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Leaders, followers, and equity risk premiums in booms and busts

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ABSTRACT

We study an investment problem in which two asymmetric firms face competition and the regime characterizing the economic condition follows a Markov switching process. We derive the value functions and investment thresholds of the leader and follower. The option value of regime uncertainty is found to be quite important for the investment decision of firms. We also show the relationship between the equity risk premium and the economic cycle that has not been done in previous studies, which proxy economic conditions by the level of demand or other state variables.

1. Introduction

The real options approach studies an investment problem in which the value of an investment opportunity is uncertain in the future and the cost of investment is somewhat irreversible. As Dixit and Pindyck (1994) point out, studying investment under competition is becoming important, not only because it enables us to analyze a more realistic situation, but also because competition is becoming fierce as a result of a globalizing economy and worldwide deregulation. In this background, many theoretical studies construct models with multiple firms in a real options framework to study the investment problem under competition.

Among them, Grenadier (1996) is regarded as a pioneering paper. He models a real estate market with two firms using a real options framework and claims that his model explains a US construction boom in the 1990s. Other important theoretical papers include Huisman and Kort (1999) and Nielsen (2002). Pawlina and Kort (2006) consider the case where two firms are asymmetric in their irreversible costs and present some theoretical results. Their model has three patterns of equilibrium: preemptive, sequential and simultaneous equilibria. Takashima et al. (2008) investigate an electricity market in which two firms are asymmetric in cost parameters and operating options. Kijima and Shibata (2005) and Bouis et al. (2009) extend these approaches to the framework of three or more symmetric firms. Nishide and Yagi (2016) introduce policy uncertainty to the preemption game. As seen above, the literature on real options in competitive environments is very extensive. For a more detailed literature review see, for example, Chevalier-Roignanta et al. (2011); Huisman et al. (2004) and Azevedo and Paxson (2014).

From another viewpoint, several studies introduce regime uncertainty within a real options analysis to capture economic cycles. As we observed in the global financial crisis after the failure of Lehman Brothers in September 2008, a change in regime can have a significant impact on economic circumstances. One example is the dislocations in the foreign exchange (FX) swap market between the US dollar and three major European currencies, which is empirically reported by Baba and Packer (2009). They report that almost all FX swap deviates from the covered interest rate parity after the Lehman failure, indicating a big effect caused by the change of economic conditions.

Theoretical papers that assume regime shifts within a real options framework include Chapter 9 of Dixit and Pindyck (1994); Guo et al. (2005); Hassett and Metcalf (1999); Pawlina and Kort (2005), and Nishide and Nomi (2009). Typically, regime uncertainty is modeled with parameters that describe the dynamics of the state variables following a Markov switching process. Among

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them, Driffill et al. (2013) study the investment decisions of a project with Markov-modulated geometric Brownian motions. They derive a simultaneous ordinary differential equation system that can calculate an investment threshold for each regime. Their main finding is that Markov switching risk causes a delay in the expected timing of the investment.

In this paper, we consider a situation where two asymmetric firms face an investment problem under competition with the market regime switching randomly. Specifically, we study the problem of investment timing where cash flow is defined by the demand shock and profit coefficient. In this paper, the key assumptions are that the coefficient is affected by the investment of the other firm, and that the dynamics of demand shock are modulated by a time-homogeneous Markov chain. The asymmetry of coefficients and investment costs enables us to investigate how a firm chooses its optimal timing, considering the firm's advantage or disadvantage in profits and costs. Investment timing is determined by its corresponding investment threshold: if a firm's investment threshold is lower (higher) and investment timing is earlier (later) than that of the other firm, the firm becomes the leader (follower). To the authors' best knowledge, this paper is the first attempt to combine a competitive real options model with a Markov switching regime. Our model not only extends previous studies to a more general and realistic setup, but also enables us to describe various patterns of competitive investment. In other words, we construct a theoretical model that produces a wide variety of strategies in a unified framework.

The major results of this study are as follows. Each finding or implication confirms that regime uncertainty is quite important for the investment decision of firms and the market equilibrium.

First, our model is flexible enough to produce a wide variety of results, such that a disadvantaged firm can be the leader even if the initial demand is low. Recall that, in previous studies, if both firms wait for investment due to low demand, only an advantaged firm has an incentive to invest earlier and always becomes a leader when the demand reaches a certain level. This means that existing theoretical studies cannot explain the fact that a less profitable firm sometimes enters a new and developing market before a more profitable firm, while our model can do so.

Following Pawlina and Kort (2006), we analyze the conditions for the occurrence of this type of equilibrium. The second result is the finding that a preemptive equilibrium, which represents a competitive situation among firms, is more likely to occur in a boom than in a bust. This result is most remarkable when the intensity of regime transition takes a moderate value. Intuitively, uncertainty of the demand evolution is higher in a bust and both the leader and follower have an incentive to wait for investment, resulting in a sequential or simultaneous equilibrium. The second result says that this situation is less likely to happen when the transition probability is extremely high or low. As we discuss later, this implies that both firms take the option value of regime uncertainty into consideration.

Third, unlike other previous studies such as Carlson et al. (2014), the equity risk premium can be non-monotonic with respect to the level of demand between the leader's and the follower's investment thresholds.[1] The reason is that both firms take the possibility of a regime change into account in our model. More specifically, potential investment caused by a sudden regime change vanishes the option value, and the risk premium in a bust changes the shape drastically at that point. Therefore, the risk premium in a bust is non-monotonic and has a kink.

