma$	Δ=-0.811* $\chi^2 = 3.579$			Δ=-0.836** $\chi^2 = 4.677$			Δ=-1.096*** $\chi^2 = 14.67$	
Panel B: γ^{CIT}, With control variables								
β_γ	-0.125***	-0.005	0.307**	-0.157***	0.009	0.392***	-0.125***	0.530***
	(0.034)	(0.043)	(0.119)	(0.036)	(0.036)	(0.131)	(0.028)	(0.116)
Obs	8,374	10,740	7,950	7,610	10,678	8,776	17,194	9,870
R^2–adj	0.345	0.508	0.476	0.472	0.537	0.464	0.465	0.459
$\Delta\beta_\gamma$	Δ=-0.432*** $\chi^2 = 10.12$			Δ=-0.549*** $\chi^2 = 16.28$			Δ=-0.655*** $\chi^2 = 26.86$	
Panel C: γ^{PAT}, Without control variables								
β_γ	-0.080**	0.128	0.465	-0.054	0.156	0.506*	-0.078	0.653***
	(0.031)	(0.144)	(0.280)	(0.054)	(0.154)	(0.274)	(0.056)	(0.212)
Obs	9,015	12,067	9,612	8,559	11,454	10,681	19,162	11,532
R^2–adj	0.058	0.124	0.192	0.030	0.132	0.174	0.056	0.165
$\Delta\beta_\gamma$	Δ=-0.545** $\chi^2 = 4.279$			Δ= -0.560** $\chi^2 = 5.596$			Δ=-0.731*** $\chi^2 = 19.14$	
Panel D: γ^{PAT}, With control variables								
β_γ	-0.082***	0.001	0.209***	-0.100***	0.002	0.274***	-0.084***	0.361***
	(0.024)	(0.030)	(0.074)	(0.027)	(0.023)	(0.080)	(0.020)	(0.073)
Obs	8,374	10,742	7,953	7,610	10,680	8,779	17,197	9,872
R^2–adj	0.345	0.508	0.476	0.470	0.537	0.465	0.465	0.460
$\Delta\beta_\gamma$	Δ= -0.291*** $\chi^2 = 11.47$			Δ= -0.374*** $\chi^2 = 19.11$			Δ= -0.445*** $\chi^2 = 29.46$	

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This table reports the estimates of the following regressions:

$$Cash_{i,t} = \beta_0 + \beta_\gamma \gamma_{n,t} + \phi D_t + \varepsilon_{i,t}, \quad (35)$$
$$Cash_{i,t} = \beta_0 + \beta_\gamma \gamma_{n,t} + \beta_{\mathbf{1}} \mathbf{X_{i,t}} + \phi D_t + \varepsilon_{i,t}, \quad (36)$$

where $\gamma_{n,t}$ is one of the two industry-wide measures of intensity of product market competition, γ^{CIT} and γ^{PAT}, $\mathbf{X_{i,t}}$ is a vector of variables that includes *Cash flow CV*, *Market-to-book*, *Size*, *Cash flow*, *Net working capital*, *Investment*, *Leverage*, *R&D to sales*, *HHI*, and *Winner advantage*, D_t is a vector of time dummies, and $\varepsilon_{i,t}$ is an i.i.d. normally distributed error term. The quantity of interest is β_γ, the regression coefficients on the industry-level measures of product market competition intensity. We run regressions on different subsamples of firms sorted by their degree of financing constraints. We use three proxies for financial constraints. When the proxy is the SA index or WW index (columns 1–3 and 4–6 respectively), firms are classified as not financially constrained (NFC) if they belong to the bottom 30% of the annual SA index (WW index) distribution and as financially constrained (FC) if they belong to the top 30% of the annual SA index (WW index). When the proxy is the dividend and repurchases dummy (columns 7 and 8), firms are classified as financially constrained if the dummy is zero, otherwise they are considered to be not financially constrained. For each measure of product market competition, we report estimates of β_γ both in the regression without control variables and the one with control variables. At the bottom of each panel, Δ is the difference in β_γ between the most constrained and least constrained subsamples. χ^2 is the Wald chi-square statistic for testing the difference between these two coefficients. *Obs.* is the number of firm-year observations and R^2–adj is the adjusted R-squared. The data are at the annual frequency over the period 1976–2003 and all the accounting variables are winsorized at the top and bottom 1% to limit the influence of outliers. The 1%, 5%, and 10% significance levels are denoted with ***, **, and *, respectively. Standard errors clustered at the industry level are reported in parentheses.

Table 6: Cash Holdings and Industry Innovation Efficiency

	SA index			WW index			Dividend dummy	
	NFC	Middle	FC	NFC	Middle	FC	NFC	FC
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)

Panel A: δ^{CIT}, Without control variables

β_δ	0.056***	-0.021	-0.131	0.064**	-0.017	-0.137	0.065**	-0.191
	(0.020)	(0.060)	(0.130)	(0.028)	(0.058)	(0.137)	(0.030)	(0.165)
Obs	8,936	11,993	9,422	8,490	11,392	10,469	18,934	11,417
R^2–adj	0.059	0.119	0.165	0.035	0.126	0.138	0.059	0.103
$\Delta\beta_\delta$	Δ=0.187 $\chi^2 = 2.071$			Δ=0.201 $\chi^2 = 2.402$			Δ=0.257* $\chi^2 = 2.726$	

