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Dynamic investment in new technology and risk management

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Abstract

In this paper, we incorporate new technology investment into a dynamic Q-theoretic framework where firms face financing constraints, and examine the interactions among investments in new technology and capital, and risk management, including cash management and financial hedging. Our model provides several important results. First, we find that financing constraints reduce investment in new technology. Second, firms with new technology adoption postpone payouts, scale up external financing, increase investment in capital and strengthen incentives for financial hedging relative to the scenario without new technology adoption. Additionally, the impact of new technology adoption on asset sales depends on whether costly refinancing is available. Finally, investment in new technology decreases with risk when cash reserves are abundant, and the relation between investment in new technology and risk depends on whether costly refinancing is available when running out of cash. In addition, we also find that financial hedging increases investment in new technology.

Keywords New technology · Investment · Payout policy · Financial hedging

JEL classification G12 · G31 · G35 · O33

1 Introduction

The contemporary global economy and societal structures are poised at a pivotal intersection of digital transformation, precipitated by the swift evolution of digital technologies (see, e.g., Goldfarb and Tucker (2019), Menz et al. (2021), and Danielsson et al. (2022)).

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Digital technology has emerged as a central component propelling corporate growth, and its influence on firms' investment and financing decisions has garnered substantial scholarly interest. As indicated in the "2023 Global Digital Economy White Paper" published by the China Academy of Information and Communications Technology, the combined value of the digital economies of the five primary nations has reached 31 trillion dollars, accounting for 58% of the GDP.[1] Firms are facing the challenge of digital transformation, which involves handling complex and closely intertwined decisions regarding investment in digital technology and capital, financing, and risk management.

Recently, a number of empirical studies have investigated the impact of digital transformation on corporate/bank strategic policies. Bollaert et al. (2021) survey research on the influences of digitalization on access to finance. Tian et al. (2022) highlight a marked positive association between digital transformation and corporate risk-taking behavior. Wen et al. (2022) demonstrate how digital transformation fosters corporate innovation. Ding et al. (2022) examine the effect of fintech development on corporate innovation. Chen and Srinivasan (2024) scrutinize the implications of increasing digital technology engagement by non-technology firms on firm value and performance. Silva et al. (2023) investigate how COVID-19 and digitalization have changed bank lending behavior. However, to our knowledge, current literature falls short of constructing a quantitative model that explicates the influence of new technology adoption, such as digital transformation, on corporate investment and financing decisions. Our model endeavors to bridge this research gap and strives to address the intertwined questions: How do firms' new technology investment strategies intersect with capital investment, financing, and risk management? And how do factors such as firms' cash reserves and volatility shape their new technology investment strategies?

In this paper, we incorporate firms' new technology adoption into the dynamic financial decisions framework presented by Bolton et al. (2011) to examine the implications of new technology on the dynamic investment in capital, financing, payout, and financial hedging policies for financially constrained firms. Building on the works of Bharadwaj et al. (2013), Brynjolfsson et al. (2019), and Wu et al. (2019), new technology adoption enhances firms' productivity. We refer to this as the positive effect of new technology adoption. However, new technology adoption incurs costs (see Karhade and Dong (2021)). As a result, the new technology investment is determined endogenously.

Our model provides several important results. First, it delineates the trade-off involved in opting for new technology investment. The model exhibits the typical trade-off: an incremental unit of new technology investment enhances the marginal Q by boosting the growth rate of cash reserves, but at a cost. Furthermore, an additional unit of new technology investment induces an additional cost by intensifying the motive for precautionary savings. This effect is borne from the concavity of the firm value due to effective risk aversion and the realization that investment in new technology increases the volatility of cash reserves.

Second, financing constraints lead firms to underinvest in capital and new technology. Intuitively, financing constraints result in the convexity of firm value, which implies that the firm becomes endogenously risk-averse. Thus, a financially constrained firm has a precautionary savings motive, which consequently results in diminished capital investment. Additionally, new technology adoption increases the volatility of cash reserves, thereby

[1] The data comes from The Global Digital Economy Conference held at the China National Convention Center in Beijing, China from July 4th to July 7th, 2023. Please see https://www.cnii.com.cn/rmydb/202307/t20230710_485462.html.

amplifying the precautionary savings effect and resulting in diminished investment in new technology.

Third, new technology adoption enhances the firm's value, attributable to the increased growth rate of productivity shocks. Furthermore, we demonstrate that the impact of digital technology adoption on the marginal value of cash is contingent on the availability of costly refinancing when running out of cash. Concretely, when a firm is running out of cash, new technology adoption increases the marginal value of cash for liquidation case. In contrast, new technology adoption decreases the marginal value of cash for refinancing case. Intuitively, for liquidation case, more cash keeps the firm away from costly liquidation, which permanently destroys the firm's future growth opportunities. New technology adoption enhances the firm's productivity, elevating the importance of cash reserves. In contrast, in the case of refinancing, new technology adoption boosts productivity and reduces the chance of costly external equity financing.

Fourth, our analysis provides insight into the implications of new technology adoption. We find that new technology adoption leads firms to delay payouts. The reason is that the cost effect and precautionary savings effect of new technology adoption lead firms to hoard more cash to avoid liquidation or costly external refinancing. We also discover that new technology adoption leads firms to raise more equity. Intuitively, new technology adoption incurs costs and increases a firm's risk, which results in a higher likelihood of costly external refinancing. Thus, a firm with new technology adoption raises more funds to keep cash reserves away from zero. In addition, new technology adoption increases capital investment due to the positive effect of new technology adoption. Furthermore, when a firm is running out of cash, the effect of new technology adoption on asset sale or disinvestment is contingent upon whether the firm has the option of costly refinancing. Specifically, in a liquidation scenario, new technology adoption strengthens disinvestment in capital since the firm sells assets to replenish its stock of cash and cover the cost of new technology adoption. In contrast, in a refinancing scenario, new technology adoption weakens disinvestment in capital. This is because, in such a case, new technology adoption enhances productivity and reduces the probability of external financing. We also find that new technology adoption stimulates a firm's motivation for financial hedging.

Lastly, we show that investment in new technology increases with cash reserves due to the precautionary savings effect of new technology. Additionally, for the firm with substantial cash reserves, investment in new technology inversely correlates with the volatility of cash reserves because an increase in volatility strengthens precautionary savings motive. Conversely, when the firm is running out of cash, for refinancing case, investment in new technology increases with the volatility of cash reserves. Because of the refinancing option, the firm with higher volatility is less likely to seek external equity financing. Furthermore, we discover that financial hedging amplifies investment in new technology. Intuitively, financial hedging reduces volatility of cash reserves, thereby mitigating the precautionary savings motive.