Fourth, we show that the firm's beta in a bust is higher than that in a boom. Aguerrevere (2009) finds that when the demand is low, firms in competitive industries are riskier, whereas firms in concentrated industries are riskier when demand is high. At first glance, our study replicates the result of Aguerrevere (2009). However, our study does not show the negative relationship between the beta and economic growth. Many empirical papers such as Chen (1991) and Hoberg and Phillips (2010) suggest that the time-varying beta is negatively associated with economic growth rate or market returns, not the absolute level of state variables. In other words, our result with regime switching model theoretically describes the relationship in a more precise way than in Aguerrevere (2009). Intuitively, a lower economic growth rate reduces the investment opportunity due to a decrease in the option value. Thus, assets in place amount to a relatively large fraction of the firm value when the economic growth rate is low. In addition, assets in place in competitive market become riskier because firms' cash flows are more sensitive to demand dynamics. This result corresponds to the results of Chen (1991) and Hoberg and Phillips (2010), that is, there exists a negative relation between beta and the rate of economic growth.

The remaining part of the paper is organized as follows. In the next section, we concisely review the model and the results of Pawlina and Kort (2006) as a benchmark case. Section 3 presents our model that introduces a Markov regime switching process. In Section 4, we implement a numerical analysis and show how each firm chooses its investment threshold depending on the regime. Following the analysis in Pawlina and Kort (2006), we examine the conditions and types of equilibrium that occur in each regime in Section 5. Additionally, we show the effect of regime uncertainty on the investment decisions of both firms and the market equilibrium. We discuss how effectively our model explains the behavior of a firm's beta in relation to the economic cycles in Section 6. Section 7 provides some concluding remarks. The appendices following Section 7 present the glossary of the notation used in the paper, and supplementary results.

2. The model

2.1. Cash flow and market settings

Consider a situation where two firms compete in a product market. The demand shock in the market is denoted by P_t. Superscript $i \in \{1, 2\}$ denotes the identity of a firm. Each firm has a single investment opportunity to increase its profit. Prior to making an investment, firm i generates the cash flow $D^i_{00}P_t$. We assume that P_t follows a stochastic differential equation as

$$\mathrm{d}P_t = \mu_{\epsilon(t)}P_t\mathrm{d}t + \sigma_{\epsilon(t)}P_t\mathrm{d}z_t,$$

with initial value $P_0 = P$. Here, the expected growth rate μ and the volatility σ depend on $\epsilon(t)$, the regime at time t. We assume that there are only two regimes in the economy, so that we have

$$(\mu_\epsilon, \sigma_\epsilon) = \begin{cases} (\mu_1, \sigma_1), & \text{if } \epsilon = 1, \\ (\mu_2, \sigma_2), & \text{if } \epsilon = 2. \end{cases}$$

The key assumption is that the regime $\{\epsilon(t)\}$ follows a stationary Markov chain as

$$1 \to 2, \quad \text{with intensity } \lambda_1,$$
$$2 \to 1, \quad \text{with intensity } \lambda_2.$$

In later discussions, we regard regime 1 as a good state (boom) and regime 2 as a bad one (bust).

Suppose that firm i currently receives the instantaneous cash flow $D^i_{00}P$ and considers an investment in the new technology. The

[1] Lambrecht et al. (2015) show that a decrease in demand level increases a firm's stock beta due to operating leverage in downturns as in Carlson et al. (2004). However when the firm switches between different procurement options, the firm's beta exhibits non-monotonic behavior, as is shown in this paper.

investment incurs an irreversible cost K^i for firm i. Let τ_L^i denote the investment timing of firm i when the firm is a leader of the investment, and τ_F^i the timing in the case it is the follower. If firm i becomes the leader, the firm receives an instantaneous cash flow $D_{10}^i P_t$ until the other firm invests. After the investment by the other firm, the cash flow of firm i changes to $D_{11}^i P_t$. On the other hand, if firm i becomes the follower, the firm receives $D_{01}^i P_t$ after the other firm's investment, and then $D_{11}^i P_t$ after the firm's own investment. Here, to examine how the preemption of a leader firm affects the investment timing of both firms, we assume that the deterministic profit coefficient $D_{N_i N_j}^i$ has the relative magnitude relation

$$\begin{array}{ccc} D_{10}^i & > & D_{00}^i \\ \vee & & \vee \\ D_{11}^i & > & D_{01}^i, \end{array} \tag{1}$$

where

$$N_k = \begin{cases} 0, & \text{if firm } k \in \{i, j\} \text{ has not invested,} \\ 1, & \text{if firm } k \in \{i, j\} \text{ has invested.} \end{cases}$$

The inequalities $D_{10}^i > D_{00}^i$ and $D_{11}^i > D_{01}^i$ imply that the firm's investment increases its profit regardless of whether the other firm has invested or not. On the other hand, $D_{11}^i < D_{10}^i$ and $D_{01}^i < D_{00}^i$ imply that the investment of the other firm decreases the cash flow due to product obsolescence.[2] Thus the instantaneous cash flow of firm i in the case of being the leader can be expressed as

$$\mathbf{1}_{\{t<\tau_L^i\}} D_{00}^i P_t + \mathbf{1}_{\{\tau_L^i \le t < \tau_F^j\}} D_{10}^i P_t + \mathbf{1}_{\{t \ge \tau_F^j\}} D_{11}^i P_t, \tag{2}$$

where $j = 3 - i$. When firm i decides to be the follower, the firm receives the instantaneous cash flow $D_{11}^i P_t$ after the investment. The cash flow in this case is written as

$$\mathbf{1}_{\{t<\tau_L^j\}} D_{00}^i P_t + \mathbf{1}_{\{\tau_L^j \le t < \tau_F^i\}} D_{01}^i P_t + \mathbf{1}_{\{t \ge \tau_F^i\}} D_{11}^i P_t. \tag{3}$$

