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中 文 摘 要 ： 本文延伸 Boyle and Guthrie (2003)之模型探討，在存在先占者優勢之雙占下，不對稱財務限制與投資成本之交互作用如何影響公司最適投資時點之決策。我們有四點重要發現。第一、財務限制較低之公司，即使存在顯著成本劣勢，在未來資金不足之風險很大之情況下仍然可能是領導者。第二、一家面對顯著財務限制之公司，甚至存在一些成本劣勢下，仍然有可能成為領導者。第三、搶先行為發生之條件不只是成本差異不大，還要在未來資金不足之風險很低時。最後，計畫價值波動度可能改變領導者與跟隨者之角色。特別來說，較高之計畫價值波動度可以使公司由跟隨者變成領導者，因此使高波動度導致提早投資。

中文關鍵詞： 實質選擇權、財務限制、雙占、搶先、波動度

英 文 摘 要 ： This paper extends Boyle and Guthrie (2003) to investigate the interdependent effects of asymmetric financing constraints and investment costs on optimal investment timing decisions in a duopoly with the first-mover advantage. We demonstrate four novel findings. First, even with a large cost disadvantage the less-contrained firm can be the leader especially when the risk of future funding shortfalls is relatively high. Second, a disadvantaged firm that is significantly more constrained with a small cost disadvantage can be the leader. Third, preemption occurs when not only the asymmetry of investment costs but also the risk of future funding shortfalls is small. Finally, the change in the project value volatility can alter the leader-follower roles. In particular, higher investment project value volatility can lower a firm’ s optimal investment trigger when the firm’ s role changes from a follower to a leader due to the increase in the project value volatility.

英文關鍵詞： Real options； Financing constraints； Duopoly； Preemption； Volatility

Real options with financing constraints in an asymmetric duopoly

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Abstract

This paper extends Boyle and Guthrie (2003) to investigate the interdependent effects of asymmetric financing constraints and investment costs on optimal investment timing decisions in a duopoly with the first-mover advantage. We demonstrate four novel findings. First, even with a large cost disadvantage the less-contrained firm can be the leader especially when the risk of future funding shortfalls is relatively high. Second, a disadvantaged firm that is significantly more constrained with a small cost disadvantage can be the leader. Third, preemption occurs when not only the asymmetry of investment costs but also the risk of future funding shortfalls is small. Finally, the change in the project value volatility can alter the leader-follower roles. In particular, higher investment project value volatility can lower a firm's optimal investment trigger when the firm's role changes from a follower to a leader due to the increase in the project value volatility.

JEL classification: G13; G31; G33; L13

Keywords: Real options; Financing constraints; Duopoly; Preemption; Volatility

摘要

本文延伸 Boyle and Guthrie (2003)之模型探討，在存在先占者優勢之雙占下，不對稱財務限制與投資成本之交互作用如何影響公司最適投資時點之決策。我們有四點重要發現。第一、財務限制較低之公司，即使存在顯著成本劣勢，在未來資金不足之風險很大之情況下仍然可能是領導者。第二、一家面對顯著財務限制之公司，甚至存在一些成本劣勢下，仍然有可能成為領導者。第三、搶先行為發生之條件不只是成本差異不大，還要在未來資金不足之風險很低時。最後，計畫價值波動度可能改變領導者與跟隨者之角色。特別來說，較高之計畫價值波動度可以使公司由跟隨者變成領導者，因此使高波動度導致提早投資。

關鍵字：實質選擇權、財務限制、雙占、搶先、波動度

1. Introduction

The finance literature has studied well the individual effects of financing constraints and industry competition on a firm's investment decision. Although their interrelated effects have been empirically investigated recently, they have not been analyzed in a dynamic theoretical framework. This paper manages to bridge such a gap by extending Boyle and Guthrie (2003) to investigate the interdependent effects of asymmetric financing constraints and investment costs on optimal investment timing decisions in a duopoly with the first-mover advantage.

We find herein that when the risk of future funding shortfalls is relatively high, the less-constrained firm tends to be the leader, whereas when the risk of future funding shortfalls is relatively low, the low-cost firm tends to be the leader. Specifically, even with a large cost disadvantage the less-constrained firm can still be the leader especially when the risk of future funding shortfalls is relatively high. Our model further shows that a disadvantaged firm that is significantly more constrained even with a small cost disadvantage can still be the leader. The main reason is that the wait-and-see flexibility value for less-constrained firms is significantly larger than that for more-constrained firms. When the risk of future funding shortfalls is reduced, the less-constrained firm starts to enjoy the flexibility of waiting and delays its investment timing. At the same time, the risk of delaying investment for the significantly more-constrained firm is still so high that its optimal investment decision is to invest as soon as possible. As a consequence, the less-constrained firm with a small cost advantage voluntarily delays investment becoming the follower, while the significantly more-constrained firm with a small cost disadvantage accelerates investment becoming the leader. Therefore, it is possible even with a small cost disadvantage that the significantly more-constrained firm can be the leader, which complements Munos (2009) who observes the fraction of new approved drugs from large pharmaceutical firms is on the decrease, while the fraction of new approved drugs from small (more financially constrained) biotechnology and pharmaceutical firms is on the rise.

Ever since the two seminal papers of McDonald and Siegel (1986) and Majd and Pindyck (1987) and the well-known book by Dixit and Pindyck (1994), the methodology of investment under uncertainty or real options has become the standard approach to feature a firm's irreversible investment flexibilities. The real options literature has recently taken production market competition into consideration, with some studies based on the assumption that firms are symmetric in Cournot-Nash oligopoly equilibria. For example, Grenadier (2002) analyzes a firm's delay option on an incremental investment project, while Jou and Lee (2008) focus on such an option for a lumpy investment project. With the same assumption, Aguerrevere (2009) specifically demonstrates that the relationship between the degree of competition and assets' expected rates of return varies with product market demand.

Firms, however, are seldom identical. The growing literature on real options games suggests that, when relatively few firms compete, there often exists a first-mover advantage (FMA). The simple asymmetric duopoly equilibrium is frequently employed to analyze a firm's irreversible investment decision when the two firms have different investment costs. The framework of Fuderberg and Tirole (1985) is then applied to capture the threat of preemptive investment and to analyze the game equilibrium. Pawlina and Kort (2006) and Mason and Weeds (2010) examine the irreversible investment behavior when there is a competitor that can potentially preempt this investment project. For some parameters, they demonstrate that a greater FMA will lead the low-cost firm to adopt a preemptive investment threshold that is significantly lower than the firm's optimal investment trigger when there is no rival. Carlson et al. (2011) examine the effects of a firm's expansion and contraction options on the risk dynamics of the required returns when there is a rival firm owning the same rights. They generally find that competition erodes the values of wait-and-see options.

Compared with these papers, our model contributes to the real options game literature by further taking asymmetric financing constraints between the two firms into consideration. We complement the literature by showing that the leader and follower in an investment project are determined by not only asymmetric investment costs, but also asymmetric financing constraints between the two firms. The interaction between financing constraints and industry competition plays a significantly important role in determining a firm's optimal investment timing when the threat from rivals' preemptive investment comes into play. We demonstrate that the preemption occurs when not only the asymmetry of investment costs but also the risk of future funding shortfalls is small. Finally, we show that the change in the project value volatility can alter the leader-follower roles. Particularly, our model offers an implication for the relationship between investment and uncertainty. Higher investment project volatility can lower a firm's optimal investment trigger when the firm's role in an investment project is first being the follower and then becoming the leader due to an increase in the project value volatility.

The remainder of this paper is organized as follows. Section 2 first introduces the investment environment and theoretical framework of our model. Section 3 numerically investigates the investment timing decisions of the two constrained firms in an asymmetric duopoly and provides some implications. Section 4 presents some concluding remarks.