Our paper is related to the literature that extends the dynamic corporate finance models of Bolton et al. (2011). Wang et al. (2012) extend Bolton et al. (2011) with incomplete-markets to explore entrepreneurship dynamics. Bolton et al. (2013) incorporate market timing into the framework of Bolton et al. (2011) to highlight the implications of market-timing motive for external financing and payout policies. Bolton et al. (2019) develop a novel theory of corporate liquidity and risk management with the inalienability of risky human capital. Based on the study of Bolton et al. (2019), Dou et al. (2021) introduce customer capital into the model and highlight the importance of its inalienability. Dou and Ji (2021) extend Bolton et al. (2011) taking into consideration endogenous markups and product market competition. Lee and Rivera (2021) and Luo and Tian (2022) incorporate robustness into the model of Bolton et al. (2011) and emphasize the implications for ambiguity aversion. In these models, the investment affects firm's financial polices via capital and the productivity is given exogenously. In our model, we introduce new technology adoption, thereby affecting the productivity shock. Our paper also relates to the literature that researches firms' capital management strategies. For example, Panetsidou and Synapis (2024) examine firms' dividend payout and investment decisions during the pandemic. Das et al. (2024) analyze the joint effects of economic policy uncertainty and inflation risk on the corporate cash holdings of US firms from 2011 to 2021. Gounopoulos and Zhang (2024) investigate the causal effect of climate uncertainty on firms' cash holdings using local temperature trends. Dai et al. (2024) propose a tractable model of dynamic investment, spinoffs, financing, and risk management for a multidivision firm facing costly external finance. Thus, our paper considers the interaction among investment in capital and new technology, financing, payout policies, and risk management. Further, our model provides some implications about new technology adoption, which are consistent with the empirical findings and provide some novel empirical predictions about digital technology.

The structure of the article is as follows: Sect. 2 lays out the model setup. Section 3 presents the model solutions and the benchmark case without financing frictions. Section 4 investigates the quantitative results. Section 5 extends the model to allow firms to hedge. Section 6 provides the empirical implications and model discussions. Section 7 concludes. All proofs are in the Appendix.

2 Model setup

In this model, time is continuous and all agents are risk neutral and discount future cash flows at the constant market interest rate r. The firm produces output from capital. The price of capital is normalized to unity. Following Bolton et al. (2011) and Wang et al. (2012), the firm's capital stock, denoted by K_t, evolves as

$$dK_t = \left(I_t - \delta K_t\right)dt, \quad \mathrm{t} \geq 0, \tag{1}$$

where I_t represents the gross capital investment, which is determined endogenously, and $\delta \geq 0$ denotes the rate of depreciation.

In our model, a firm can implement technology transformation and invest in new technology (such as digital technology) to enhance productivity (Bharadwaj et al. 2013; Brynjolfsson et al. 2019; Wu et al. 2019). Let dA_t denote the firm's productivity over time increment dt before new technology transformation (or new technology adoption). When a firm adopts new technology, its productivity dA_t improves to $(1 + s_t)dA_t$, where $s_t \geq 0$ represents the investment in new technology and is determined endogenously. Following Bolton et al. (2011) and Wang et al. (2012), the firm's cumulative productivity, dA_t, evolves according to

$$dA_t = \mu dt + \sigma dZ_t, \tag{2}$$

where $\left\{Z_t\right\}_{t\geq 0}$ is a standard Brownian motion, the parameters $\mu > 0$ and $\sigma > 0$ are the mean and volatility of the productivity, respectively.

The firm's incremental operating profit dY_t over time increment dt is given by

$$dY_t = K_t(1+s_t)dA_t - I_t dt - G(I_t, K_t)dt - f(s_t)K_t dt, \tag{3}$$

where $K_t(1+s_t)dA_t$ is the firm's operation revenue. $G(I_t, K_t)$ is the adjustment cost that the firm triggers in the capital investment process, and $f(s_t)K_t$ denotes the new technology investment cost. Following Bolton et al. (2011) and Wang et al. (2012), we assume that the adjustment cost takes the form $G(I, K) = g(i)K$, where $i = I/K$ is the firm's investment capital ratio and $g(i)$ is a quadratic form, i.e., $g(i) = \theta i^2/2$, where θ measures the degree of the adjustment cost. Besides, $f(s)$ is increasing and convex in s, and we further assume that $f(s)$ is quadratic, i.e., $f(s) = \psi s^2/2$, where ψ denotes the marginal cost in the new technology investment process.[2]

The firm's cash reserves W evolve according to the following cash accumulation equation:

$$dW_t = dY_t + (r-\lambda)W_t dt + dH_t - dU_t. \tag{4}$$

There are four terms on the right-hand side. The first term from dY_t is the operation revenue. We further obtain $dY_t = [(1+s)\mu - i - \frac{\theta i^2}{2} - \frac{\psi s^2}{2}]K_t dt + (1+s)\sigma K_t dZ_t$. The dt term implies that new technology adoption increases the growth rate and incurs the cost. The dZ_t term shows new technology adoption causes higher uncertainty of cash reserves.[3] The second term $(r-\lambda)W_t\mathrm{d}t$ represents the cash savings from inventory, where the parameter $\lambda > 0$ characterizes carry cost. The third term, dH_t, refers to the cash inflow from external financing, and the fourth term, dU_t, signifies the cash outflow to investors. Accordingly, the difference between these latter two terms, $(dH_t - dU_t)$, constitutes the net cash flow generated from financing activities. Furthermore, let X_t denote the cumulative costs of external financing up to time t, with dX_t representing the incremental costs associated with raising additional external funds, dH_t. Lastly, we assume that the firm can liquidate its assets at any time. The liquidation value L_t is proportional to the firm's capital, $L_t = lK_t$, where l is given exogenously.

The firm's optimization problem is to choose its capital investment I, new technology investment s, payout policy U, external financing policy H, and liquidation time τ to maximize shareholder value:

$$\max_{I,s,U,H,\tau} \mathbb{E}^{\mathbb{P}}\left[\int_0^{\tau} e^{-rt}\left(\mathrm{d}U_t - \mathrm{d}H_t - \mathrm{d}X_t\right) + e^{-r\tau}\left(lK_\tau + W_\tau\right)\right], \tag{5}$$

subject to Eqs. (1) and (4). The first term of Eq. (5) represents the present value of the flow of net dividends to shareholders. The second term represents the present value of the cash flow to shareholders once liquidation. In our model, we have $\tau = \infty$ when the firm never liquidates.