Finally, the discount rate r is assumed to be constant for simplicity.[3]

2.2. The asymmetric case without regime shift

In this subsection, we quickly review the investment problem of asymmetric firms without regime switching, considered by Pawlina and Kort (2006). The setup corresponds to the case $\mu \equiv \mu_1 = \mu_2$ and $\sigma \equiv \sigma_1 = \sigma_2$.[4]

Suppose first that firm i is the follower and let V_F^i and τ_F^i denote the value function and the investment timing of firm i, respectively. The optimal investment timing takes the form of a first hitting time as

$$\tau_F^i = \inf\{t \ge 0;\ P_t \ge \bar{P}_F^i\}.$$

Let G_L^i denote the net present value of the project for firm i as a leader for $t < \tau_F^j$.[5] If we assume the equilibrium notion of Fudenberg and Tirole (1985), firm i has an incentive to invest in the project when $G_L^i(P) - K^i \ge V_F^i(P)$. In other words, denoting the investment threshold of firm i as the leader by $\bar{P}_L^i$, $\bar{P}_L^i$ satisfies the equation

$$G_L^i(\bar{P}_L^i) - K^i = V_F^i(\bar{P}_L^i). \tag{4}$$

Throughout the following analysis, we lose no generality in assuming that $\bar{P}_F^1 < \bar{P}_F^2$. Hereafter, if this inequality holds, we say that firms 1 and 2 are advantaged and disadvantaged, respectively. In what follows we consider only the case where $\bar{P}_L^1 < \bar{P}_L^2$ in addition to $\bar{P}_F^1 < \bar{P}_F^2$.[6]

In some cases, both firms are willing to invest simultaneously, even though each firm knows that the other firm invests at the same time. Although the firms compete in the market, it results in a noncooperative outcome, which is often referred to as tacit collusion. Let V_S^i denote the value function of firm i's simultaneous investment. Simultaneous investment occurs if and only if

$$G_L^i(x) - K^i \le V_S^i(x), \quad \forall x. \tag{5}$$

The following proposition describes the strategies of both firms, depending on the three cases.

Proposition 1 (Pawlina and Kort, 2006)**.** *In the case of asymmetric firms and no regime switch, each firm takes the following strategy, depending on parameters, especially $\bar{P}_L^2$ and the initial value of P.*

(i) *Simultaneous investment: If (5) holds, both firms invest at the same time.*
(ii) *Preemptive investment: Suppose that (5) does not hold and there exist two real numbers $\bar{P}_L^2$ and $\tilde{P}_L^2$ that satisfy (4) with $\bar{P}_L^2 < \tilde{P}_L^2$. Only for $\bar{P}_L^2 \le P < \tilde{P}_L^2$, both firms have an incentive to invest immediately. Otherwise, firm 2 has no incentive to invest.*
(iii) *Sequential investment: Otherwise, the strategy of each firm is described by the following:[7] For all P, only firm 1 has an incentive to be the first investor.*

Remark 1. In this paper, we focus on the strategy adopted by each firm, and consequently, the characteristics of the market. Equivalently, we pay no attention to which firm actually becomes a leader. We also exclude the case of a coordination failure in which both firms simultaneously invest although it is not optimal. On the timing game and the results, refer to Fudenberg and Tirole (1985) for a general explanation, and to Huisman and Kort (1999) for related topics in a real options analysis.

Hereafter, firm 2 is said to be fully disadvantaged if there exists no real number that satisfies (4) for $i = 2$. In other words, firm 2 has no incentive to become the leader if firm 2 is fully disadvantaged. Otherwise, we call firm 2 partly disadvantaged.

We observe from Proposition 1 that firm 1 is always the leader when the state variable starts at a low level. In other words, if investments in a newly developing market are considered within this setup, a firm that is profitable or has an advanced technology in costs can always invest first and increase its profit before the other firm does. However, in actual markets, there are some cases in which a firm that seems less profitable invests before an advantaged firm. For example, in the thin-film transistor-liquid crystal display (TFT-LCD) industry, various firms including followers have invested in a boom by following an economic cycle in the industry; this phenomenon is called the "crystal cycle" (Mathews, 2005). As a result Korean and Taiwanese companies like Samsung and LG Display, which were follower companies previously, account for more than 80% of the TFT-LCD market. In the next section, we present a model that can explain this fact. That is, a disadvantaged firm may invest and increase its profit before an advantaged firm in our model.

[2] By imposing $D_{00}^i = D_{01}^i = 0$, we can consider the market entry model as in Grenadier (1996); Nielsen (2002); Takashima et al. (2008), and other studies.

[3] We do not consider the case where the discount rate r is modulated by a Markov chain because it produces no qualitative difference.

[4] Pawlina and Kort (2006) consider the case where only cost parameters $\{K^i\}$ are asymmetric. The results in this subsection are essentially the same as theirs despite the difference.

[5] The closed form expressions of V_F^i, G_L^i and $\bar{P}_F^i$ are obtained by Pawlina and Kort (2006).

[6] The sufficient conditions for $\bar{P}_L^1 < \bar{P}_L^2$ and $\bar{P}_F^1 < \bar{P}_F^2$ are that

$$\frac{D_{10}^1 - D_{00}^1}{K^1} \ge \frac{D_{10}^2 - D_{00}^2}{K^2} \text{ and } \frac{D_{11}^1 - D_{01}^1}{K^1} > \frac{D_{11}^2 - D_{01}^2}{K^2},$$

which are always assumed throughout this paper.