2. The model

This section first introduces the basic set-up where the two firms are asymmetric in both investment costs and financial resources. To clearly explain our model and compare it with Boyle and Guthrie (2003), we start with the case where the firm is financially constrained in a monopoly and then analyze the case for firms financially constrained in a duopoly.

2.1. The environment of the two firms with asymmetric investment costs and financial resources

Two risk-neutral firms, Firm 1 and Firm 2, both own perpetual rights to invest in a new project at asymmetric investment costs I_i, $i = 1, 2$, and the project has zero recovery value, i.e., the investment is irreversible. Assume the project value of investment follows the geometric Brownian motion as follows:

$$\frac{dV(t)}{V(t)} = (r - \delta)dt + \sigma dW(t), \tag{1}$$

where the risk-free interest rate r, convenience yields δ, and project value volatility σ are three constants, and W is a Wiener process. Each firm can exercise the rights and invest in the project, or delay investment and retain the rights at any time. Investment by the two firms may occur sequentially or simultaneously, depending on the payoffs they can receive after investing.

Consider the outcome when the firms invest sequentially. The first investor is named the leader, and the second investor is named the follower. Before the follower invests, the leader's post-investment payoff is the whole project value of investment

V, which is the same as the case when the leader is the sole investor. After the follower has invested, the leader's payoff becomes $(1+q_L)V$ and the follower's payoff is $(1+q_F)V$. On the other hand, if the two firms invest simultaneously, then both receive the same payoff $(1+q_S)V$.

Since we shed light on the cases where preemption always occurs, this project assumes that $-1<q_F<q_L<0$ and $-1<q_S<q_L<0$ unless otherwise specified. This reduced-form set-up is designed to grant the leader a persistent first-mover advantage, thereby motivating the two firms to preempt due to a less favorable simultaneous-move. As a result, the two firms play a continuous-time investment timing game. We employ the framework of Fudenberg and Tirole (1985), where the two key assumptions underlying the preemption game, among others, are that information lags are very short and that the payoffs are common knowledge.

In addition to the uncertainty of future investment, the two firms also face the uncertainty of cash flows generated by some existing assets. Through the set-up of Boyle and Guthrie (2003), we assume each firm owns cash holdings X_i, $i=1,2$ and some existing perpetual assets with market values G_i, $i=1,2$. The existing assets do not incur any cash flow reinvestment, and so their market values are fixed.

Following the set-up of financing constraints by Boyle and Guthrie (2003), we assume each firm is subject to the asymmetric financing constraints. First, investing the project is possible for the two firms, if and only if:

$$I_i \le X_i + G_i + \alpha_i(1+q_k)V, \quad i=1,2, \quad k=L,F, \tag{2}$$

where the two constants $\alpha_i \in [0,1)$ show the friction that uncertainty about the firms' ability or willingness to extract the full project value for outside investors limits the amount of funding. The right-hand side of Equation (2) represents the whole funding resources available to each firm, consisting of cash reserves plus the realizable values of the firms' existing and potential assets.

We assume for simplicity the two firms have the same initial cash balance $\left(X_1 = X_2 \equiv X\right)$ and face the same friction $\left(\alpha_1 = \alpha_2\right)$, but possess different market values of existing assets, $G_1 \ne G_2$ and $G_i = v_i/r$, $i=1,2$. Since no firm is pre-determined as a leader or a follower and the two firms have the same initial cash balances, the firm with a greater $G-I$, i.e., the greater difference between the existing asset values and the investment cost, is named as the less-constrained firm hereafter. To focus the effects of asymmetric financing constraints and investment costs on optimal timing decisions, we assume that $G_1 - I_1 \ne G_2 - I_2$ and $I_1 \ne I_2$.

The two firms' cash balances vary over time according to:

$$dX_i = rX_i\,dt + v_i dt + \phi dB(t), i=1,2, \tag{3}$$

where v_i and ϕ are constants and B is another Wiener process with $dW(t)dB(t)=\rho dt$. The first term of the right-hand side in Equation (3) is the amount from investing cash in riskless securities, and the other terms show the uncertain cash flows generated by the firms' existing assets.

Next, we assume that when a shortage of the two firms' cash reserves occurs, $X_i < 0$, both firms will face cash deficits. If the cash deficits of the firms exceed the realizable value of the firms' non-cash assets, then the firms must be liquidated and sell out the options to invest.

We now respectively denote the values of options to invest for the leader and follower as $L_i^c(X,V)$ and $F_i^c(X,V)$, $i=1,2$, when the two firms are financially constrained. Notice that both firms can be the leader or follower. Therefore, Firm i, $i=1,2$, will be forced to liquidate if $X_i + G_i + L_i^u(\gamma(1+q_L)V) \le 0$, when Firm i is the leader and forced to liquidate if $X_i + G_i + F_i^u(\gamma_i(1+q_F)V) \le 0$ when Firm i is the follower, where L_i^u and F_i^u respectively denote the values of options to invest for the leader and follower when the two firms are financially unconstrained. Following Boyle and Guthrie (2003), we assume that the projects of the two firms possess some unique feature so that the options to invest are not fully transferable, thereby $\gamma_i \in [0,1)$. This makes selling less attractive and ensures that the firms must confront the investment policy consequences due to a lack of cash reserves. For simplicity, we assume the two firms face the same imperfection $\left(\gamma_1 = \gamma_2\right)$.

It is noteworthy that the constrained real options values should converge to their corresponding unconstrained real options values when the risk of future funding shortfalls disappears, i.e., $\lim_{X\to\infty} L_i^c(X,V) = L_i^u(V)$ and $\lim_{X\to\infty} F_i^c(X,V) = F_i^u(V)$. At the same time, the constrained investment decisions should also converge to their corresponding unconstrained investment policies, $\hat{V}_{i,L}^u$ and $\hat{V}_{i,F}^u$, respectively , i.e., $\lim_{X\to\infty} \hat{V}_{i,L}^c(X) = \hat{V}_{i,L}^u$ and $\lim_{X\to\infty} \hat{V}_{i,F}^c(X) = \hat{V}_{i,F}^u$. In the following, we first introduce the case when the firm is financially constrained in a monopoly, which is helpful in order to gain a better understanding of and to make a direct comparison with the case when firms are financially constrained in a duopoly.

2.2. The firm is financially constrained in a monopoly

When the two firms are financially constrained, but not subject to the investment decisions of the rival, their optimal investment policies are exactly the same as the model in Boyle and Guthrie (2003). Because the real options values of monopolistic firms, $M_i^c(X,V)$, $i=1,2$, are functions of X and V, the corresponding optimal investment decisions $\hat{V}_{i,M}^c(X)$ must also be functions of X, rather than constants as in the case of the two unconstrained firms.