[2] The functional form of quadratic cost implies increasing marginal costs (with $f'(s) > 0$ and $f''(s) > 0$). The assumption is is widely used in the literature (see, e.g., He (2011), Gryglewicz et al. (2020), Hackbarth et al. (2022)).

[3] In this paper, we use digital technology as an example of new technology. Numerous empirical studies have underscored the positive implications of digital transformation on firm behavior, with notable examples including (Brynjolfsson et al. 2019), Wu et al. (2019) and Goldfarb and Tucker (2019). Conversely, a subset of the literature has illuminated potential negative impacts of the same process, as evidenced by works such as Dremel et al. (2017), Yeow et al. (2018), Karhade and Dong (2021), and Danielsson et al. (2022). Thus, it implies the inherent uncertainty associated with digital transformation's effect on a firm's cash reserves.

3 Model solution

Following Bolton et al. (2011), the model solutions are considered in the following three regions: (i) an external financing/liquidation region, (ii) an internal financing region, and (iii) a payout region. Concretely, when cash reserves $W \geq \overline{W}$, where $\overline{W}$ denotes payout threshold and is determined endogenously, and we refer to this as the payout region. When cash reserves $W \leq \underline{W}$, where $\underline{W}$ is an endogenous lower threshold, and we refer to this as the external financing/liquidation region. Last, the firm is in the internal financing region when cash reserves W are in between $\underline{W}$ and $\overline{W}$. Besides, the firm value is denoted by $P(K, W)$.

Internal financing region In this region, the firm's value, $P(K, W)$, satisfies the following Hamilton-Jacobi-Bellman(HJB) equation:

$$\begin{aligned} rP(K,W) = \max_{i,s\geq 0}(i-\delta)KP_K + [(r-\lambda)W + \mu(1+s)K - iK - g(i)K - f(s)K]P_W \\ + \frac{1}{2}(1+s)^2\sigma^2K^2P_{WW}. \end{aligned} \tag{6}$$

The left-side of Eq. (6) represents the return required by shareholders. The right-hand side of Eq. (6) represents the expected change in firm value in the internal financing region. The first term describes the marginal increase of firm value if capital increases by a unit. The second term captures the marginal increase of firm value from cash reserves. The last term reflects the effect of volatility in cash reserves.

Following Bolton et al. (2011), the scale invariance of the firm allows us to write firm value as:

$$P(K, W) = p(w)K, \tag{7}$$

where $w = W/K$ denotes the firm's cash-capital ratio. Subsequently, this formulation allows us to simplify the problem by reducing it to a single state variable, w. We then proceed to compute the firm's value-capital ratio, denoted as $p(w)$. Further, we obtain that marginal q is $P_K = p(w) - wp'(w)$, the marginal value of cash is $P_W = p'(w)$, and $P_{WW} = p''(w)/K$. Substituting these terms into Eq. (6), we obtain the following equation for $p(w)$:

$$\begin{aligned} rp(w) = \max_{i,s\geq 0}(i-\delta)(p(w) - wp'(w)) + ((r-\lambda)w + \mu(1+s) - i - g(i) - f(s))p'(w) \\ + \frac{1}{2}(1+s)^2\sigma^2 p''(w). \end{aligned} \tag{8}$$

By the first-order conditions with respect to capital investment i and new technology investment s, respectively, we have the following equations:

$$p(w) - wp'(w) = p'(w) + \theta ip'(w), \tag{9}$$

and

$$\mu p'(w) = \psi sp'(w) - (1+s)\sigma^2 p''(w). \tag{10}$$

Equations (9) and (10) provide intuitive insight into the firm's capital investment and new technology investment strategies, respectively. Equation (9) outlines the decision-making process for capital investment. The model presents a trade-off: an additional unit of capital investment augments the marginal q (valued at $p(w) - wp'(w)$), but this also incurs an adjustment cost (valued at $\theta i p'(w)$). Additionally, an increase in capital investment leads to a decrease in firm value by reducing cash reserves (valued at $p'(w)$).

Equation (10) captures the trade-offs associated with the choice of new technology investment. The benefits associated with an incremental unit of investment in new technology arise from increased growth rate of cash reserves (valued at $\mu p'(w)$). Increasing in new technology results in the new technology transformation cost (valued at $\psi s p'(w)$). In addition, an additional unit of investment in new technology incurs an extra cost by increasing precautionary savings motive (valued at $-(1+s)\sigma^2 p''(w)$). This precautionary savings effect comes from: (i) The concavity of the firm value due to effective risk aversion ($-p''(w) > 0$, which is proved in Appendix A), and (ii) The fact that new technology investment increases the volatility of cash reserves (see Eq. (4)).

Payout region A firm will distribute excess cash to its shareholders to avoid cash-carrying costs once the cash reserves surpass a specified threshold. The payout threshold is denoted by $\overline{w}$. We have the following equation for $p(w)$ for $w > \overline{w}$:

$$p(w) = p(\overline{w}) + (w - \overline{w}), \tag{11}$$

and the endogenous payout boundary $\overline{w}$ satisfies that

$$p'(\overline{w}) = 1. \tag{12}$$

Besides, we have the following super-contact condition:

$$p''(\overline{w}) = 0. \tag{13}$$

External financing/Liqudation region Let $\underline{w}$ denote the external funding/liquidation boundary. In situations where expected productivity μ is low and/or the cost of financing is high, firms may opt for liquidation over refinancing. In this context, given that the optimal liquidation boundary is $\underline{w} = 0$, the value of the firm upon liquidation is $p(0)K = lK$. Therefore, we have:

$$p(0) = l. \tag{14}$$

Conversely, when expected productivity μ is high and/or the cost of financing is low, the firm is likely to prefer refinancing over liquidation when it depletes its cash reserves. Let ϕ denote the fixed cost of external funding. We propose that the total equity issue amount is mK, where $m > 0$ is endogenously determined by the following value matching condition at the threshold $\underline{w} = 0$:

$$p(0) = p(m) - \phi - (1+\gamma)m, \tag{15}$$

where γ denotes the marginal cost of funding, and the optimal equity issue amount satisfies the smooth-pasting condition:

$$p'(m) = 1 + \gamma. \tag{16}$$

This implies that the marginal value of the last dollar raised must equate to the sum of the dollar itself and the marginal cost associated with external financing.

Proposition 3.1 *The function* $p(w)$ *is strictly concave on* $[0, \overline{w})$.

Proof See Appendix C. □

Intuitively, after negative shocks drive cash reserves, w, down to zero, the firm faces the necessity of inefficient liquidation or costly external financing, which stems from financial constraints. Consequently, the firm becomes risk-averse concerning the volatility of its cash reserves, leading to a strictly concave firm value within the internal region.