Panel B: δ^{CIT}, With control variables

β_δ	0.040***	-0.006	-0.065*	0.045***	-0.002	-0.075*	0.026*	-0.110*
	(0.013)	(0.014)	(0.038)	(0.014)	(0.011)	(0.044)	(0.013)	(0.054)
Obs	8,315	10,668	7,844	7,558	10,614	8,655	17,025	9,802
R^2–adj	0.342	0.510	0.472	0.467	0.537	0.458	0.463	0.448
$\Delta\beta_\delta$	Δ=0.105** $\chi^2 = 5.093$			Δ= 0.121** $\chi^2 = 5.736$			Δ= 0.136** $\chi^2 = 4.655$	

Panel C: δ^{PAT}, Without control variables

β_δ	0.019	-0.076	-0.126	0.026	-0.083	-0.134	0.016	-0.222
	(0.019)	(0.051)	(0.120)	(0.035)	(0.050)	(0.124)	(0.034)	(0.155)
Obs	8,936	11,993	9,422	8,490	11,392	10,469	18,934	11,417
R^2–adj	0.050	0.121	0.162	0.028	0.130	0.135	0.053	0.099
$\Delta\beta_\delta$	Δ=0.145 $\chi^2 = 1.561$			Δ=0.160 $\chi^2 = 1.865$			Δ= 0.238* $\chi^2 = 2.699$	

Panel D: δ^{PAT}, With control variables

β_δ	0.021*	0.005	-0.050	0.032*	0.002	-0.057	0.010	-0.108*
	(0.011)	(0.019)	(0.036)	(0.017)	(0.016)	(0.039)	(0.014)	(0.057)
Obs	8,315	10,668	7,844	7,558	10,614	8,655	17,025	9,802
R^2–adj	0.338	0.509	0.471	0.465	0.537	0.457	0.462	0.446
$\Delta\beta_\delta$	Δ=0.071* $\chi^2 = 2.897$			Δ= 0.089* $\chi^2 = 3.967$			Δ=0.117 $\chi^2 = 3.445$	

This table reports the estimates of the following regressions:

$$Cash_{i,t} = \beta_0 + \beta_\delta \delta_{n,t} + \phi D_t + \varepsilon_{i,t}, \tag{37}$$
$$Cash_{i,t} = \beta_0 + \beta_\delta \delta_{n,t} + \beta_{\mathbf{1}} \mathbf{X_{i,t}} + \phi D_t + \varepsilon_{i,t}, \tag{38}$$

where $\delta_{n,t}$ is one of the two industry-wide measures of innovation efficiency, δ^{CIT} and δ^{PAT}, $\mathbf{X_{i,t}}$ is a vector of variables that includes *Cash flow CV*, *Market-to-book*, *Size*, *Cash flow*, *Net working capital*, *Investment*, *Leverage*, *R&D to sales*, *HHI*, and *Winner advantage*, D_t is a vector of time dummies, and $\varepsilon_{i,t}$ is an i.i.d. normally distributed error term. The quantity of interest is β_δ, the regression coefficients on the industry-level measures of innovation efficiency. We run regressions on different subsamples of firms sorted by their degree of financing constraints. We use three proxies for financial constraints. When the proxy is the SA index or WW index (columns 1–3 and 4–6 respectively), firms are classified as not financially constrained (NFC) if they belong to the bottom 30% of the annual SA index (WW index) distribution and as financially constrained (FC) if they belong to the top 30% of the annual SA index (WW index). When the proxy is the dividend and repurchases dummy (columns 7 and 8), firms are classified as financially constrained if the dummy is zero, otherwise they are considered to be not financially constrained. For each measure of innovation efficiency, we report estimates of β_δ both in the regression without control variables and the one with control variables. At the bottom of each panel, Δ is the difference in β_δ between the most constrained and least constrained subsamples. χ^2 is the Wald chi-square statistic for testing the difference between these two coefficients. *Obs.* is the number of firm-year observations and R^2–adj is the adjusted R-squared. The data are at the annual frequency over the period 1976–2003 and all the accounting variables are winsorized at the top and bottom 1% to limit the influence of outliers. The 1%, 5%, and 10% significance levels are denoted with ***, **, and *, respectively. Standard errors clustered at the industry level are reported in parentheses.

Table 7: Cash-to-Value Ratios and Financial Constraints

	(1)	(2)	(3)
SA dummy	0.030***		
	(0.006)		
WW dummy		0.034***	
		(0.007)	
Dividend dummy			-0.032***
			(0.007)
Cash flow volatility	0.006***	0.006***	0.006***
	(0.002)	(0.002)	(0.002)
Market-to-book	-0.030***	-0.029***	-0.030***
	(0.001)	(0.001)	(0.001)
Size	-0.008***	-0.006***	-0.009***
	(0.002)	(0.002)	(0.001)
Cash flow	-0.068***	-0.069***	-0.065***
	(0.009)	(0.009)	(0.009)
Net working capital	-0.267***	-0.272***	-0.268***
	(0.008)	(0.009)	(0.008)
Investment	-0.287***	-0.285***	-0.283***
	(0.031)	(0.031)	(0.030)
Leverage	-0.307***	-0.313***	-0.316***
	(0.017)	(0.017)	(0.017)
R&D to sales	-0.000	-0.000	-0.000
	(0.000)	(0.000)	(0.000)
HH	-0.022**	-0.023**	-0.021**
	(0.009)	(0.009)	(0.009)
Winner advantage	0.002***	0.002***	0.002***
	(0.001)	(0.001)	(0.001)
Constant	0.302***	0.294***	0.353***
	(0.014)	(0.015)	(0.011)
Observations	28,066	28,066	28,066
R^2–adj	0.334	0.334	0.336
Year FE	YES	YES	YES