The real options values with financing constraints therefore satisfy the following partial differential equation (PDE) and boundary conditions:

$$\frac{1}{2}\sigma^2 V^2 \frac{\partial^2 M_i^c}{\partial V^2} + \rho\sigma\phi V \frac{\partial^2 M_i^c}{\partial V \partial X} + \frac{1}{2}\phi^2 \frac{\partial^2 M_i^c}{\partial X^2} + (r-\delta)V \frac{\partial M_i^c}{\partial V} + r(X+G_i)\frac{\partial M_i^c}{\partial X} - rM_i^c = 0. \tag{4}$$

$$\lim_{X\uparrow\infty} M_i^c(X,V) = M_i^u(V) = \left(\hat{V}_{i,M}^u - I_i\right)\left(V/\hat{V}_{i,M}^u\right)^{\beta_1} \tag{5}$$

$$\lim_{V\uparrow\hat{V}_{i,M}^c(X)} M_i^c(X,V) = \hat{V}_{i,M}^c(X) - I_i, \tag{6}$$

$$\lim_{X\downarrow X_{i,M}(V)} M_i^c(X,V) = M_i^u(\gamma V), \text{ and } \lim_{V\downarrow 0} M_i^c(X,V) = 0. \tag{7}$$

Equation (5) shows that the real options values after considering financing constraints will converge to their unconstrained values as the cash balance goes to infinity. Equation (6) illustrates that the firm will invest when the project value is high enough, whereby $\hat{V}_{i,M}^c(X)$ denotes the firm's optimal investment trigger depending on the firm's cash balance when the firm is constrained, and as the cash balance goes to infinity the trigger converges to its unconstrained counterpart $\lim_{X\uparrow\infty}\hat{V}^c_{i,M}(X)\equiv\hat{V}^u_{i,M}=\beta_1 I_i/(\beta_1-1)$. Equation (7) demonstrates the firm's liquidation constraint is binding when the cash balance is low enough, and the follower's real options values become worthless as the underlying project value goes to zero, where $X_{i,M}(V)$ is the firm's liquidation trigger of cash balance determined by the first time that $X_i+G_i+M^u_i(\gamma V)\le 0$.

The greater complexity of this PDE means that analytical solutions of $\hat{V}^c_{i,M}(X)$ and $M^c_i(X,V)$ are, to our best knowledge, not available. Using a finite difference method with parameters of $I=G=100$, $\sigma=0.3$, $r=\delta=0.03$, $\rho=0.5$, $\phi=80$, $q_L=-0.45$, $q_F=-0.55$, and $\alpha=\gamma=0.8$, we employ Figure 1 (which is similar to Figure 1 of Boyle and Guthrie (2003)), so as to underline the effects of financing constraints on Firm 1's optimal investment decision, where Firm 1 ignores the policy of Firm 2 (the rival) and makes a decision as it exclusively owns the right to invest in this project.

Firm 1's optimal investment trigger is basically V-shaped. The left-hand side of the V-shape shows the effect of financing constraints on Firm 1's investment decisions. In low states of X (X is lower than X^* in Figure 1), the risk of future funding shortfalls is relatively high, and therefore the risk of delaying investment is so large that the firm will invest as soon as it has enough funds to do so. In the right-hand side of the V-shape, the risk of future funding shortfalls is reduced, and the possibility that the firm will have insufficient funds to finance the project in the future drops. Therefore, the firms start to enjoy their wait-and-see options and gradually raise their investment thresholds in high states of X (X is greater than X^*). Finally, if X goes to infinity, then the optimal investment trigger converges to the optimal investment decisions when Firm 1 is financially unconstrained.

2.3. Firms are financially constrained in a duopoly

The investment decisions of the constrained firms in a duopoly are more complicated, because a firm's decision is relevant to the other firm and vice versa. As usual in dynamic games, the leader-follower timing game is solved backwards. First of all, we consider the optimal investment decision of the follower. Since the follower decides its optimal investment timing after the leader has invested, the follower's real options value $F^c_i(X,V)$ is relevant to the leader's decision, but are determined given the leader's decision, $i=1,2$, which is governed by the following PDE and boundary conditions: For the states that the follower has not invested:

$$\frac{1}{2}\sigma^2V^2\frac{\partial^2F^c_i}{\partial V^2}+\rho\sigma\phi V\frac{\partial^2F^c_i}{\partial V\partial X}+\frac{1}{2}\phi^2\frac{\partial^2F^c_i}{\partial X^2}+(r-\delta)V\frac{\partial F^c_i}{\partial V}+r(X+G_i)\frac{\partial F^c_i}{\partial X}-rF^c_i=0\,. \quad (8)$$

$$\lim_{X\uparrow\infty}F^c_i(X,V)=F^u_i(V)\,, \quad (9)$$

$$\lim_{V\uparrow\hat{V}^c_{i,F}(x)}F^c_i(X,V)=(1+q_F)\hat{V}^c_{i,F}(x)-I_i\,, \quad (10)$$

$$\lim_{X\downarrow X_{i,F}(V)}F^c_i(X,V)=F^u_i(\gamma(1+q_F)V) \text{ and } \lim_{V\downarrow 0}F^c_i(X,V)=0\,. \quad (11)$$

Equations (9) and (11) share the same explanations as those in Equations (5) and (7), while Equation (10) is the value-matching condition showing that the follower's real options value is indifferent before and after its investment, where $X_{i,F}(V)$ is the follower's liquidation trigger of its cash balance determined by the first time that $X_i + G_i + F_i^u(\gamma(1+q_F)V) \le 0$. Solving this PDE by the finite difference method yields a V-shaped optimal investment trigger for the follower $\hat{V}_{i,F}^c(X)$, which is similar to the cases of a single firm as demonstrated in Figure 1.

Second, the leader's investment value after the leader has invested is $\mathcal{L}_i^c(X,V)$, which accounts for the adjustment value when the follower invests. Here, $\mathcal{L}_i^c(X,V)$ is governed by the following PDE and boundary conditions:

$$\frac{1}{2}\sigma^2 V^2 \frac{\partial^2 \mathcal{L}_i^c}{\partial V^2} + \rho\sigma\phi V \frac{\partial^2 \mathcal{L}_i^c}{\partial V \partial X} + \frac{1}{2}\phi^2 \frac{\partial^2 \mathcal{L}_i^c}{\partial X^2} + (r-\delta)V \frac{\partial \mathcal{L}_i^c}{\partial V} + r(X+G_j)\frac{\partial \mathcal{L}_i^c}{\partial X} - r\mathcal{L}_i^c = 0 \tag{12}$$

$$\lim_{X\uparrow\infty} \mathcal{L}_i^c(X,V) = \mathcal{L}_i^u(V) = V + q_L \hat{V}_{j,F}^u \left(\frac{V}{\hat{V}_{j,F}^u}\right)^{\beta_1}, \tag{13}$$

$$\lim_{V\uparrow\hat{V}_{j,F}^c(X)} \mathcal{L}_i^c(X,V) = (1+q_L)\hat{V}_{j,F}^c(X), \tag{14}$$

$$\lim_{X\downarrow X_{i,\mathcal{L}}(V)} \mathcal{L}_i^c(X,V) = \gamma(1+q_L)V \text{ and } \lim_{V\downarrow 0} \mathcal{L}_i^c(X,V) = 0. \tag{15}$$

Notice that the market value of the leader's existing asset G_i is not included in Equation (12), but the rival's G_j is. This shows that $\mathcal{L}_i^c(X,V)$ is relevant to X, but independent from the leader's financing constraints since the investment has been done. However, it depends on the follower's investment trigger and therefore on its financing constraints. Equations (13) and (15) share the similar explanations as those in Equations (5) and (7), while Equation (14) is the value-matching condition showing that the leader's immediate investment value is indifferent before and after the follower's investment, where $X_{i,\mathcal{L}}(V)$ is the firm's liquidation trigger of its cash balance determined by the first time that $X_i + G_i + \gamma(1+q_L)V \le 0$.