First-best capital investment and new technology investment policies We regard the scenario without financing frictions as the first-best outcome. Under the first-best case, the first-best firm value, $p^{FB}(K)$, reads

$$p^{FB}(K) = \max_{i,s} \frac{[\mu(1+s) - i - g(i) - f(s)]K}{r + \delta - i} \equiv q^{FB}K, \tag{17}$$

where q^{FB} denotes the Tobin's q in the absence of financing constraints. Through algebraic derivations, we derive the following result:

Proposition 3.2 *The first-best capital investment and new technology investment are given as follows*:

$$i^{FB} = r + \delta - \sqrt{(r+\delta)^2 - 2(\mu(1+\frac{\mu}{2\psi}) - (r+\delta))/\theta}, \tag{18}$$

and

$$s^{FB} = \frac{\mu}{\psi}, \tag{19}$$

respectively.

Proposition 3.2 provides several implications. First, both capital investment and new technology investment increase with growth rate of productivity, μ, and decrease with the marginal cost, ψ. Second, when $s = 0$, it implies that the firm does not implement new technology transformation. To highlight the implication of new technology adoption on capital investment, the capital investment under new technology adoption is given by $i^{FB} = r + \delta - \sqrt{(r+\delta)^2 - 2(\mu(1+\frac{\mu}{2\psi}) - (r+\delta))/\theta}$ and the capital investment under absent new technology adoption is given by $i^{FB}(s=0) = r + \delta - \sqrt{(r+\delta)^2 - 2(\mu - (r+\delta))/\theta}$, and then we further simply show $i^{FB} > i^{FB}(s=0)$. It implies that new technology adoption leads to overinvestment relative to the case without such adoption. This is intuitive as new technology adoption enhances productivity growth rate. Finally, under the first-best case, new technology investment is not subject to the volatility of cash reserves. In the absence of financing constraints, the firm value's concavity, i.e., $p''(K) = 0$, disappears, thereby eliminating the precautionary savings effect.

Implication of financing constraints We now examine the implications of financing constraints for capital and new technology investment policies. We first derive the optimal capital investment by the first-order condition in Eq. (9) and provide the following result:

Proposition 3.3 (i) *Optimal capital investment is given by*

$$i(w) = \frac{\overbrace{p(w) - wp'(w)}^{\text{Benefit of investment in capital}} \quad \overbrace{-p'(w)}^{\text{Reducing firm value}}}{\underbrace{\theta p'(w)}_{\text{Cost of investment in capital}}}. \tag{20}$$

(*ii*) *$i(w)$ increases in w.*

(*iii*) *Capital investment is strictly lower than under first-best case, i.e., $i(w) < i^{FB}$.*

Proof See Appendix B. □

Proposition 3.3 provides several insights as follows: First, Eq. (20) characterizes the implications for capital investment. This investment decision hinges on balancing the benefits and adjustment costs of capital investment with the potential reduction in firm value. Second, an enhancement in cash reserves decreases the likelihood of liquidation or costly external financing, thereby incentivizing capital investment. Finally, financing constraints result in underinvestment for capital investment. This outcome is driven by the firm's risk aversion induced by financing constraints. In other words, financing constraints introduce a convexity in firm value, rendering the firm endogenously risk-averse. Consequently, a financially constrained firm exhibits a precautionary savings behavior and invests less in capital.

Subsequently, we ascertain the optimal new technology investment through the application of the first-order condition in Eq. (10), resulting in the following conclusion:

Proposition 3.4 (i) *The optimal new technology investment is given by*

$$s(w) = \frac{\overbrace{\mu p'(w)}^{\text{Benefit of investment in new technology}} \quad - \quad \overbrace{(-\sigma^2 p''(w)))}^{\text{Precautionary savings effect}}}{\underbrace{\psi p'(w)}_{\text{Cost of investment in new technology}} \quad \underbrace{-\sigma^2 p''(w)}_{\text{Precautionary savings effect}}}. \tag{21}$$

(*ii*) *New technology investment is strictly lower than under first-best case except at the payout threshold in that $s(w) < s^{FB}$ for $w < \overline{w}$ and $s(\overline{w}) = s^{FB}$.*

Proof See Appendix C. □

Proposition 3.4 provides the following implications: First, Eq. (21) captures the implications for capital investment. This investment decision involves balancing the potential benefits of new technology investment, the corresponding adjustment costs, and the precautionary savings effects brought about by new technology adoption. Second, financing constraints also lead to underinvestment for new technology. Intuitively, financing constraints lead firm to become risk-averse. Moreover, new technology adoption increases the volatility of cash reserves and amplifies the precautionary savings effect, thereby resulting in reduced investment in new technology.

4 Model implications

In this section, we explore the influences of new technology adoption on firm's dynamic investment and risk management. To highlight the implications for new technology adoption, we refer to the scenario without new technology adoption as the benchmark. Following Bolton et al. (2011), the risk-free rate is $r = 6\%$, the rate of depreciation is $\delta = 10.07\%$, the investment adjustment cost is $\theta = 1.5$, the cash-carrying cost is $\lambda = 1\%$. The mean of productivity shock is $\mu = 0.17$, the volatility of productivity shock is $\sigma = 9\%$ and the liquidation value $l = 0.9$. The proportional financing cost is $\gamma = 6\%$ and the fixed cost of financing is $\phi = 1\%$. Finally, we set the marginal cost of new technology investment $\psi = 1.5$.[4]

4.1 The impact of new technology

Panel A and A$'$ of Fig. 1 illustrate that the firm with new technology adoption possesses higher value due to the productivity enhancements attributable to new technology. Additionally, Panel A and A$'$ depict the firm with new technology adoption exhibit a tendency to delay payouts. Intuitively, this behavior can be interpreted as a strategic response to the cost implications and precautionary savings effect of new technology investments, leading firm to hoard more cash to mitigate the risks of liquidation or costly external refinancing. Furthermore, Panel A$'$ suggests that the firm with new technology adoption raises more equity. Intuitively, the need for increased fund raising can be inferred as a response to the associated costs and risks of new technology investments, which amplify the likelihood of costly external refinancing. Therefore, in an attempt to maintain cash reserves above zero, a firm with new technology adoption appears to raise more funds.

Panel B and B$'$ of Fig. 1 depict the marginal value of cash $p'(w)$ with respect to the cash reserves w. Panel B reveals that new technology adoption increases the marginal value of cash $p'(w)$ as w approaches zero. This is intuitively coherent with the assertion of Bolton et al. (2011), emphasizing that maintaining higher cash reserves keeps the firm insulated from costly liquidation, which could potentially destroy future growth prospects. The value and significance of cash are amplified by the productivity enhancements resulting from new technology adoption. In contrast, Panel B$'$ shows that new technology adoption reduces the marginal value of cash as w approaches zero. This is because in refinancing case, new technology adoption enhances productivity and reduces the chance of costly external equity financing. However, Panel B$'$ also shows that new technology adoption increases marginal value of cash when cash reserves are far from zero. This trend can be intuitively linked to the costs and risks associated with new technology investment, which augment the probability of incurring costly external financing.