Table 8: Cash-to-Value Ratios and Industry Intensity of PMC

	SA index			WW index			Dividend dummy	
	NFC	Middle	FC	NFC	Middle	FC	NFC	FC
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Panel A: γ^{CIT}, Without control variables								
β_γ	-0.186***	-0.090	0.053	-0.152***	-0.067	0.031	-0.189***	0.169*
	(0.046)	(0.068)	(0.119)	(0.048)	(0.078)	(0.115)	(0.032)	(0.088)
Obs	8,841	11,216	8,214	8,173	10,988	9,111	18,116	10,156
R^2–adj	0.043	0.054	0.061	0.039	0.055	0.063	0.033	0.058
$\Delta\beta_\gamma$	Δ= -0.235* $\chi^2 = 3.292$			Δ=-0.183 $\chi^2 = 2.244$			Δ=-0.358*** $\chi^2 = 15.78$	
Panel B: γ^{CIT}, With control variables								
β_γ	-0.124***	-0.168***	-0.011	-0.193***	-0.101***	-0.032	-0.146***	0.059
	(0.028)	(0.032)	(0.038)	(0.032)	(0.023)	(0.045)	(0.031)	(0.038)
Obs	8,374	10,740	7,950	7,610	10,678	8,776	17,194	9,870
R^2–adj	0.259	0.349	0.359	0.276	0.341	0.345	0.351	0.328
$\Delta\beta_\gamma$	Δ=-0.113** $\chi^2 = 6.324$			Δ=-0.162*** $\chi^2 = 10.01$			Δ=-0.205*** $\chi^2 = 14.24$	
Panel C: γ^{PAT}, Without control variables								
β_γ	-0.108***	-0.026	0.043	-0.087***	-0.011	0.040	-0.110***	0.135***
	(0.026)	(0.042)	(0.074)	(0.028)	(0.048)	(0.072)	(0.021)	(0.048)
Obs	8,776	11,161	8,183	8,113	10,936	9,071	18,000	10,120
R^2–adj	0.036	0.052	0.062	0.034	0.054	0.065	0.029	0.061
$\Delta\beta_\gamma$	Δ=-0.151* $\chi^2 = 3.250$			Δ= -0.127* $\chi^2 = 2.804$			Δ=-0.245*** $\chi^2 = 22.24$	
Panel D: γ^{PAT}, With control variables								
β_γ	-0.080***	-0.112***	0.001	-0.124***	-0.070***	-0.002	-0.096***	0.047*
	(0.019)	(0.025)	(0.023)	(0.023)	(0.018)	(0.029)	(0.022)	(0.024)
Obs	8,374	10,742	7,953	7,610	10,680	8,779	17,197	9,872
R^2–adj	0.258	0.348	0.359	0.273	0.341	0.345	0.350	0.329
$\Delta\beta_\gamma$	Δ= -0.081*** $\chi^2 = 8.455$			Δ= -0.122*** $\chi^2 = 14.24$			Δ= -0.143*** $\chi^2 = 16.93$	

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Table 9: Cash-to-Value Ratios and Industry Innovation Efficiency

	SA index			WW index			Dividend dummy	
	NFC	Middle	FC	NFC	Middle	FC	NFC	FC
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Panel A: δ^{CIT}, Without control variables								
β_δ	0.045**	0.003	-0.023	0.043**	-0.001	-0.025	0.051***	-0.068*
	(0.019)	(0.017)	(0.031)	(0.019)	(0.019)	(0.030)	(0.016)	(0.038)
Obs	8,699	11,100	8,049	8,046	10,882	8,920	17,807	10,041
R^2–adj	0.028	0.053	0.063	0.028	0.055	0.065	0.024	0.058
$\Delta\beta_\delta$	Δ=0.068* $\chi^2 = 2.856$			Δ=0.067* $\chi^2 = 3.254$			Δ=0.118*** $\chi^2 = 7.166$	
Panel B: δ^{CIT}, With control variables								
β_δ	0.024**	0.031*	-0.013	0.041**	0.016	-0.011	0.030**	-0.034*
	(0.012)	(0.016)	(0.016)	(0.015)	(0.012)	(0.015)	(0.012)	(0.018)
Obs	8,315	10,668	7,844	7,558	10,614	8,655	17,025	9,802
R^2–adj	0.253	0.343	0.360	0.258	0.339	0.346	0.346	0.330
Δ β_δ	Δ=0.037* $\chi^2 = 2.847$			Δ= 0.052** $\chi^2 = 5.607$			Δ= 0.064*** $\chi^2 = 7.268$	
Panel C: δ^{PAT}, Without control variables								
β_δ	0.043*	-0.024	-0.029	0.035	-0.023	-0.029	0.028	-0.077*
	(0.023)	(0.020)	(0.040)	(0.027)	(0.019)	(0.041)	(0.020)	(0.045)
Obs	8,699	11,100	8,049	8,046	10,882	8,920	17,807	10,041
R^2–adj	0.026	0.053	0.063	0.025	0.055	0.065	0.020	0.057
$\Delta\beta_\delta$	Δ= 0.0717 $\chi^2 = 2.267$			Δ=0.0641 $\chi^2 = 1.719$			Δ= 0.105** $\chi^2 = 4.988$	
Panel D: δ^{PAT}, With control variables								
β_δ	0.026*	0.031*	-0.020	0.049**	0.017	-0.008	0.024*	-0.034
	(0.014)	(0.018)	(0.020)	(0.018)	(0.013)	(0.020)	(0.012)	(0.022)
Obs	8,315	10,668	7,844	7,558	10,614	8,655	17,025	9,802
R^2–adj	0.253	0.342	0.360	0.257	0.338	0.346	0.345	0.329
$\Delta\beta_\delta$	Δ=0.0459* $\chi^2 = 2.837$			Δ= 0.0570** $\chi^2 = 3.959$			Δ= 0.0585** $\chi^2 = 4.429$	