Third and finally, the real options value of the leader $L_i^c(X,V)$ when the leader has not invested is governed by the following PDE and boundary conditions:

$$\frac{1}{2}\sigma^2 V^2 \frac{\partial^2 L_i^c}{\partial V^2} + \rho\sigma\phi V \frac{\partial^2 L_i^c}{\partial V \partial X} + \frac{1}{2}\phi^2 \frac{\partial^2 L_i^c}{\partial X^2} + (r-\delta)V \frac{\partial L_i^c}{\partial V} + r(X+G_i)\frac{\partial L_i^c}{\partial X} - rL_i^c = 0. \tag{16}$$

$$\lim_{X\to\infty} L_i^c(X,V) = L_i^u(V), \tag{17}$$

$$\lim_{V\to\hat{V}_{i,L}^c(X)} L_i^c(X,V) = \mathcal{L}_i^c(X,\hat{V}_{i,L}^c(X)) - I_i, \tag{18}$$

$$\lim_{X\to X_{i,L}(V)} L_i^c(X,V) = L_i^u(\gamma(1+q_L)V), \text{ and } \lim_{V\to 0} L_i^c(X,V) = 0. \tag{19}$$

Equations (17) and (19) again share the same explanations as those in Equations (5) and (7), while Equation (18) is the value-matching condition showing that the leader's investment value is indifferent before and after its investment, where $X_{i,L}(V)$ is the firm's liquidation trigger of its cash balance determined by the first time that $X_i + G_i + L_i^u(\gamma(1+q_L)V) \le 0$. Solving this PDE by the finite difference method yields a V-shaped optimal investment trigger $\hat{V}_{i,L}^c(X)$.

We next define the earliest investment timing under which Firm i still has an incentive to preempt as the leader when the two firms are subject to financing constraints. Let $\hat{V}_{i,P}^{c}(X)$ be the smallest solution of $F_i^c\left(X,\hat{V}_{i,P}^{c}(X)\right)=\mathcal{L}_i^c\left(X,\hat{V}_{i,P}^{c}(X)\right)-I_i$ for a given X, $i=1,2$. Since the two firms are financially constrained, when the cash reserve is too low the preemptive investment decision is not attainable. Therefore, we have to redefine the two firms' preemptive investment triggers as $\hat{V}_{i,P}^{cm}(X)=\max\left(\hat{V}_{i,P}^{c}(X),\hat{V}_{i,L}^{cm}(X)\right)$, where $\hat{V}_{i,L}^{cm}(X)\equiv(I_i-G_i-X)/\alpha(1+q_L)$, which is high as the project value has to be in order for the leader to have sufficient funds to finance the investment project. When $\hat{V}_{i,P}^{c}(X)$ is lower than $\hat{V}_{i,L}^{cm}(X)$, the firm cannot preempt to invest due to its own financing constraint and can make a preemptive investment only when the project value is at least larger than $\hat{V}_{i,L}^{cm}(X)$.

To determine which firm tends to be the leader, we have to compare $\hat{V}_{i,L}^{c}(X)$ and $\hat{V}_{i,P}^{cm}(X)$ for each X. We first assume that the initial state of the project value is strictly less than the leader's optimal investment trigger for simplicity. Similar to Pawlina and Kort (2006) and Carlson et al. (2011), we define the equilibria of this two-player investment timing game when the two firms have asymmetric investment costs and financing constraints as below. If $\min\left(\hat{V}_{i,L}^{c}(X),\hat{V}_{i,P}^{cm}(X),i=1,2\right)$ $=\hat{V}_{i,L}^{c}(X)$ or $\hat{V}_{i,P}^{cm}(X)$, then Firm i is the leader taking $\min\left(\hat{V}_{i,L}^{c}(X),\hat{V}_{j,P}^{cm}\right)$ as its optimal investment decision, while Firm j is the follower choosing $\hat{V}_{j,F}^{c}(X)$ as its optimal one, where $i,j=1,2$ and $i\neq j$. If $\min\left(\hat{V}_{i,L}^{c}(X),\hat{V}_{i,P}^{cm}(X),i=1,2\right)=\hat{V}_{i,L}^{c}(X)=\hat{V}_{i,P}^{cm}(X)$, then Firm i is the leader taking $\hat{V}_{i,L}^{c}(X)=\hat{V}_{i,P}^{cm}(X)$, while Firm j is the follower choosing $\hat{V}_{i,F}^{c}(X)$, where $i,j=1,2$ and $i\neq j$.

We now offer some explanations. In the first situation, Firm i has a greater incentive to invest earlier or to preempt the investment, and thus it tends to be the leader. The second situation prevails when $\hat{V}_{i,L}^{c}(X)>\hat{V}_{i,L}^{cm}(X)$ and $\hat{V}_{j,P}^{cm}(X)=\hat{V}_{j,L}^{cm}(X)$. Since both firms know this information, Firm i tends to be the leader, while Firm j will be the follower.

3. Numerical analyses and implications

In this section we present some numerical analyses to our model, which provide some interesting financial and economic insights. The basic parameters employed are: $I_1=G_1=100$, $\sigma=0.3$, $r=\delta=0.03$, $\rho=0.5$, $\phi=80$, $\alpha=\gamma=0.8$, $q_L=-0.45$ and $q_F=-0.55$. We utilize the numerical procedure mentioned in Appendix B and employ the rule of the game equilibrium mentioned in the last section to the following numerical analyses.

To completely explore our analyses, without loss of generality, we index the firm with a cost advantage (lower investment cost) as Firm 1 and the firm with a cost disadvantage (higher investment cost) as Firm 2. Therefore, we first separate our results into two classifications: (1) Firm 1 is less constrained while Firm 2 is more constrained; and (2) Firm 1 is more constrained while Firm 2 is less constrained. In other words, we have the following two cases: The first is that $I_1 < I_2$ and $G_1 - I_1 > G_2 - I_2$, and the second is that $I_1 < I_2$ and $G_1 - I_1 < G_2 - I_2$. In order to clarify our numerical results, we investigate the impacts due to the different degrees of asymmetric financing constraints on the optimal investment timing decisions for these two scenarios: the cost disadvantage of Firm 2 is large or small.

3.1. The effects of asymmetric financing constraints and investment costs on investment timing decisions when the cost disadvantage is large

Figure 2 demonstrates the optimal investment decisions of the two-player investment timing game, where Panel A of Figure 2 presents the case that Firm 2 is significantly more constrained with a large cost disadvantage and Panel B of Figure 2 shows the case that Firm 2 is significantly less constrained with a large cost disadvantage. In other words, the only one difference between Panels A and B is that Firm 2 is significantly more constrained in Panel A ($G_2 - I_2 = -140 < G_1 - I_1 = 0$), while is significantly less constrained in Panel B ($G_2 - I_2 = 70 > G_1 - I_1 = 0$), given that Firm 2 has a large cost disadvantage ($I_1 = 100 < I_2 = 170$).

In view of Panel A, Firm 1 is always the leader while Firm 2 is always the follower. This is intuitive since Firm 1 has two significant advantages over Firm 2 in both investment costs and financing constraints. Panel B demonstrates that less-constrained Firm 2 is the leader when the risk of future funding shortfalls is relatively high (when X is lower than the critical value X_C in Panel B of Figure 2), whereas low-cost Firm 1 is the leader when the risk of future funding shortfalls is relatively low (when X is greater than the critical value X_C). The findings complement the literature, showing that the low-cost firm is always the leader when firms are financially unconstrained.

We now show that the less-constrained firm tends to be the leader when the risk of future funding shortfalls is relatively high, and it still holds even when the firm has a large cost disadvantage. On the other hand, the low-cost firm tends to be the leader when the risk of future funding shortfalls is relatively low. In other words, the roles of the leader and follower in an investment opportunity may change due to a change in the risk of future funding shortfalls. Comparing Panel A with Panel B, a greater improvement in Firm 2's financing strength (an increase in G_2) alters the role of Firm 2 from being a follower to being a leader when the risk of future funding shortfalls is relatively high, whereas the role of Firm 2 is not changed when the risk of future funding shortfalls is relatively low. Therefore, Panels A and B of Figure 2 demonstrate that in addition to the asymmetric investment costs, the asymmetric financing constraints between the two firms crucially impact the optimal investment timing decisions.