Panels C and C$'$ of Fig. 1 show that new technology adoption stimulates investment in capital when cash reserves are far away from zero, as new technology improves productivity. When cash reserves are close to zero, Panel C shows that new technology adoption strengthens disinvestment in capital. Intuitively, firm is forced to liquidate assets in order to replenish its cash reserves and covers the costs associated with new technology adoption. In contrast, Panel C$'$ reveals that new technology adoption weakens the disinvestment in capital. This may occur because, in the refinancing scenario, the productivity improvements brought on by new technology adoption diminish the likelihood of requiring expensive external financing.

[4] For simplicity, we set ψ equal to θ. Our results remain robust to variations in the value of ψ.

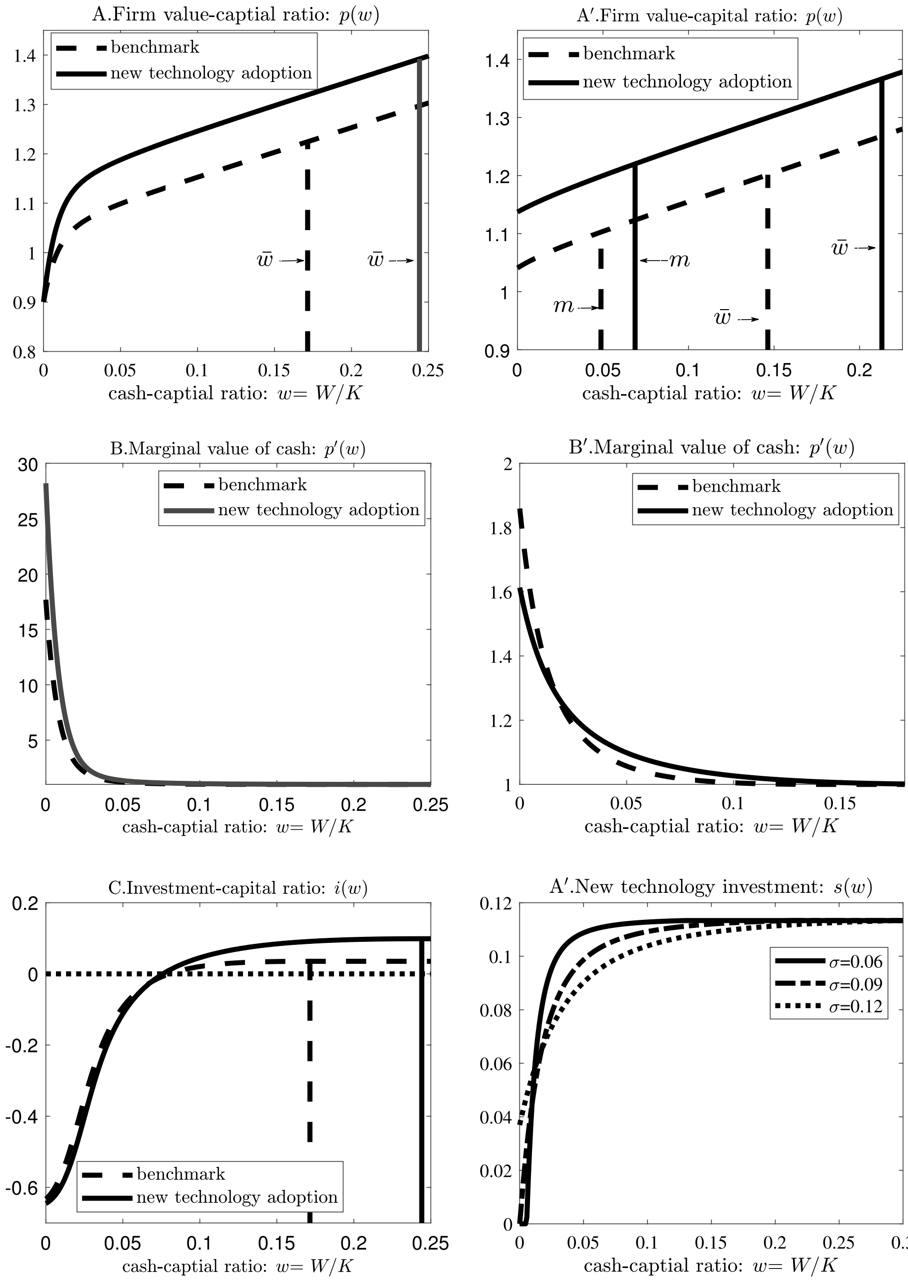

Fig. 1 Liquidation and optimal refinancing. This figure illustrates the model solutions for both liquidation and refinancing scenarios, in the context of the benchmark case and new technology adoption. Panel A and Panel A′ present the firm value-capital ratio $p(w)$ for the liquidation and refinancing scenarios, respectively. Panels B and B′ detail the marginal value of cash $p'(w)$ for the corresponding scenarios. Finally, Panels C and C′ depict the investment-capital ratio $i'(w)$ for each of these scenarios

4.2 Investment in new technology

Figure 2 displays that investment in new technology increases with cash reserves w. The intuition behind the result is the precautionary savings effect associated with new technology adoption. An increase in cash reserves w leads to a decrease in the risk aversion $-p''(w)$, thereby reducing the precautionary savings motive. Furthermore, Panel B shows that investment in new technology decreases with volatility in cash reserves. Because an increase in the volatility of cash reserves strengthens precautionary savings motive. In contrast, Panel B$'$ in the refinancing case shows that investment in new technology decreases with volatility of cash reserves when cash reserves are close to zero. Because of the refinancing option, firm with higher volatility has a lower probability of external equity financing, implying an increase in volatility reduces the risk aversion $(-p''(w))$. Consequently, higher volatility results in a lower incentives for precautionary savings.