[7] If (4) has exactly one solution for firm 2, firm 2 is at this point indifferent between being the leader and the follower and strictly prefers being the follower for the remaining values of P. Therefore, it always weakly prefers to be the follower.

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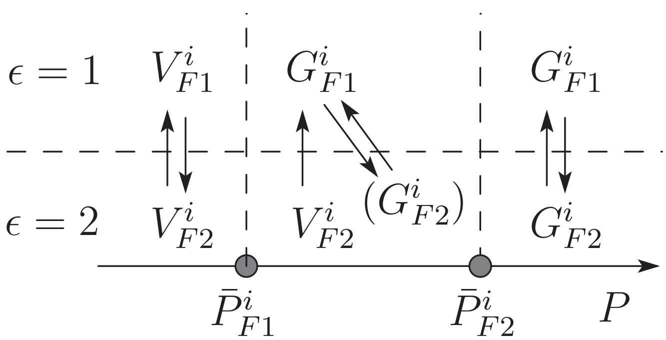

Fig. 1. Regime shifts and the value functions for the follower firm.

3. The asymmetric case with Markov regime switching

In this section, we propose our original model that introduces a Markov switching regime into Pawlina and Kort (2006), and show how results are different from the case of no regime switch. As in the previous section, we assume that firm 1 has the advantage for all regimes.

3.1. The follower's problem

First, we consider the problem of the follower's investment decision. $V^i_{F\epsilon}$ denotes the value function of firm i in regime ϵ, and $G^i_{F\epsilon}$ denotes the net present value of an immediate investment.

Recall that many papers, such as Bloome (2009), report the negative relationship between uncertainty and economic conditions. Following this empirical finding, we assume $\mu_1 > \mu_2$ and $\sigma_1 < \sigma_2$, implying that regimes 1 and 2 represent a boom and a bust, respectively. Other variables such as $D^i_{N_iN_j}$ are assumed to be independent of the regime. When the parameters μ and σ are modulated by a Markov chain with two possible states, there are two thresholds $\bar{P}^i_{F1}$ and $\bar{P}^i_{F2}$ with $\bar{P}^i_{F1} < \bar{P}^i_{F2}$.[8] Suppose that $\bar{P}^i_{F1} \le P < \bar{P}^i_{F2}$ and the regime shifts from 2 to 1. Then the follower firm has an incentive to invest in the project all at once. Note that an investment is irreversible in the sense that the firm cannot cancel the project if the regime becomes 2 again. Fig. 1 describes how the project values changes, depending on the value of P and the regime.

We need to take the possibility of a regime shift into account to derive the value function for each regime. The derivation procedure is exactly the same as Driffill et al. (2013), and thus we refer to their paper for a detailed discussion.

First suppose that $P \ge \bar{P}^i_{F2}$. Firm i immediately invests in the project regardless of the realized regime. Hence the value function $V^i_{F\epsilon}$ is equal to the net present value of the project minus the cost, or $V^i_{F\epsilon} = G^i_{F\epsilon} - K^i$. It is easily confirmed from Ito's formula that $\{G^i_{F\epsilon}\}_{\epsilon=1,2}$ satisfy the following simultaneous ordinary differential equation (ODE hereafter) system:

$$\begin{cases} \frac{\sigma_1^2}{2}P^2\frac{\mathrm{d}^2\ G^i_{F1}}{\mathrm{d}P^2} + \mu_1 P\frac{\mathrm{d}G^i_{F1}}{\mathrm{d}P} - rG^i_{F1} + \lambda_1(G^i_{F2} - G^i_{F1}) + D^i_{11}P = 0, \\ \frac{\sigma_2^2}{2}P^2\frac{\mathrm{d}^2\ G^i_{F2}}{\mathrm{d}P^2} + \mu_2 P\frac{\mathrm{d}G^i_{F2}}{\mathrm{d}P} - rG^i_{F2} + \lambda_2(G^i_{F1} - G^i_{F2}) + D^i_{11}P = 0. \end{cases} \tag{6}$$

The last terms of (6) represent the received cash flow of the follower in regime ϵ because both firms have already invested, and the fourth term represents the possibility of a regime shift from one to the other.

[8] From numerical implementation with a wide variety of parameter settings, $\bar{P}^i_{F1}$ is always lower than $\bar{P}^i_{F2}$ if $\mu_1 > \mu_2$ and $\sigma_1 < \sigma_2$.

Since $G^i_{F\epsilon}$ evidently includes no option value, we conjecture that the function takes a linear form

$$G^i_{F\epsilon}(P) = \pi_\epsilon D^i_{11}P.$$

Substituting it into the simultaneous ODEs, we have

$$\pi_\epsilon = \frac{r + \lambda_\epsilon + \lambda_{\hat{\epsilon}} - \mu_{\hat{\epsilon}}}{(r + \lambda_\epsilon - \mu_\epsilon)(r + \lambda_{\hat{\epsilon}} - \mu_{\hat{\epsilon}}) - \lambda_\epsilon\lambda_{\hat{\epsilon}}}, \tag{7}$$

where $\hat{\epsilon} = 3 - \epsilon$.