3.2. The effects of asymmetric financing constraints and investment costs on investment timing decisions when the cost disadvantage is small

Figure 3 mainly illustrates the effects of asymmetric financing constraints on investment timing decisions when Firm 2 has a small cost disadvantage. Panel A of Figure 3 demonstrates the case where Firm 2 is significantly more constrained ($G_1 - I_1 = 0 > G_2 - I_2 = -33$) and has a small cost disadvantage ($I_1 = 100 < I_2 = 103$). In view of Panel A, when the risk of future funding shortfalls is relatively high (when

X is lower than X_C^L in Panel A of Figure 3), Firm 1 is the leader and Firm 2 is the follower due to the less-constrained effect of Firm 1. When the risk of future funding shortfalls is medium (when X is between X_C^L and X_C^H in Panel A of Figure 3), less-constrained Firm 1 becomes the follower and Firm 2 becomes the leader.

What we observe here is a disadvantaged firm that is significantly more constrained with even a small cost disadvantage can be the leader. In this region, Firm 1's incentive to be the leader has been weakened much more by its desire to enjoy the wait-and-see option, whereas the investment incentive of Firm 2 is still governed by its significant financing constraints. As the risk of future funding shortfalls turns relatively low (when X is greater than X_C^H and becomes larger), the effects of asymmetric financing constraints on the two firms' optimal investment decisions vanish. At the same time, the effect of the small cost disadvantage becomes significant, thereby leading Firm 1 again to be the leader while Firm 2 is the follower.

Panel A of Figure 3 particularly shows a disadvantaged firm that is significantly more constrained even with a small cost disadvantage can still be the leader. This complements the findings of Munos (2009) who provides evidence that the fraction of new approved drugs from large pharmaceutical firms dropped from 75% (in the early 1980s) to roughly 35% (2008), whereas the fraction of new approved drugs from small biotechnology and pharmaceutical firms rose from 23% to nearly 70%. This suggests that small (more financially constrained) firms can win innovation races (being the leader), especially after 1980 when venture capital funded much of the 'biotech boom' and the risk of future funding shortfalls in that industry improved. Our model suggests that when the firms have limited access to external financing, then less financing constraints not only allow for current investment, but also decrease the possibility that future investment will be constrained.

When the asymmetry between the two firms' investment cost is relatively small and the risk of future funding shortfalls is medium, the significantly more-constrained firm with a small cost disadvantage (Firm 2 in Panel A) is forced to invest as early as possible due to the threat of future cash shortfalls, thus becoming the leader. At the same time, the significantly less-constrained firm with a slightly lower investment cost (Firm 1 in Panel A) prefers to defer investment and forgoes current investment due to the lower possibility that future investment will be constrained, therefore becoming the follower. Unlike conventional wisdom that being bigger is advantageous, we show that even with a small cost disadvantage a small firm that is significantly more constrained can still be the leader when its competitor prefers to defer investment due to the greater wait-and-see flexibility value.

In Panel B of Figure 3, the existing market asset value of Firm 2, G_2, increases from 70 to 100, and therefore Firm 2 becomes just slightly more constrained ($G_1 - I_1 = 0 > G_2 - I_2 = -3$) with the same small cost disadvantage, other things being equal. Panel B demonstrates that Firm 2 is always the follower, which is consistent with Panel A of Figure 2. Comparing Panel A with Panel B of Figure 3, unlike conventional wisdom we observe that when the financing strength of Firm 2 improves (G_2 increases while Firm 2 is still slightly more constrained than Firm 1), the possibility that Firm 2 is the leader vanishes and instead Firm 2 is always the follower, other things being equal. The reason is that when the asymmetry between the financing constraints of the two firms is small, the timings for when the two firms start to enjoy waiting are so close that Firm 2 has no chance to be the leader.

In Panel C of Figure 3, we further increase the market asset value of Firm 2 to be

130, and therefore Firm 2 becomes less constrained than Firm 1, ($G_2 - I_2 = 27 > G_1 - I_1 = 0$) with the same small cost disadvantage, other things being equal. Panel C here is similar to Panel B of Figure 2, where less-constrained Firm 2 is the leader when the risk of future funding shortfalls is relatively high (when X is smaller than X_C), and low-cost Firm 1 is the leader when the risk of future funding shortfalls is relatively low.

All three panels of Figure 3 demonstrate how the interaction between financing constraints and preemption affects the firms' optimal investment timing decisions. They show that the threat of the follower's preemptive investment generates negative sensitivity for a firm's optimal investment timing to the cash balance when the risk of future funding shortfalls is low. This complements the result of Pawlina and Kort (2006) in that the low-cost firm preempts the high-cost firm when the first-mover advantage is large and the asymmetry of investment cost is small. In sum, we particularly show that the preemption occurs when the asymmetry of investment costs is small and when the risk of future funding shortfalls is low.

3.3. Investment and uncertainty

Our model also contributes to the effect of volatility on the leader-follower roles and the relationship between investment and uncertainty. When investment is financially unconstrained, the real options literature shows that the change in volatility always has no effect on the leader-follower roles and a greater uncertainty in the investment project value increases the value of waiting, thereby raising the optimal investment trigger and deferring the timing of investment. However, when investment is subject to financing constraints, we show that the change in volatility can change the leader-follower roles. In addition, we extend Boyle and Guthrie (2003) to show that the effect of project value volatility on the optimal investment trigger is ambiguous in an asymmetric duopoly.

Figure 4 illustrates the case of Panel B in Figure 2 for $\sigma = 0.2$ and $\sigma = 0.4$. We first demonstrate that higher project value volatility makes Firm 1 become the leader earlier, i.e., the region that Firm 1 is the leader becomes larger. The reason is that higher project value volatility increases the waiting option value of Firm 1, and thus Firm 1 is more likely to enjoy wait-and-see flexibility instead of investing as soon as it has enough funds to do so. Figure 4 particularly posits that there are three regions showing three different impacts of project value volatility on Firm 1's optimal investment trigger. The left region (when X is smaller than X_C^L in Figure 4) presents that project value volatility has no impact on Firm 1's optimal investment trigger. In addition, Firm 1 is always the follower when $\sigma = 0.2$ and $\sigma = 0.4$ in this region. The middle region (when X is between X_C^L and X_C^H in Figure 4) demonstrates that higher project value volatility lowers Firm 1's optimal investment trigger. In this region, Firm 1 changes its role from a follower to a leader when volatility goes from 0.2 to 0.4. Finally, the right region (when X is greater than X_C^H) shows that project value volatility first has no impact and then has a positive impact on Firm 1's optimal investment trigger as X increases. Firm 1 is always the leader when $\sigma = 0.2$ and $\sigma = 0.4$ in this region.

When the investment project is financially constrained and when there is a rival firm that can invest earlier to get the first-mover advantage, different from traditional literature, the change in the project value volatility can alter the leader-follower roles when the risk of future funding shortfalls is taken into consideration. The increase in project value volatility can make the firm’s optimal investment trigger unchanged, higher, or even lower. Higher investment project value volatility can specifically lower a firm’s optimal investment trigger when the firm’s role in an investment project is first to be the follower and then to be the leader due to the increase in the project value volatility.

4. Conclusions

When access to external financing is restricted, firms rely more on their internal funds to finance investment. Although this issue has long been recognized and analyzed in the literature, the interrelated effects of financing constraints and investment costs among firms have not yet previously been scrutinized. In this paper we investigate the interdependent effects of asymmetric financing constraints and investment costs on optimal investment timing decisions in a duopoly with the first-mover advantage where the two firms’ roles in the investment timing game are endogenously determined.