5 Dynamic hedging

In this section, we investigate the influence of margin requirements on a firm's optimal decision-making. Beyond liquidity management, the firm has the option to utilize financial derivatives, such as futures or options contracts, as tools to mitigate operational risks. Suppose the firm has the capacity to engage in margin trading to acquire index futures in the market. We denote the price of the futures on the market index at time t as F_t. Under the risk-adjusted probability measure, F_t abides by the following dynamic process:

$$dF_t = \sigma_m F_t dB_t, \tag{22}$$

where σ_m is the volatility of the aggregate market portfolio. B_t is a standard Brownian motion. Furthermore, the correlation between B_t and Z_t is defined by ρ. Without loss of generality, we can assume that $0 < \rho < 1$. Let Φ_t denote the hedge ratio, i.e., the position in the market index futures as a proportion of the firm's total cash, denoted W_t. The cash held in the margin account is represented as $\kappa_t W_t$, where κ_t $(0 \le \kappa_t \le 1)$ signifies the fraction

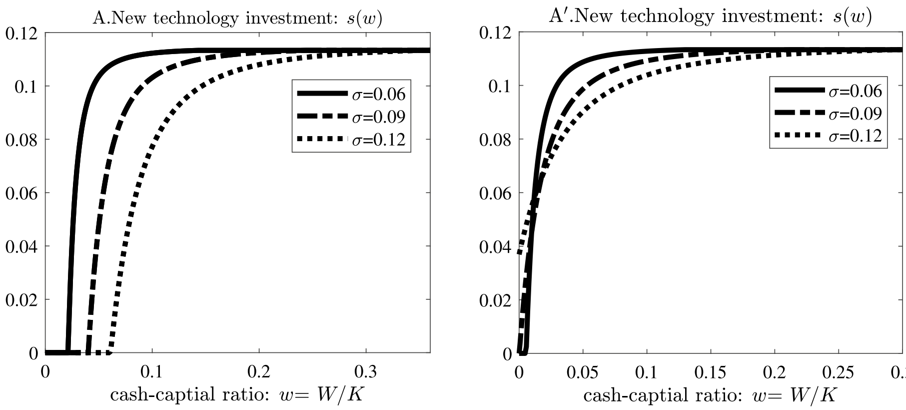

Fig. 2 Optimal new technology investment. The figure depicts the model solutions concerning new technology investments, considering both liquidation and refinancing scenarios, across benchmark and new technology adoption cases. This is evaluated under varied risk degrees, represented by σ values of 0.06, 0.09, and 0.12

of the firm's total cash W_t allocated to the margin account. In the realm of practical operations, leveraged trading mandates that the margin in the derivatives account must not fall below a constant factor of $1/\pi$ times the firm's hedge position, hence the requirement is:

$$\left|\Phi_t W_t\right| \le \pi \kappa_t W_t. \tag{23}$$

The cash reserves evolve as follow:

$$\begin{aligned} dW_t =& K_t(1+s)\left(\mu dt + \sigma dZ_t\right) - \left(I_t + G_t + f\left(s_t\right)\right)dt + dH_t - dU_t \\ &+ (r-\lambda)W_t dt - \epsilon \kappa_t W_t dt + \Phi_t \sigma_m W_t dB_t, \end{aligned} \tag{24}$$

where ϵ denotes the cash held in this margin account which incurs an additional flow cost. Next, we consider the dynamic process of the firm's value. Now, the firm's Hamilton-Jacobi-Bellman (HJB) equation is given by:

$$\begin{aligned} rP(K,W) = \max_{I,s,\Phi,\kappa} & (I - \delta K)P_K(K,W) \\ &+ [(r-\lambda)W + (1+s)\mu K - iK - g(i)K - f(s)K - \epsilon\kappa W]P_W(K,W) \\ &+ \frac{1}{2}\left(\sigma^2 K^2 + \Phi^2 \sigma_m^2 W^2 + 2\rho\sigma_m \sigma \Phi W K\right)P_{WW}(K,W), \end{aligned} \tag{25}$$

subject to

$$\kappa = \min\left\{\frac{|\Phi|}{\pi}, 1\right\}. \tag{26}$$

Because firm value is homogeneous of degree one in W and K in each state. Then, we can obtain the first-order condition with respect to hedge ratio Φ as follows:

$$\Phi^* = \frac{1}{w}\left(\frac{-(1+s)\rho\sigma}{\sigma_m} - \frac{\epsilon}{\pi}\frac{p'(w)}{p''(w)}\frac{1}{\sigma_m^2}\right), \tag{27}$$

and the first-order with respect to the new technology investment s is given by:

$$s = \frac{\mu p'(w) + (\sigma^2 + \rho\Phi^*\sigma\sigma_m w)p''(w)}{\psi p'(w) - \sigma^2 p''(w)}. \tag{28}$$

Following Bolton et al. (2011), for the low cash reserves region, we establish that $\Phi^* = -\pi$ for $w \le w\_$. This maximum-hedging boundary $w\_$ is the unique value that satisfies $\Phi^* = -\pi$, as delineated in Eqs. (27) and (28). Subsequently, when w reaches a sufficiently high level, we determine that $\Phi^* = 0$ for $w \ge w_+$, where the zero-hedging boundary w_+ stands as the unique solution for $\Phi^* = 0$, in accordance with Eqs. (27) and (28).

Specifically, following Bolton et al. (2011), we set the correlation coefficient between the market and the firm at $\rho = 0.8$. The margin requirement is maintained at $\pi = 5$, and the flow cost in the margin account is $\epsilon = 0.5\%$. The volatility of the aggregate market portfolio is considered as $\sigma_m = 0.2$. As demonstrated in Panel A of Fig. 3, the adoption of new technology bolsters firms' motivation for risk hedging. The underlying rationale for this outcome lies in the cost implications and the amplified risk effects resultant from new technology adoption. New technology adoption incurs cost and increases the probability of the costly external financing. Moreover, it escalates the volatility of the firm's operations. Therefore, firms with new technology adoption exhibit a stronger inclination towards risk hedging. Conversely, Panel B reveals that risk hedging amplifies investment

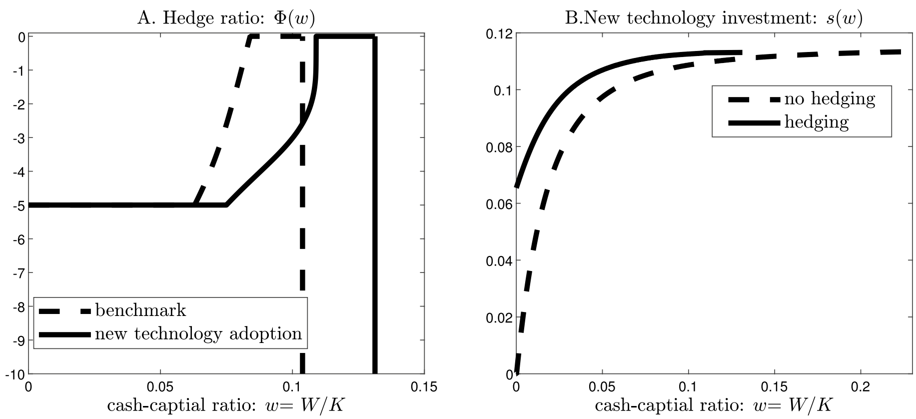

Fig. 3 Optimal hedging and new technology investment. Panel A of this figure plots the dynamic optimal hedging results of the baseline model and the new technology transformation. Panel B depicts optimal new technology investment with hedging and without hedging. The right of each line(Panel A) correspond to the respective payout boundary

in new technology compared to scenarios without new technology adoption. Intuitively, risk hedging serves to decrease volatility, as shown in Eq. (28), thereby weakening the precautionary savings motive. In addition, to ensure the robustness of the implications of new technology adoption and the determinant of investment in new technology for the refinancing case, we provide the numerical results under the scenario with financial hedging, which is shown in the Appendix D.