Figure 1: Timing of Events

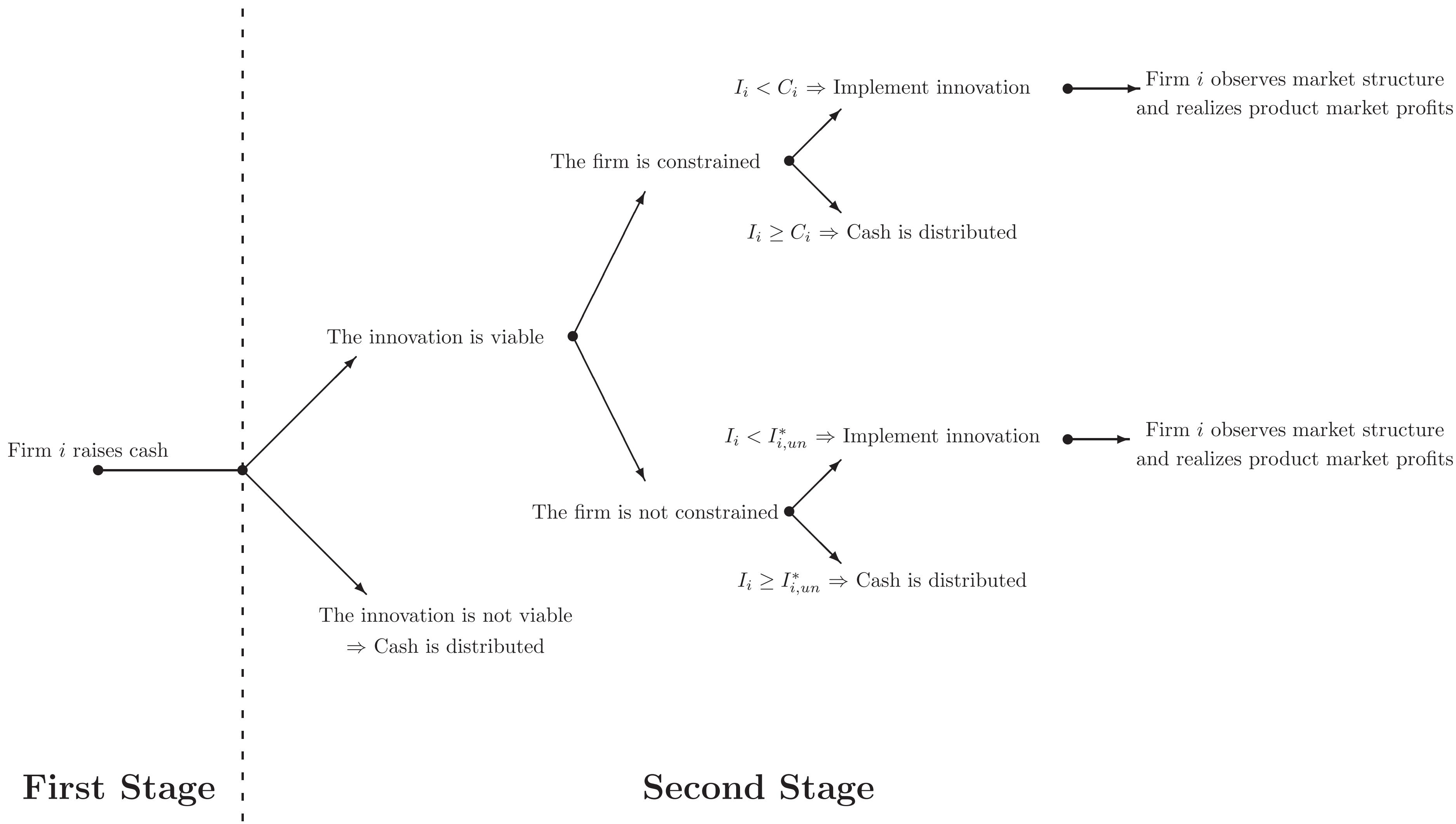