Second, we consider the case $\bar{P}^i_{F1} \le P < \bar{P}^i_{F2}$. When $\epsilon = 1$, the follower firm immediately invests in the project and value function is equal to $\pi_1 D^i_{11}P - K^i$ with coefficient π_1 given by (7). On the other hand, the value function in regime 2, which includes the value of a potential investment in the future, satisfies the following ODE:

$$\frac{\sigma_2^2}{2}P^2\frac{\mathrm{d}^2\ V^i_{F2}}{\mathrm{d}P^2} + \mu_2 P\frac{\mathrm{d}V^i_{F2}}{\mathrm{d}P} - rV^i_{F2} + \lambda_2(G^i_{F1} - K^i - V^i_{F2}) + D^i_{01}P = 0.$$

We conjecture that the candidate function takes the form

$$V^i_{F2}(P) = b^i_{21}P^{\alpha_1} + b^i_{22}P^{\alpha_2} + b^i_{23}P + b^i_{24}. \tag{8}$$

The first two terms of (8) represent the option value to wait for the investment in the project, while the last two terms are the net present value of the cash flow after investment due to a sudden regime shift. Substituting it into the ODE, we obtain

$$b^i_{23} = \frac{D^i_{01} + \lambda_2\pi_1 D^i_{11}}{r + \lambda_2 - \mu_2}, \quad b^i_{24} = -\frac{\lambda_2}{r + \lambda_2}K^i$$

and find that α_1 and α_2 are the roots of the quadratic equation

$$\frac{\sigma_2^2}{2}\alpha(\alpha - 1) + \mu_2\alpha - (r + \lambda_2) = 0. \tag{9}$$

Note also that the value function in regime 2 must satisfy

$$V^i_{F2}(\bar{P}^i_{F2}) = G^i_{F2}(\bar{P}^i_{F2}) - K^i,$$

and

$$\lim_{P \uparrow \bar{P}^i_{F2}} \frac{\mathrm{d}V^i_{F2}}{\mathrm{d}P}(P) = \lim_{P \downarrow \bar{P}^i_{F2}} \frac{\mathrm{d}G^i_{F2}}{\mathrm{d}P}(P)$$

as value-matching and smooth-pasting conditions, respectively.

Third, for $P < \bar{P}^i_{F1}$, the value functions satisfy the following ODE system:

$$\begin{cases} \frac{\sigma_1^2}{2}P^2\frac{\mathrm{d}^2\ V^i_{F1}}{\mathrm{d}P^2} + \mu_1 P\frac{\mathrm{d}V^i_{F1}}{\mathrm{d}P} - rV^i_{F1} + \lambda_1(V^i_{F2} - V^i_{F1}) + D^i_{01}P = 0, \\ \frac{\sigma_2^2}{2}P^2\frac{\mathrm{d}^2\ V^i_{F2}}{\mathrm{d}P^2} + \mu_2 P\frac{\mathrm{d}V^i_{F2}}{\mathrm{d}P} - rV^i_{F2} + \lambda_2(V^i_{F1} - V^i_{F2}) + D^i_{01}P = 0. \end{cases} \tag{10}$$

The candidate function of $V^i_{F\epsilon}$ is conjectured to be

$$V^i_{F\epsilon}(P) = c^i_{\epsilon 1}P^{\gamma_1} + c^i_{\epsilon 2}P^{\gamma_2} + c^i_{\epsilon 3}P, \quad \epsilon = 1, 2. \tag{11}$$

In contrast to (8), (11) does not contain a constant term associated with the cost K^i since a sudden regime shift does not induce an immediate investment. Substituting (11) into (10) leads to the particular solution

$$c^i_{\epsilon 3} = \pi_\epsilon D^i_{01},$$

and the four equations:

$$\begin{cases} \left(\frac{\sigma_1^2}{2}\gamma_1(\gamma_1-1)+\mu_1\gamma_1-(r+\lambda_1)\right)c_{11}^i+\lambda_1 c_{21}^i=0, \\ \left(\frac{\sigma_1^2}{2}\gamma_2(\gamma_2-1)+\mu_1\gamma_2-(r+\lambda_1)\right)c_{12}^i+\lambda_1 c_{22}^i=0, \\ \left(\frac{\sigma_2^2}{2}\gamma_1(\gamma_1-1)+\mu_2\gamma_1-(r+\lambda_2)\right)c_{21}^i+\lambda_2 c_{11}^i=0, \\ \left(\frac{\sigma_2^2}{2}\gamma_2(\gamma_2-1)+\mu_2\gamma_2-(r+\lambda_2)\right)c_{22}^i+\lambda_2 c_{12}^i=0. \end{cases}$$

Since $\lim_{P\downarrow 0} V_{F\epsilon}^i(P)=0$, γ_1 and γ_2 must be the positive roots of the following quartic equation:

$$\left[\frac{\sigma_1^2}{2}\gamma(\gamma-1)+\mu_1\gamma-(r+\lambda_1)\right] \times\left[\frac{\sigma_2^2}{2}\gamma(\gamma-1)+\mu_2\gamma-(r+\lambda_2)\right]=\lambda_1\lambda_2. \quad (12)$$

The threshold in regime 1, denoted by $\bar{P}_{F1}^i$, satisfies

$$V_{F1}^i(\bar{P}_{F1}^i)=G_{F1}^i(\bar{P}_{F1}^i)-K^i$$

and

$$\lim_{P\uparrow\bar{P}_{F1}^i}\frac{\mathrm{d}V_{F1}^i}{\mathrm{d}P}(P)=\lim_{P\downarrow\bar{P}_{F1}^i}\frac{\mathrm{d}G_{F1}^i}{\mathrm{d}P}(P)$$

as value-matching and smooth-pasting conditions. Similarly, in regime 2, the continuity and high-contact conditions are given by

$$\lim_{P\uparrow\bar{P}_{F1}^i}V_{F2}^i(P)=\lim_{P\downarrow\bar{P}_{F1}^i}V_{F2}^i(P)$$

and

$$\lim_{P\uparrow\bar{P}_{F1}^i}\frac{\mathrm{d}V_{F2}^i}{\mathrm{d}P}(P)=\lim_{P\downarrow\bar{P}_{F1}^i}\frac{\mathrm{d}V_{F2}^i}{\mathrm{d}P}(P),$$

respectively.