Our model provides the following new insights, complementing some existing findings in the literature. First, in addition to asymmetric investment costs, we show that asymmetric financing constraints crucially impact a firm’s optimal investment timing decisions. We demonstrate that even with a significant cost disadvantage the less-constrained firm can be the leader when the risk of future funding shortfalls is relatively high. Second, the significantly more-constrained firm even with a small cost disadvantage can be the leader when its competitor prefers to defer investment due to a lower risk of future funding shortfalls. Unlike conventional wisdom, we show that when the financing strength of the significantly more-constrained firm with a small cost disadvantage improves, but is still slightly more constrained, the possibility that the firm can be the leader totally vanishes. Third, the interaction between financing constraints and industry competition (preemption) plays a significantly important role in determining firms’ optimal investment timing decisions when the threat of a rival’s preemptive investment comes into play. We show that the preemption occurs when not only the asymmetry of investment costs but also the risk of future funding shortfalls is small. Finally, we demonstrate that the change in the project value volatility can alter the leader-follower roles. An increase in project value volatility can make the firm’s optimal investment trigger unchanged, higher, or even lower. In particular, higher investment project value volatility can lower a firm’s optimal investment trigger when the firm’s role in an investment project is first as the follower and then as the leader due to the increase in the project value volatility.

Figure 1 Optimal investment triggers when the firm is financially constrained in a monopoly

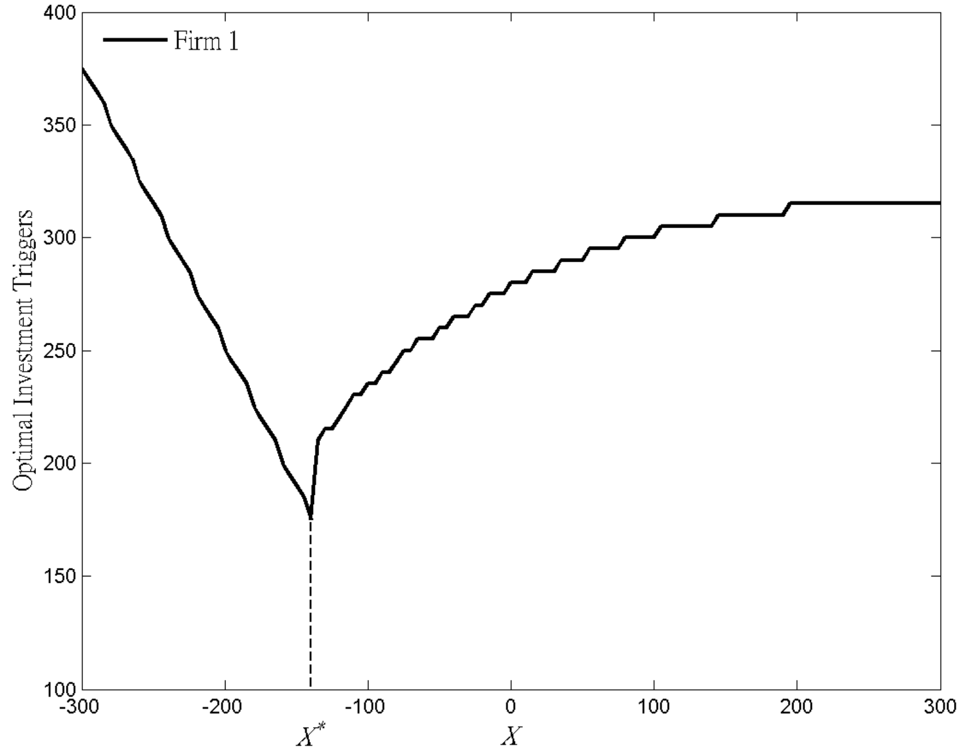
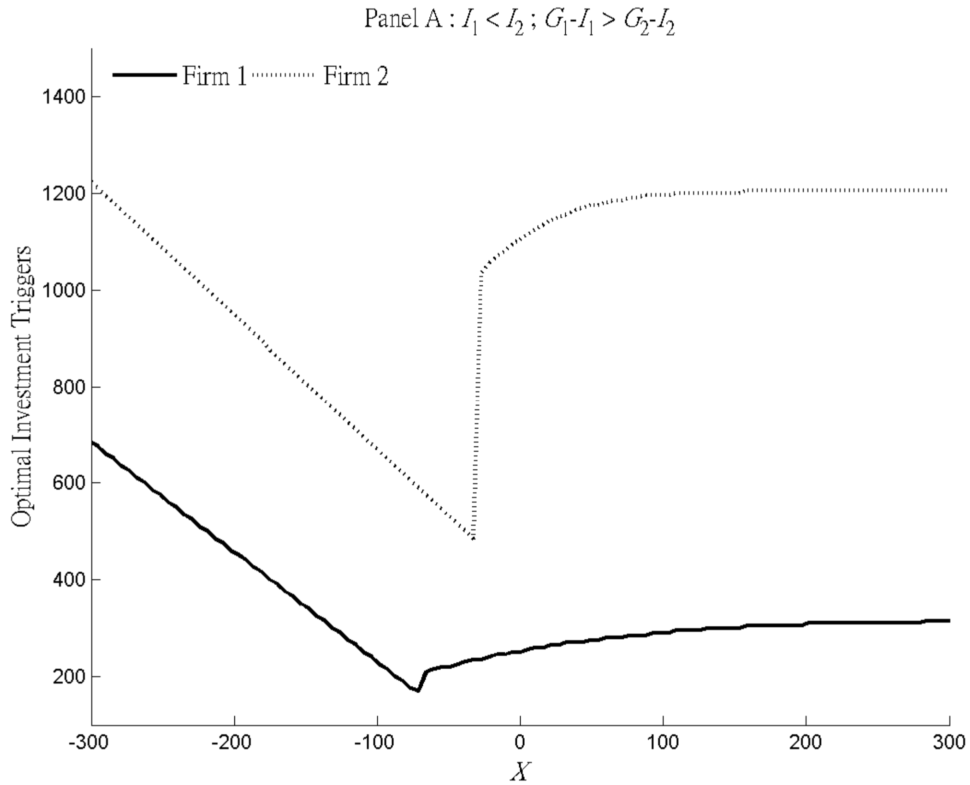


Figure 2 The effects of asymmetric financing constraints and investment costs on optimal investment triggers when the cost disadvantage is large