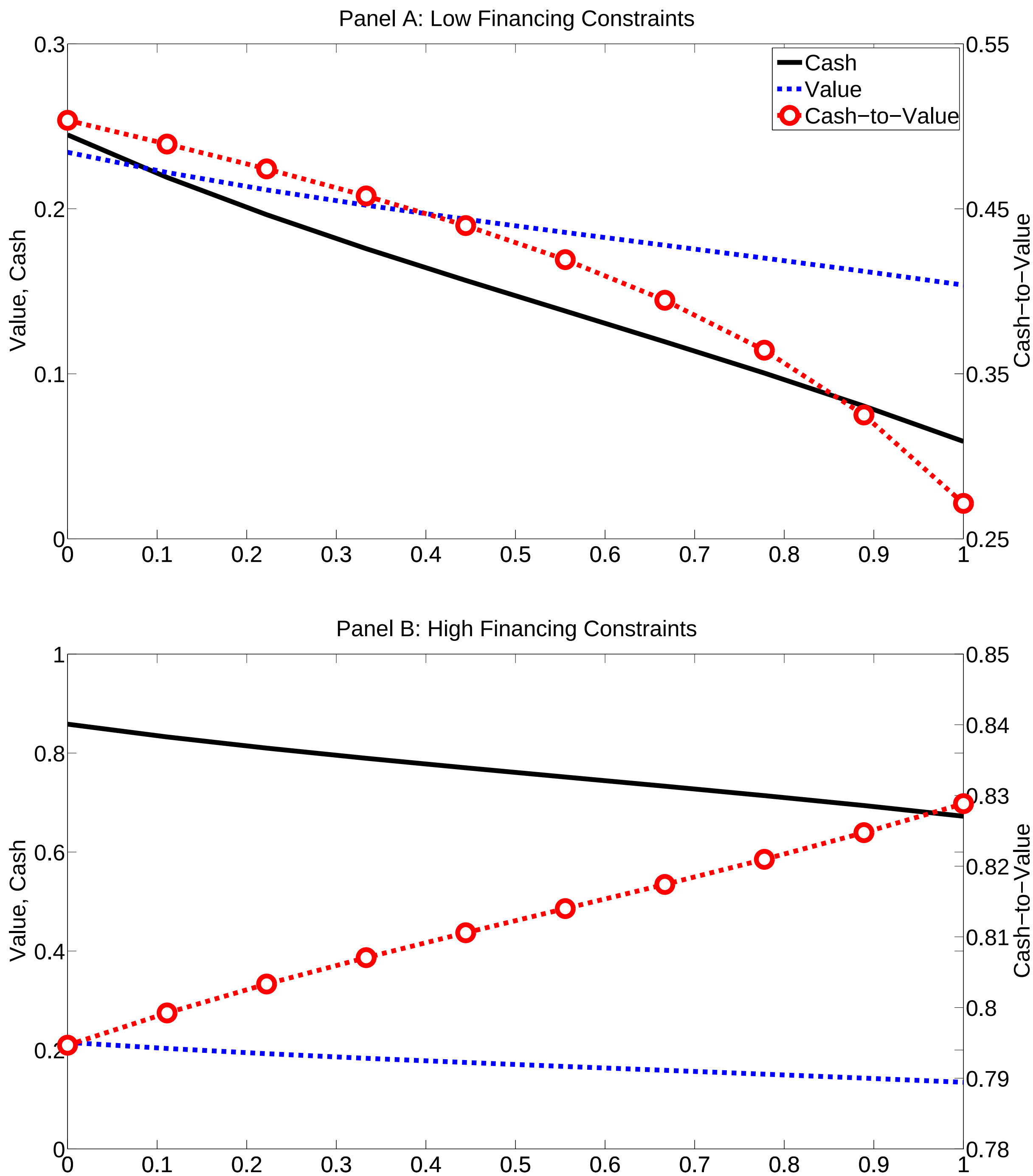
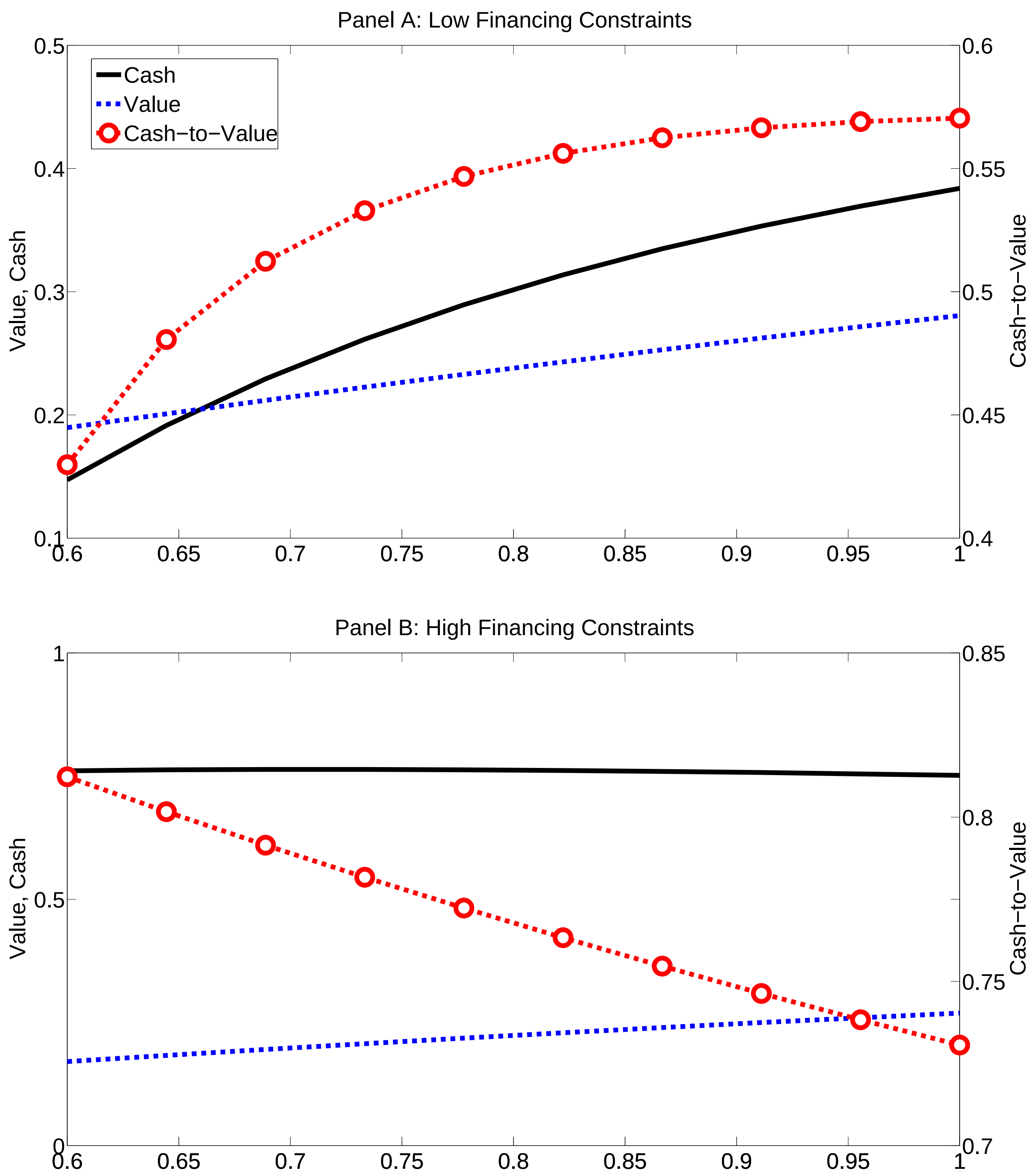