6 Empirical implications and model discussions

Empirical implications In our paper, we use digital technology as an example of new technology. Thus, our model provides qualitative predictions that align well with existing empirical evidence concerning the interplay between digital technology investment and corporate financial strategies. Here, we focus on making qualitative connections to the empirical findings, recognizing that our model operates under ceteris paribus conditions.

There are some findings in the literature consistent with the predictions of our model. First, Chen and Srinivasan (2024) document that a positive relationship between digital technology adoption and firm value. Specifically, Chen and Srinivasan (2024) find that firms with digital technology adoption have a 8–26% higher market-to-book ratio than industry peers. Following Brynjolfsson and Hitt (1996) and Hitt (1999), digital technology adoption allows firms to produce more and expand more effectively. Moreover, recent studies that explore the potential consequences of adopting digital technologies suggest that these will also improve firm productivity (such as Bharadwaj et al. (2013), Brynjolfsson et al. (2019), and Wu et al. (2019)). Consequently, Chen and Srinivasan (2024) conclude that firms with digital technology adoption possess higher value due to the productivity enhancements. This result is broadly consistent with the prediction of our model concerning the influence of digital technology adoption on firm value. Second, using a sample of Chinese listed companies from 2013 to 2019, Zhang and Liu (2023) investigate the impact of implementing digital economy strategies on corporate inventory and cash holdings.

Zhang and Liu (2023) find that these strategies improve the level of corporate cash holdings. This result is broadly consistent with our finding that a firm adopting digital technology tends to hoard more cash. Last, Lin et al. (2022) use the China Micro and Small Enterprise Survey data to examine how digital finance affects the investment behavior of MSEs in China. They find that digital technology adoption significantly increases both MSEs' probability of applying for new investment projects and the number of projects applied. The finding that capital investment is stimulated when firms adopt digital technologies is consistent with our model predictions.

Model discussions Our model builds on the benchmark model of Bolton et al. (2011) to incorporate investment in new technology, alongside dividend policy, investment, equity issuance, and dynamic hedging decisions. The model is clearly laid out and competently solved. We note limitations to our approach, which involves adding a layer of investment flexibility referred to as new technology investments, allowing the firm to continuously adjust such investments. However, particularly if the firm is considering upgrading its software (tangible assets), it is likely that such an investment will be lumpy and not smooth, as currently modeled. Instead of allowing firms to invest continuously, a more realistic approach would be to model it using a real options framework.

7 Conclusion

In this paper, based on the active innovation of digital technologies represented by big data, artificial intelligence, cloud computing and blockchain, we extend the classic Tobin's Q theoretical model by incorporating new technology investment. We attempt to explore the impact of new technology adoption on dynamic investment in capital, financing, and risk management behaviors of firms. First, we show that financing constraints restrict firms' motivation of investment in new technology and capital. Second, we demonstrate that, compared to the case without new technology adoption, new technology adoption enhances firm value, increases capital investment, postpones dividends, raises external equity financing, and strengthens the motivation for hedging. Furthermore, it stimulates capital investment motivation, and the impact of new technology adoption on asset sales depends on whether costly refinancing is available. Third, optimal new technology investment increases with cash reserves. In addition, investment in new technology decreases with risk when cash reserves are abundant, and the relation between investment in new technology and risk depends on whether costly refinancing is available when running out of cash. We also find that financial hedging promotes investment in new technology.

In the face of complex economic circumstances such as epidemics and wars, firms operate within an environment marked by random fluctuations. Currently, our analysis does not take into account the scenario of stochastic financing conditions, as addressed in studies such as Bolton et al. (2013) and Della Seta et al. (2020). Consequently, our future research will investigate the interplay among investment in capital and new technology, financing, and risk management behavior under the conditions of stochastic financing.

Appendix A. The proof of Proposition 3.1

The ODE (8) of firm value $p(w)$ can be reformulated as follows:

$$(r+\delta-i(w))p(w) = \begin{bmatrix} (r+\delta-\lambda-i(w))w+\mu(1+s(w)) \\ -i(w)-g(i(w))-f(s(w)) \end{bmatrix} p'(w) \\ +\frac{1}{2}(1+s(w))^2\sigma^2 p''(w) \tag{A.1}$$

Given the continuity of $p''(\cdot)$, $i(\cdot)$, and $s(\cdot)$ over the interval $[0,\bar{w})$, the third derivative $p'''(\cdot)$ can be derived through the envelope theorem as follows:

$$p'''(w) = \frac{\lambda p'(w) - [(r+\delta-i(w)-\lambda)w+\mu(1+s(w))-i(w)-g(i(w))-f(s(w))]p''(w)}{\frac{1}{2}(1+s(w))^2\sigma^2} \tag{A.2}$$

Hence, when $w=\bar{w}$, subject to the boundary conditions as per Eqs. (12) and (13), we find $p'''(\bar{w}) = 2\lambda/\left((1+s(\bar{w}))^2\sigma^2\right) > 0$. This suggests the presence of $p'''(\cdot)$ in a neighborhood of $\bar{w}$. Consequently, $p''(w)<0$ holds within the interval $(\bar{w}-\varepsilon,\bar{w})$ for an appropriate $\varepsilon>0$.

Next, let us prove $p''(w)<0$ on the interval $[0,\bar{w})$. Assuming there exists $w_1\in[0,\bar{w}]$ with $p''(w_1)>0$, and define $w_2=\sup\left\{w\in[0,\bar{w}) : p''(w)\geq 0\right\}$. Due to the continuity, we can infer that $p''(w_2)=0$ and $w_2<\bar{w}$. Given that $p'(w_2)>1$, we derive that $p'''(\bar{w}) = 2\lambda p'\left(w_2\right)/\left(1+s\left(w_2\right)\right)^2\sigma^2>0$, which suggests that $p'''(\cdot)>0$ in a neighborhood of w_2. Consequently, there exists $\hat{w}>w_2$ with $p''(\hat{w})>0$, which contradicts the definition of w_2.