We now summarize the result as a proposition.

Proposition 2. *The value function of firm i in the case of being the follower for regime 1 is given by*

$$V_{F1}^i(P)=\begin{cases}\pi_1 D_{11}^i P-K^i, & \text{for } P\geq\bar{P}_{F1}^i,\\ c_{11}^i P^{\gamma_1}+c_{12}^i P^{\gamma_2}+\pi_1 D_{01}^i P, & \text{for } P<\bar{P}_{F1}^i\end{cases}$$

and for regime 2 by

$$V_{F2}^i(P)=\begin{cases}\pi_2 D_{11}^i P-K^i, & \text{for } P\geq\bar{P}_{F2}^i,\\ b_{21}^i P^{\alpha_1}+b_{22}^i P^{\alpha_2} & \\ \quad+\frac{D_{01}^i+\lambda_2\pi_1 D_{11}^i}{r+\lambda_2-\mu_2}P-\frac{\lambda_2}{r+\lambda_2}K^i, & \text{for } \bar{P}_{F1}^i\leq P<\bar{P}_{F2}^i,\\ \ell_1 c_{11}^i P^{\gamma_1}+\ell_2 c_{12}^i P^{\gamma_2}+\pi_2 D_{01}^i P, & \text{for } P<\bar{P}_{F1}^i,\end{cases}$$

where

$$\ell_k=\frac{r+\lambda_1-\mu_1\gamma_k-\frac{\sigma_1^2}{2}\gamma_k(\gamma_k-1)}{\lambda_1},\quad k=1,2.$$

The coefficients and the investment thresholds are determined by the system of six simultaneous Eqs. (B.1)–(B.6) in Appendix B.

The formulae of value functions are the same as in Driffill et al. (2013) because the follower no longer competes with the other firm. Since the system has totally six unknowns $\bar{P}_{F1}^i$, $\bar{P}_{F2}^i$, b_{21}^i, b_{22}^i, c_{11}^i and c_{12}^i and has six equations at the same time, it is theoretically solvable. However, it is difficult to obtain a closed-form solution. Therefore, we shall numerically calculate the simultaneous equations to solve and derive the investment thresholds.

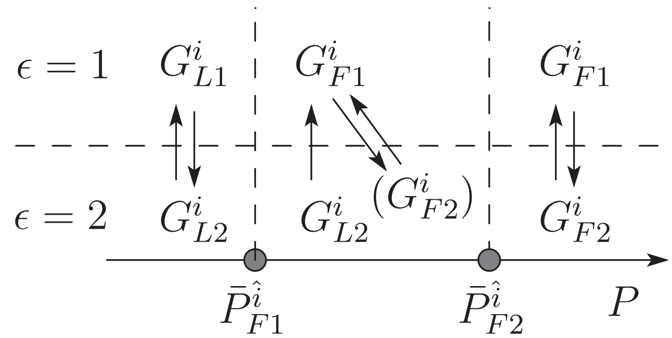

Fig. 2. Regime shifts and the NPV of the leader firm.

3.2. The leader's problem

In this subsection, we consider the investment decision of firm i as the leader. Let $G_{L\epsilon}^i$ denote the net present value (NPV hereafter) of the project for the leader in regime ϵ after investment. Note that the function $G_{L\epsilon}^i$ depends on the thresholds of the follower firm $\bar{P}_{F\epsilon}^j$, since the cash flow is affected by whether the other firm invests or not. Taking this into consideration, the NPVs of an immediate investment by the leader are described as Fig. 2.

We derive the functions $G_{L\epsilon}^i$ by noting these relations.

First, consider the case $P\geq P_{F2}^j$. In this situation the other firm is willing to immediately invest regardless of the regime, and we have $G_{L\epsilon}^i(P)=G_{F\epsilon}^i(P)=\pi_\epsilon D_{11}^i P$, where π_ϵ are given by (7).

For $\bar{P}_{F1}^j\leq P<\bar{P}_{F2}^j$, the other firm immediately invests and receives the cash flow in regime 1, implying that $G_{L1}^i(P)=G_{F1}^i(P)=\pi_1 D_{11}^i P$. On the other hand, G_{L2}^i, the NPV of firm i in regime 2 as a leader, satisfies the following ODE

$$\frac{\sigma_2^2}{2}P^2\frac{\mathrm{d}^2\ G_{L2}^i}{\mathrm{d}P^2}+\mu_2 P\frac{\mathrm{d}G_{L2}^i}{\mathrm{d}P}-rG_{L2}^i+\lambda_2(G_{F1}^i-G_{L2}^i)+D_{10}^i P=0. \quad (13)$$

Note that (13) includes G_{F1}^i and that it is already solved in the previous discussions. The last term of (13) represents the current cash flow of firm i as the leader. Let the candidate function of G_{L2}^i be conjectured as

$$G_{L2}^i(P)=e_{21}^i P^{\alpha_1}+e_{22}^i P^{\alpha_2}+e_{23}^i P. \quad (14)$$

The first two terms describe the (negative) option value that represents the future entry by the other firm, while the last term is equal to the net present value of the cash flow in the future. Substituting the particular solution $e_{23}^i P$ into the ODE yields

$$e_{23}^i=\frac{D_{10}^i+\lambda_2\pi_1 D_{11}^i}{r+\lambda_2-\mu_2}.$$

In the case of a leader firm, only the value-matching condition at $\bar{P}_{F2}^j$ holds, that is,

$$G_{L2}^i(\bar{P}_{F2}^j)=G_{F2}^i(\bar{P}_{F2}^j)$$

and any smooth-pasting condition is not necessary. See Driffill et al. (2013) for further discussion of this issue.