Figure 2: Competition Intensity, Firm Value, and Cash Holdings



The figure depicts the relation between equilibrium cash holdings, C_i^{EQ}/r and value, V_i^{EQ} (left y axis), and cash-to-value ratio, $\widetilde{C}_i^{EQ}$ (right y axis) and intensity of product market competition, γ (x axis). The solid line represents equilibrium cash holdings, the dashed line represents equilibrium firm value, and the dashed–dotted line represents equilibrium cash-to-value ratio. The parameters we use are: $r = 1.03$, $R = 1.10$, $\alpha_j = 0.4$, $\delta = 0.6$. We vary γ between 0 and 0.9. Panel A presents the case of low financial constraints, $\alpha_i = 0.15$, while Panel B depicts the case of high financial constraints, $\alpha_i = 0.8$.

Figure 3: Innovation Efficiency, Firm Value, and Cash Holdings



The figure depicts the relation between equilibrium cash holdings, C_i^{EQ}/r and value, V_i^{EQ} (left y axis), and cash-to-value ratio, $\widetilde{C}_i^{EQ}$ (right y axis) and innovation efficiency, δ (x axis). The solid line represents equilibrium cash holdings, the dashed line represents equilibrium firm value, and the dashed–dotted line represents equilibrium cash-to-value ratio. The parameters we use are: $r = 1.03$, $R = 1.10$, $\alpha_j = 0.4$, $\gamma = 0.5$. We vary δ between 0.6 and 1. Panel A presents the case of low financial constraints, $\alpha_i = 0.15$, while Panel B depicts the case of high financial constraints, $\alpha_i = 0.8$.