Panel B : $I_1 < I_2$; G_1-$I_1 < G_2$-I_2

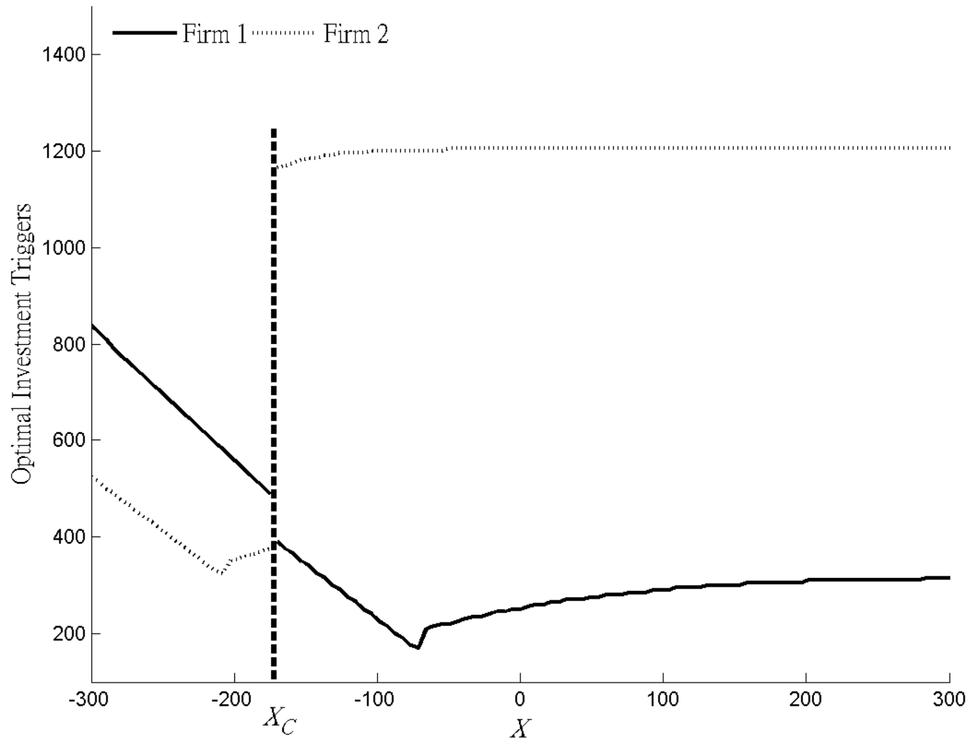
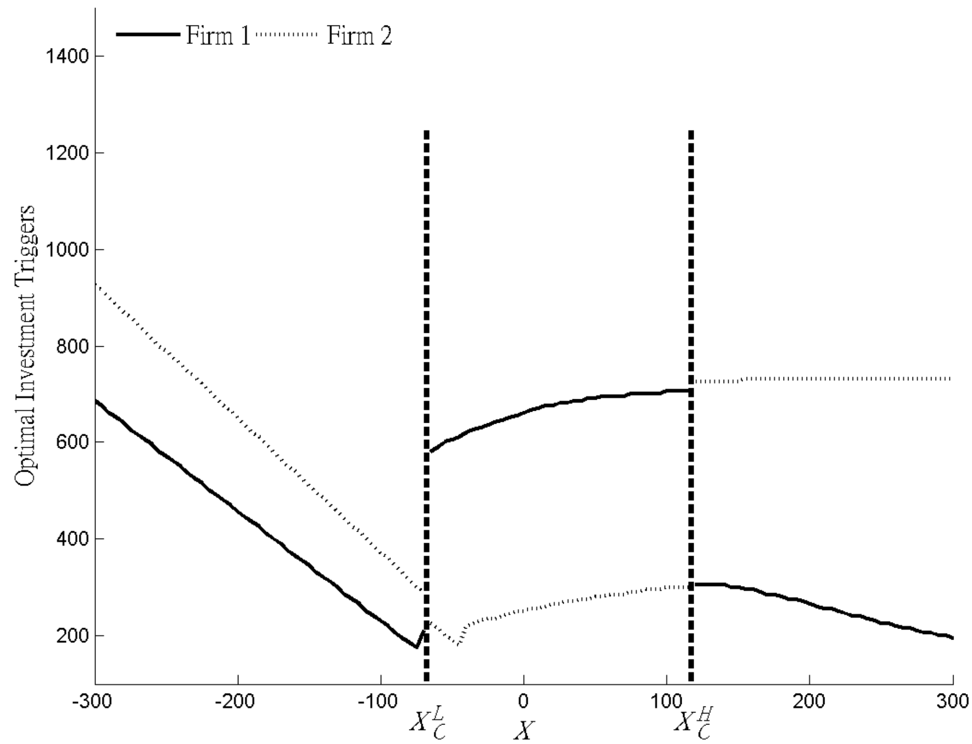
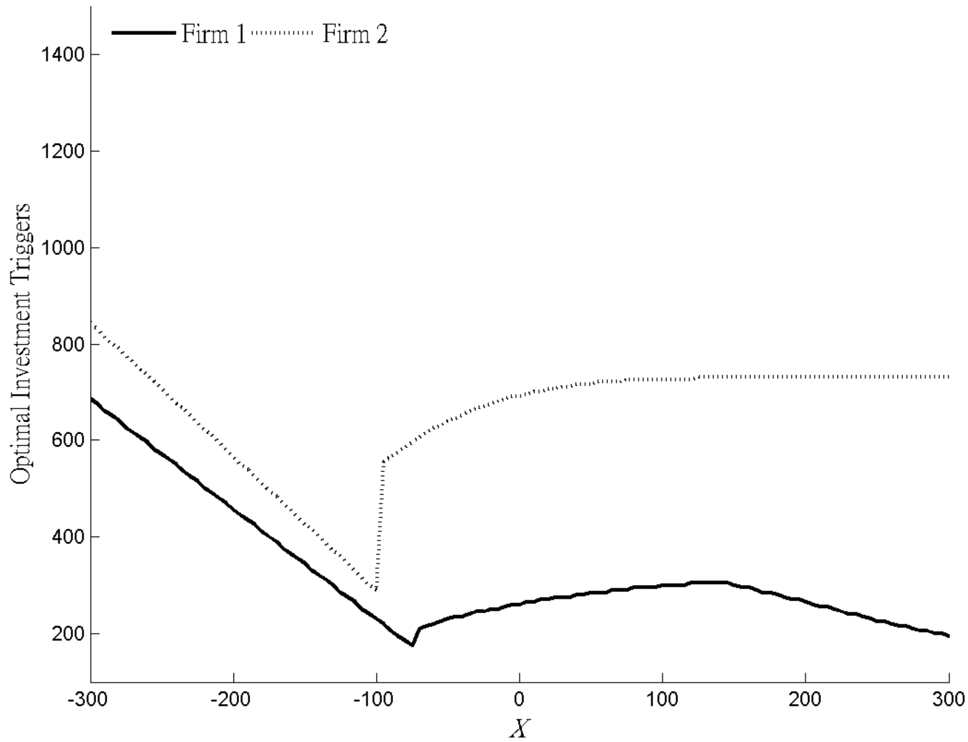


Figure 3 The effects of asymmetric financing constraints and investment costs on optimal investment triggers when the cost disadvantage is small