For $P<\bar{P}_{F1}^j$, the ODEs of $G_{L\epsilon}^i$ are given by

$$\begin{cases}\frac{\sigma_1^2}{2}P^2\frac{\mathrm{d}^2\ G_{L1}^i}{\mathrm{d}P^2}+\mu_1 P\frac{\mathrm{d}G_{L1}^i}{\mathrm{d}P}-rG_{L1}^i+\lambda_1(G_{L2}^i-G_{L1}^i)+D_{10}^i P=0,\\ \frac{\sigma_2^2}{2}P^2\frac{\mathrm{d}^2\ G_{L2}^i}{\mathrm{d}P^2}+\mu_2 P\frac{\mathrm{d}G_{L2}^i}{\mathrm{d}P}-rG_{L2}^i+\lambda_2(G_{L1}^i-G_{L2}^i)+D_{10}^i P=0.\end{cases} \quad (15)$$

The candidate function of $G_{L\epsilon}^i$ is conjectured to be

$$G_{L\epsilon}^i(P)=h_{\epsilon 1}^i P^{\gamma_1}+h_{\epsilon 2}^i P^{\gamma_2}+h_{\epsilon 3}^i P. \quad (16)$$

We can provide an interpretation for (16) in a way that is similar to that for (8). Substituting the particular solution $h^i_{\epsilon 3}P$ into the ODEs, we obtain

$$h^i_{\epsilon 3} = \pi_\epsilon D^i_{10}.$$

In regime 1, the value-matching condition at $\bar{P}^j_{F1}$ is given by

$$G^i_{L1}(\bar{P}^j_{F1}) = G^i_{F1}(\bar{P}^j_{F1}).$$

In regime 2, we have continuity and high-contact conditions as

$$\lim_{P\uparrow \bar{P}^j_{F1}} G^i_{L2}(P) = \lim_{P\downarrow \bar{P}^j_{F1}} G^i_{L2}(P)$$

and

$$\lim_{P\uparrow \bar{P}^j_{F1}} \frac{\mathrm{d}G^i_{L2}(P)}{\mathrm{d}P} = \lim_{P\downarrow \bar{P}^j_{F1}} \frac{\mathrm{d}G^i_{L2}(P)}{\mathrm{d}P},$$

respectively.[9]

The following proposition summarizes the case of a leader.

Proposition 3. *The NPV of cash flow for firm i as a leader is given by*

$$G^i_{L1}(P) = \begin{cases} \pi_1 D^i_{11}P, & \text{for } P \geq \bar{P}^j_{F1}, \\ h^i_{11}P^{\gamma_1} + h^i_{12}P^{\gamma_2} + \pi_1 D^i_{10}P, & \text{for } P < \bar{P}^j_{F1} \end{cases}$$

in regime 1 and

$$G^i_{L2}(P) = \begin{cases} \pi_2 D^i_{11}P, & \text{for } P \geq \bar{P}^j_{F2}, \\ e^i_{21}P^{\alpha_1} + e^i_{22}P^{\alpha_2} + \frac{D^i_{10}+\lambda_2\pi_1 D^i_{11}}{r+\lambda_2-\mu_2}P, & \text{for } \bar{P}^j_{F1} \leq P < \bar{P}^j_{F2}, \\ \ell_1 h^i_{11}P^{\gamma_1} + \ell_2 h^i_{12}P^{\gamma_2} + \pi_2 D^i_{10}P, & \text{for } P < \bar{P}^j_{F1} \end{cases}$$

in regime 2. The coefficients and the investment thresholds are determined by the system of four simultaneous Eqs. (B.7)–(B.10) in Appendix B. The threshold of firm i as a leader in regime ϵ, which denotes $\bar{P}^i_{L\epsilon}$, can be obtained by the condition $G^i_{L\epsilon}(\bar{P}^i_{L\epsilon}) - K^i = V^i_{F\epsilon}(\bar{P}^i_{L\epsilon})$.

The formulae of the NPV cash flow for the leader are different from Driffill et al. (2013) unlike that of value functions for the follower. We remark on the difference by the decomposition of $G^i_{L\epsilon}$.

Remark 2. As in Carlson et al. (2014), each term in the function $G^i_{L\epsilon}$ represents:

$$\underbrace{\pi_\epsilon D^i_{10}P}_{\text{assets in place}} + \underbrace{h^i_{\epsilon 1}P^{\gamma_1} + h^i_{\epsilon 2}P^{\gamma_2}}_{\textbf{rival-value adjustment}}$$

for $P < \bar{P}^j_{F1}$, and

$$\underbrace{\frac{D^i_{10}+\lambda_2\pi_1 D^i_{11}}{r+\lambda_2-\mu_2}P}_{\text{assets in place + cashflow for regime change}} + \underbrace{e^i_{21}P^{\alpha_1} + e^i_{22}P^{\alpha_2}}_{\textbf{rival-value adjustment}} \tag{17}$$

for $\bar{P}^j_{F1} \geq P < \bar{P}^j_{F2}$ and $\epsilon = 2$.[10] The first term in (17) includes the NPV associated with a sudden regime change from 2 to 1. The rival-value adjustment reflects the effect of competitor expansion and is always negative.

[9] The function G^i_{L2} must be of C^1 except for $P = \bar{P}^j_{F2}$.