Figure 4: Timing of Events – Alternative Model

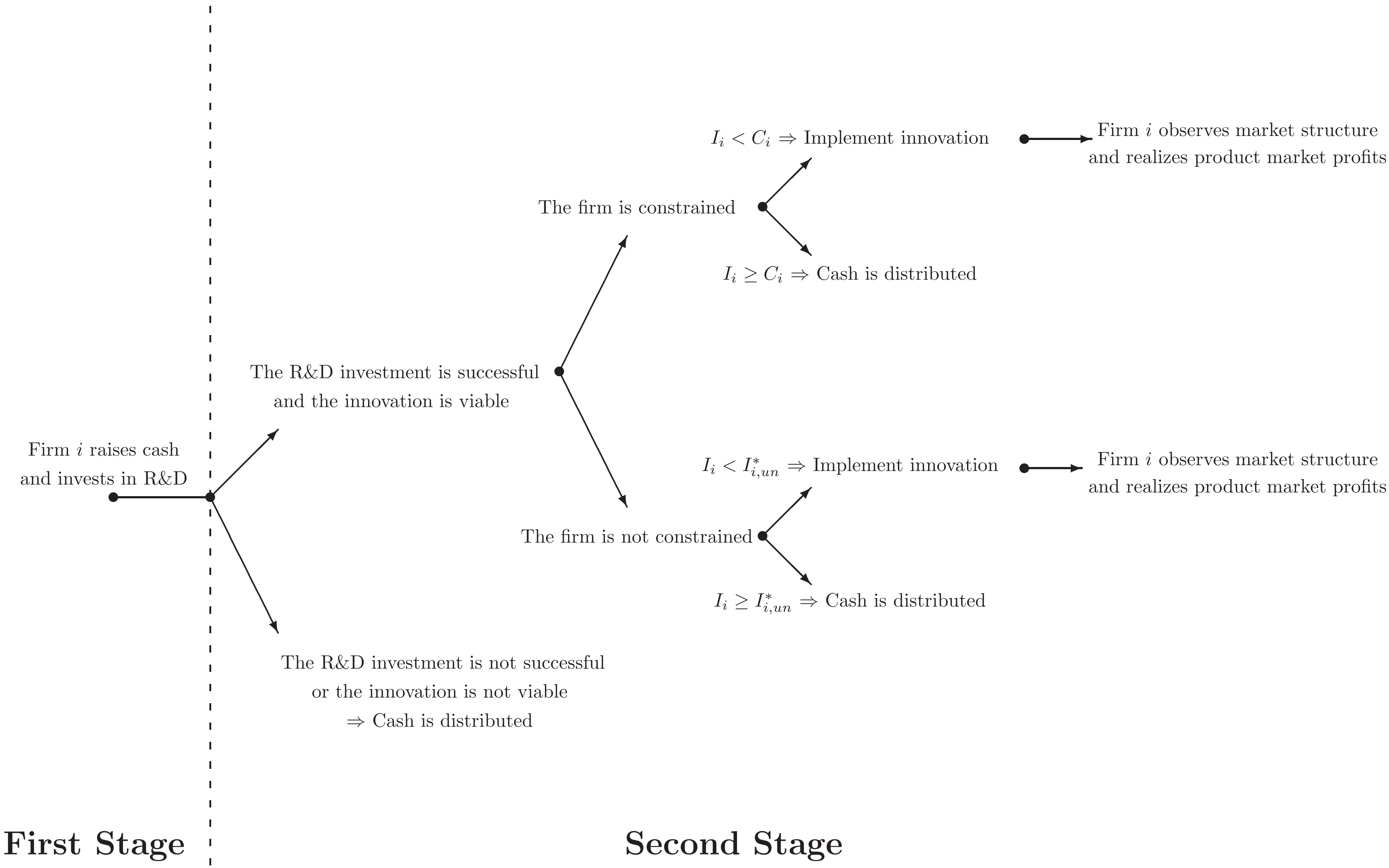
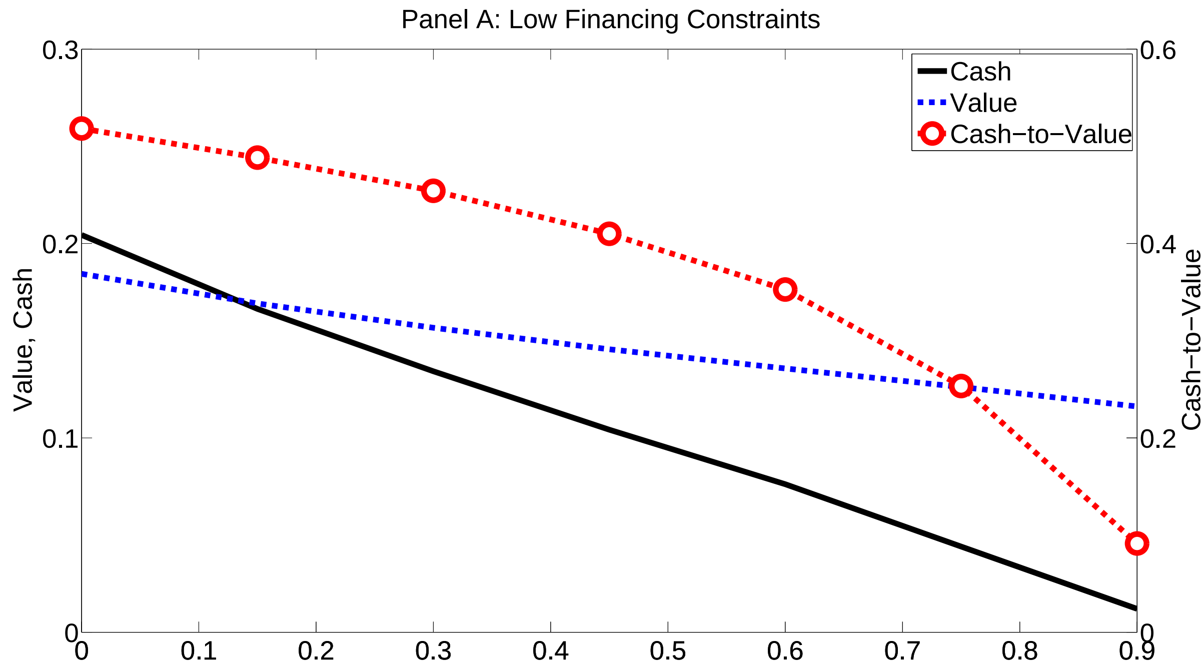
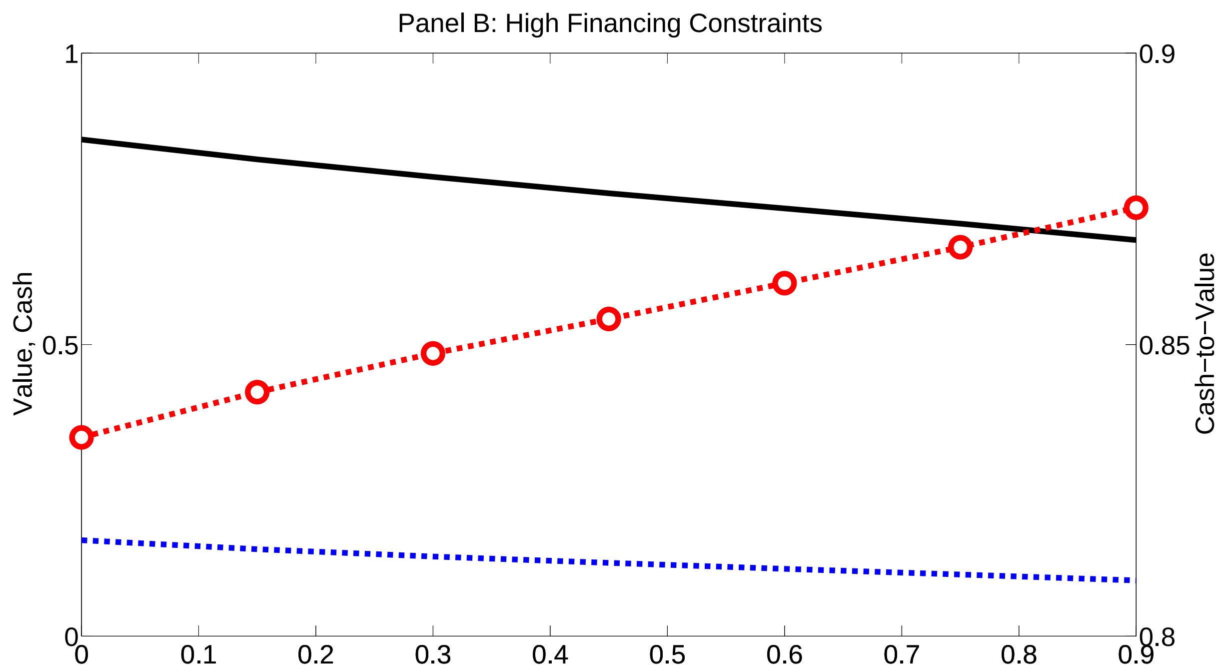