Appendix B. Proof of Proposition 3.3

Upon rearranging Eq. (9), we obtain the investment-capital ratio, $i(w)$, which adheres to the subsequent equation:

$$i(w) = \frac{1}{\theta}\left(\frac{p(w)}{p'(w)}-w-1\right) \\ = \frac{p(w)-wp'(w)-p'(w)}{\theta p'(w)} \tag{B.1}$$

Taking the derivative of the investment-capital ratio $i(w)$ with respect to w from Eq. (B.1), we obtain:

$$i'(w) = -\frac{1}{\theta}\frac{p(w)p''(w)}{p'(w)^2} > 0. \tag{B.2}$$

From observing Eq. (B.2), we can deduce that $i(w)$ increases with w.

We perform an evaluation of the ordinary differential equation denoted by Eq. (8) at the payout boundary where w equals $\bar{w}$.

$$(r+\delta-i(\bar{w}))p(\bar{w}) = (r+\delta-\lambda-i(\bar{w}))\bar{w}+\mu(1+s(\bar{w})) \\ -i(\bar{w})-g(i(\bar{w}))-f(s(\bar{w})) \tag{B.3}$$

Directly from the aforementioned Eq. (B.3), we derive that

$$\begin{aligned}(r+\delta-i(\bar{w}))p(\bar{w}) =&(r+\delta-\lambda-i(\bar{w}))\bar{w}+\mu(1+s(\bar{w}))\\&-i(\bar{w})-g(i(\bar{w}))-f(s(\bar{w}))\\<&(r+\delta-i(\bar{w}))\bar{w}+\mu(1+s(\bar{w}))\\&-i(\bar{w})-g(i(\bar{w}))-f(s(\bar{w}))\end{aligned} \tag{B.4}$$

Thus, we obtain

$$\begin{aligned}p(\bar{w})-\bar{w}<&\frac{\mu(1+s(\bar{w}))-i(\bar{w})-g(i(\bar{w}))-f(s(\bar{w}))}{r+\delta-i(\bar{w})}\\ \leq q^{FB} :=& \max_{i,s}\frac{\mu(1+s)-i-g(i)-f(s)}{r+\delta-i}\end{aligned} \tag{B.5}$$

where the superscript “FB" denotes the case without financing frictions as the benchmark. We define $H(i)=i+g(i)$. This leads us to the results that $H'\left(i^{FB}\right)=1+\theta i^{FB}=q^{FB}$ and $H'(i(\bar{w}))=p(\bar{w})-\bar{w}$. Clearly, as derived from Eq. (B.5), we find that $H'(i(\bar{w}))<H'\left(i^{FB}\right)$. Consequently, due to $H''(i)=\theta>0$, we can infer that $i(\bar{w})<i^{FB}$. Building upon Eq. (B.2), we establish that $i(w)<i(\bar{w})$ for any $w<\bar{w}$. Thus, we ultimately deduce that $i(w)<i^{FB}$.

Appendix C. Proof of Proposition 3.4

By reconfiguring Eq. (10), we derive the value of new technology investment, $s(w)$, that fulfills the subsequent equation:

$$s(w)=\frac{\mu p'(w)+\sigma^2 p''(w)}{\psi p'(w)-\sigma^2 p''(w)} \tag{C.1}$$

Proceeding further, we aim to demonstrate that $s(w)<s^{FB}$. Given that $p''(\bar{w})=0$, it is straightforward to assert that $s(w)=s^{FB}$ when $w=\bar{w}$. Clearly, as we have previously established that $p''(w)<0$ within the interval $[0,\bar{w})$, it follows that

$$s(w)<\frac{\mu p'(w)-\left(-\sigma^2 p''(w)\right)}{\psi p'(w)}<\frac{\mu p'(w)}{\psi p'(w)}=s^{FB} \tag{C.2}$$

Appendix D. Robust numerical results

See Fig. 4.

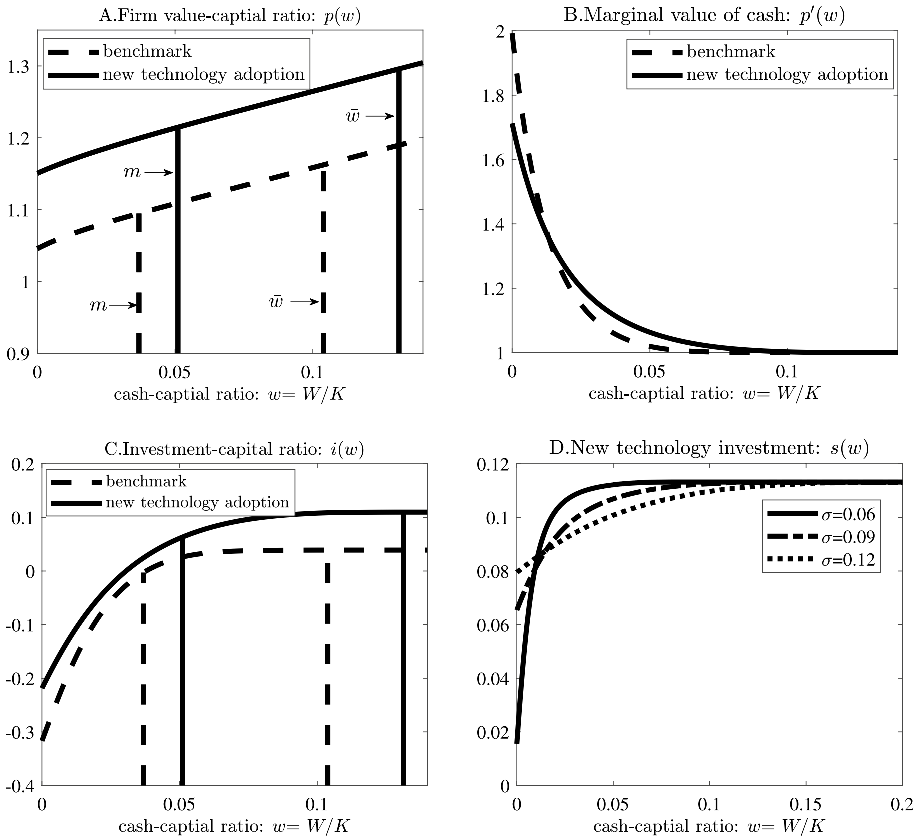

Fig. 4 This figure plots the firm value-capital ratio, the marginal value of cash, optimal capital investment and optimal new technology investment for refinancing case with hedging

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