Panel A : $G_2 = 70$



Panel B : $G_2 = 100$



Panel C : $G_2 = 130$

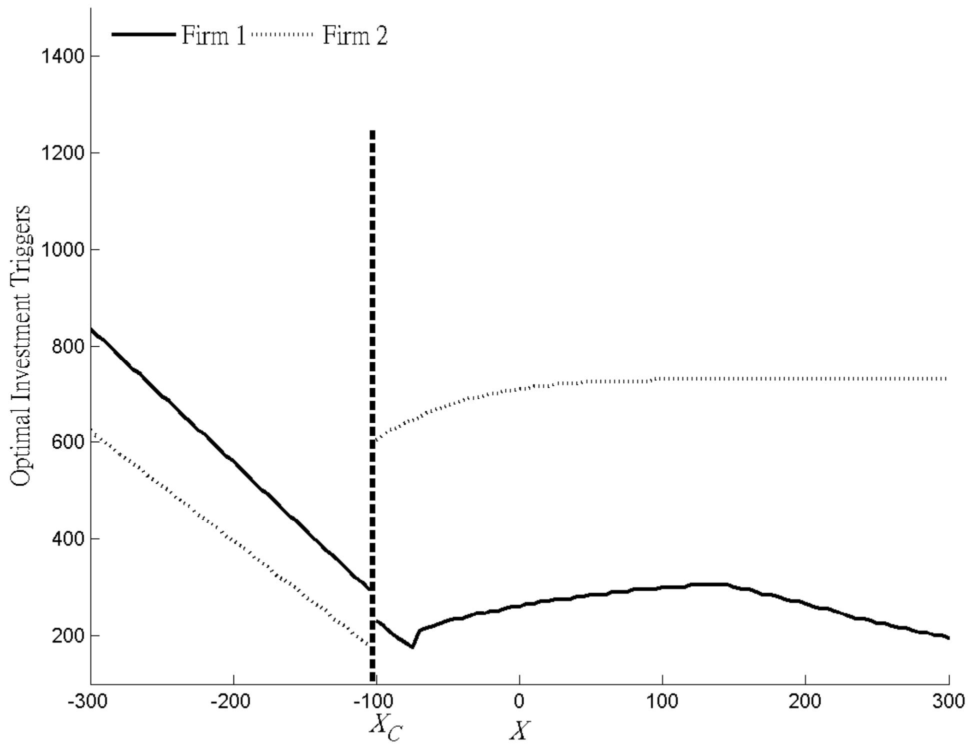
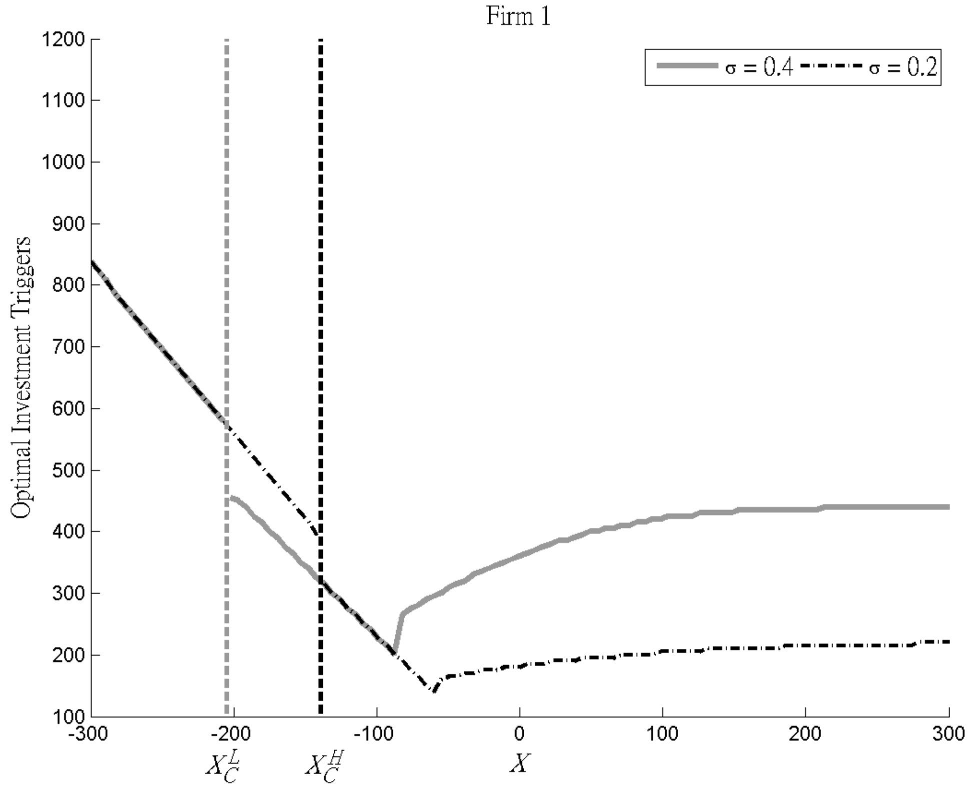


Figure 4 The effects of project value volatility on optimal investment triggers



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國科會補助計畫衍生研發成果推廣資料表

日期:2012/10/21

國科會補助計畫	計畫名稱: 實質選擇權、財務限制與先佔投資
	計畫主持人: 黃星華
	計畫編號: 100-2410-H-009-023- 學門領域: 財務

無研發成果推廣資料

100 年度專題研究計畫研究成果彙整表

計畫主持人：黃星華	計畫編號：100-2410-H-009-023-
計畫名稱：實質選擇權、財務限制與先佔投資	

成果項目			量化			單位	備註（質化說明：如數個計畫共同成果、成果列為該期刊之封面故事...等）
			實際已達成數（被接受或已發表）	預期總達成數(含實際已達成數)	本計畫實際貢獻百分比		
國內	論文著作	期刊論文	0	0	100%	篇	
		研究報告/技術報告	0	0	100%		
		研討會論文	0	0	100%		
		專書	0	0	100%		
	專利	申請中件數	0	0	100%	件	
		已獲得件數	0	0	100%		
	技術移轉	件數	0	0	100%	件	
		權利金	0	0	100%	千元	
	參與計畫人力（本國籍）	碩士生	0	0	100%	人次	
		博士生	1	1	100%		
		博士後研究員	0	0	100%		
		專任助理	0	0	100%		
國外	論文著作	期刊論文	0	1	80%	篇	
		研究報告/技術報告	0	0	100%		
		研討會論文	0	0	100%		
		專書	0	0	100%	章/本	
	專利	申請中件數	0	0	100%	件	
		已獲得件數	0	0	100%		
	技術移轉	件數	0	0	100%	件	
		權利金	0	0	100%	千元	
	參與計畫人力（外國籍）	碩士生	0	0	100%	人次	
		博士生	0	0	100%		
		博士後研究員	0	0	100%		
		專任助理	0	0	100%		

其他成果 (無法以量化表達之成果如辦理學術活動、獲得獎項、重要國際合作、研究成果國際影響力及其他協助產業技術發展之具體效益事項等，請以文字敘述填列。)	無

	成果項目	量化	名稱或內容性質簡述
科教處計畫加填項目	測驗工具(含質性與量性)	0	
	課程/模組	0	
	電腦及網路系統或工具	0	
	教材	0	
	舉辦之活動/競賽	0	
	研討會/工作坊	0	
	電子報、網站	0	
	計畫成果推廣之參與（閱聽）人數	0	

國科會補助專題研究計畫成果報告自評表

請就研究內容與原計畫相符程度、達成預期目標情況、研究成果之學術或應用價值（簡要敘述成果所代表之意義、價值、影響或進一步發展之可能性）、是否適合在學術期刊發表或申請專利、主要發現或其他有關價值等，作一綜合評估。

1. 請就研究內容與原計畫相符程度、達成預期目標情況作一綜合評估

■達成目標

□未達成目標（請說明，以 100 字為限）

　　□實驗失敗

　　□因故實驗中斷

　　□其他原因

說明：

2. 研究成果在學術期刊發表或申請專利等情形：

論文：□已發表 ■未發表之文稿 □撰寫中 □無

專利：□已獲得 □申請中 ■無

技轉：□已技轉 □洽談中 ■無

其他：（以 100 字為限）

3. 請依學術成就、技術創新、社會影響等方面，評估研究成果之學術或應用價值（簡要敘述成果所代表之意義、價值、影響或進一步發展之可能性）（以 500 字為限）

(1)主要學術成果如下：

First, we demonstrate that even with a significant cost disadvantage the less-constrained firm can be the leader when the risk of future funding shortfalls is relatively high. Second, the significantly more-constrained firm even with a small cost disadvantage can be the leader.

Third, we show that the preemption occurs when not only the asymmetry of investment costs but also the risk of future funding shortfalls is small. Finally, we demonstrate that higher investment project value volatility can lower a firm's optimal investment trigger when the firm's role in an investment project is first as the follower and then as the leader due to the increase in the project value volatility.

(2)主要影響及未來發展之可能性

1. 我們將公司間競爭之策略投資關係之探討，擴展至參與公司間資金與技術之互動結果。可作為公司進行策略投資決策時之參考依據。

2. 我們所發現之資金能力較弱之公司仍然可能成為領導者，可協助解釋 Munos(2009)所觀察到，大生技公司核可之新藥比率在下降而小生技公司核可之新藥比率在上升。此發現可作為生技或高科技新設或創投公司投資策略之參考。

3. 我們也發現公司間之競爭不僅是來自技術，與其資金能力亦有關，更重要的是技術與

資金之間會有交互作用。我們結果顯示公司在發展技術時不能忽略資金的重要性，同時也顯示出資本市場對公司競爭能力扮演顯著之角色。