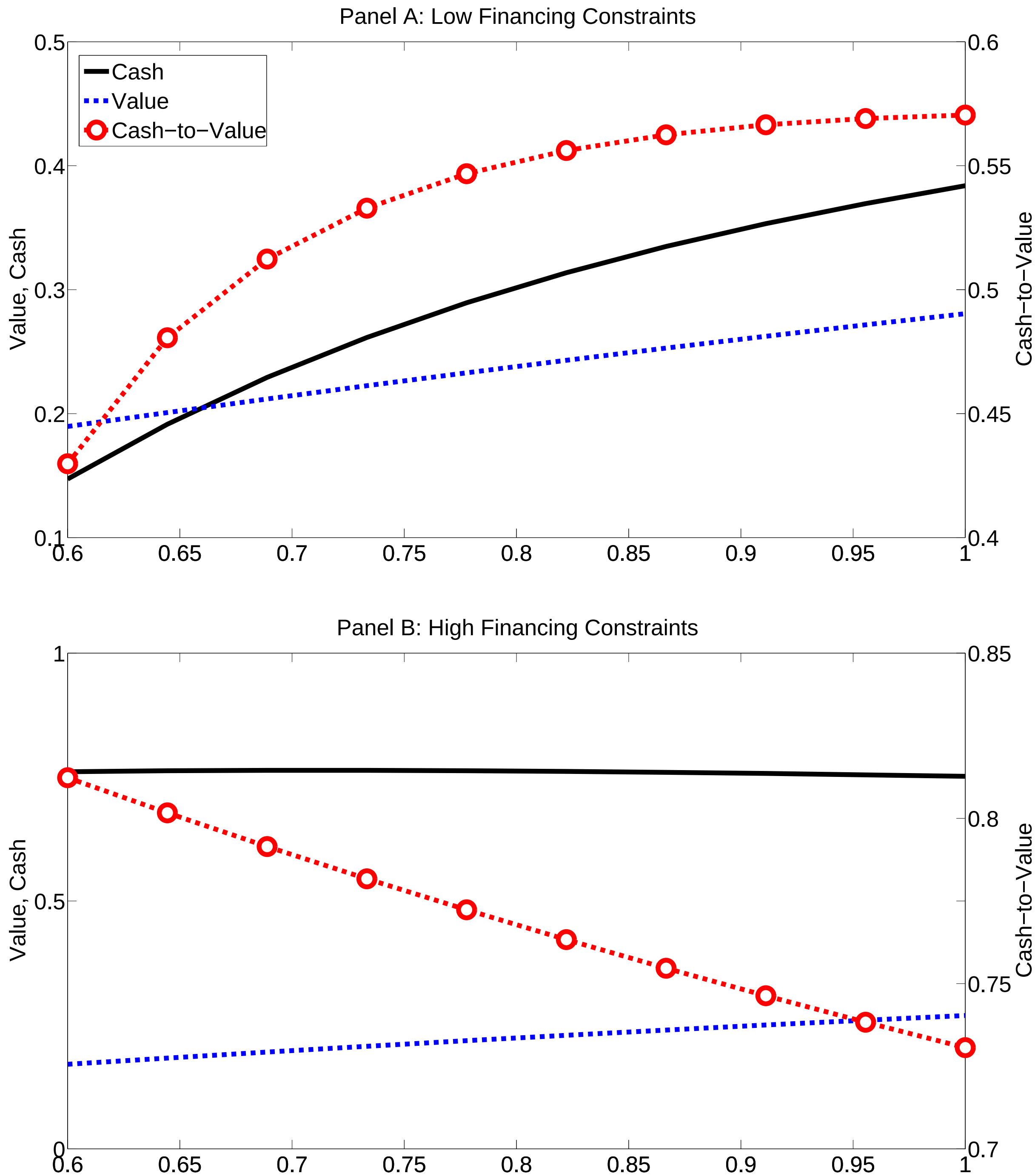
Figure 5: Competition Intensity, Firm Value, and Cash Holdings – Alternative Model





The figure depicts the relation between equilibrium cash holdings, C_i^{EQ}/r and value, V_i^{EQ} (left y axis), and cash-to-value ratio, $\widetilde{C}_i^{EQ}$ (right y axis) and intensity of product market competition, γ (x axis). The solid line represents equilibrium cash holdings, the dashed line represents equilibrium firm value, and the dashed–dotted line represents equilibrium cash-to-value ratio. The parameters we use are: $r = 1.03$, $R = 1.10$, $\alpha_j = 0.4$, $\delta = 0.6$. We vary γ between 0 and 0.9. Panel A presents the case of low financial constraints, $\alpha_i = 0.15$, while Panel B depicts the case of high financial constraints, $\alpha_i = 0.8$.

Figure 6: Innovation Efficiency, Firm Value, and Cash Holdings – Alternative Model



The figure depicts the relation between equilibrium cash holdings, C_i^{EQ}/r and value, V_i^{EQ} (left y axis), and cash-to-value ratio, $\widetilde{C}_i^{EQ}$ (right y axis) and innovation efficiency, δ (x axis). The solid line represents equilibrium cash holdings, the dashed line represents equilibrium firm value, and the dashed–dotted line represents equilibrium cash-to-value ratio. The parameters we use are: $r = 1.03$, $R = 1.10$, $\alpha_j = 0.4$, $\gamma = 0.5$. We vary δ between 0.6 and 1. Panel A presents the case of low financial constraints, $\alpha_i = 0.15$, while Panel B depicts the case of high financial constraints, $\alpha_i = 0.8$.

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