[10] Formally,

$$\pi_\epsilon D^i_{10}P = \mathbb{E}_{(\epsilon,P)}\left[\int_0^\infty e^{-rt}D^i_{10}P_t \mathrm{d}t\right],$$

$$\frac{D^i_{10}+\lambda_2\pi_1 D^i_{11}}{r+\lambda_2-\mu_2}P = \mathbb{E}_{(\epsilon=2,P)}\left[\int_0^{T_1} e^{-rt}D^i_{10}P_t \mathrm{d}t + \int_{T_1}^\infty e^{-rt}D^i_{11}P_t \mathrm{d}t\right],$$

where $T_1 = \inf\{t \geq 0; \epsilon(t) = 1\}$.

3.3. Simultaneous investment

Let $\tau_{S\epsilon} = \inf\{t \geq 0;\ P_t \geq \bar{P}_{S\epsilon}\}$ denote the timing of simultaneous investment by both firms in regime ϵ. Thus the instantaneous cash flow of firm i's simultaneous investment can be expressed as

$$\mathbf{1}_{\{t<\tau_{S\epsilon}\}}D^i_{00}P_t + \mathbf{1}_{\{t\geq\tau_{S\epsilon}\}}D^i_{11}P_t, \tag{18}$$

which means that the value function of simultaneous investment is given by replacing D^i_{01} with D^i_{00} in the value function of the follower.

Since firm 1 has advantage in profit and cost, the optimal investment threshold of firm 1 is always lower than that of firm 2. Firm 2 reluctantly follows firm 1's timing and only firm 1 can maximize the value of simultaneous investment. Therefore, the smooth-pasting condition is satisfied only for firm 1, implying that

$$V^i_{S\epsilon}(\bar{P}_{S\epsilon}) = G^i_{F\epsilon}(\bar{P}_{S\epsilon}) - K^i,$$

for $i = 1, 2$ and

$$\lim_{P\uparrow\bar{P}_{S\epsilon}} \frac{\mathrm{d}V^1_{S\epsilon}}{\mathrm{d}P}(P) = \lim_{P\downarrow\bar{P}_{S\epsilon}} \frac{\mathrm{d}G^1_{F\epsilon}}{\mathrm{d}P}(P).$$

We now summarize the result for the simultaneous investment as a proposition.

Proposition 4. *The value function of a simultaneous investment in regime 1 is given by*

$$V^i_{S1}(P) = \begin{cases} \pi_1 D^i_{11}P - K^i, & \text{for } P \geq \bar{P}_{S1}, \\ q^i_{11}P^{\gamma_1} + q^i_{12}P^{\gamma_2} + \pi_1 D^i_{00}P, & \text{for } P < \bar{P}_{S1} \end{cases}$$

and in regime 2 by

$$V^i_{S2}(P) = \begin{cases} \pi_2 D^i_{11}P - K^i, & \text{for } P \geq \bar{P}_{S2}, \\ m^i_{21}P^{\alpha_1} + m^i_{22}P^{\alpha_2} \\ \quad + \frac{D^i_{00}+\lambda_2\pi_1 D^i_{11}}{r+\lambda_2-\mu_2}P - \frac{\lambda_2}{r+\lambda_2}K^i, & \text{for } \bar{P}_{S1} \leq P < \bar{P}_{S2}, \\ \ell_1 q^i_{11}P^{\gamma_1} + \ell_2 q^i_{12}P^{\gamma_2} + \pi_2 D^i_{00}P, & \text{for } P < \bar{P}_{S1}. \end{cases}$$

The coefficients and the investment thresholds are determined by the system of six simultaneous Eqs. (B.11)–(B.16) in Appendix B.

The formulae of value functions are the same as in Proposition 2 because the value function of simultaneous investment is given by replacing D^i_{01} with D^i_{00} in the value function of the follower. Note that the system for firm 2 only has four simultaneous Eqs. (B.11)–(B.14) and unknowns m^i_{21}, m^i_{22}, q^i_{11} and q^i_{12} since firm 2 cannot determine investment thresholds.

4. Investment strategies

In this section, we study with numerical examples how each firm chooses its investment strategy, depending on the strategy of the other firm. We present three examples to show that our model is rich and flexible enough to explain many actual situations within a unified framework.

4.1. Case 1: benchmark case

The parameter values in Table 1 are used for the numerical analysis as a benchmark case.

With these parameter values, we obtain thresholds in Table 2. The numerical results actually show that $\bar{P}^1_{F\epsilon} < \bar{P}^2_{F\epsilon}$ for $\epsilon = 1, 2$. Note that firm 2 is partly disadvantaged in regime 1 but fully disadvantaged in regime 2.

Table 3 summarizes the investment strategies that each firm chooses, depending on the range of the state variable P.

Table 1
Parameter setting in the benchmark case.

μ_1	μ_2	σ_1	σ_2	r	λ_1	λ_2	K^1	K^2
0.05	0	0.2	0.5	0.1	0.2	0.2	10	12
D^1_{00}	D^2_{00}	D^1_{01}	D^2_{01}	D^1_{10}	D^2_{10}	D^1_{11}	D^2_{11}	
0.5	0.5	0.25	0.25	1.5	1.4	1	0.9	

Table 2
Thresholds of the firms for the benchmark case.

$\bar{P}^1_{L1}$	$\bar{P}^1_{L2}$	$\bar{P}^1_{F1}$	$\bar{P}^1_{F2}$	$\bar{P}_{S1}$	$\bar{P}_{S2}$
0.8635	1.1383	2.1706	3.4224	3.2558	5.1336
$\bar{P}^2_{L1}$	$\tilde{P}^2_{L1}$	$\bar{P}^2_{F1}$	$\bar{P}^2_{F2}$		
1.6159	1.8054	3.0054	4.7387		

Table 3
Investment strategies of each firm in case 1.

$\epsilon = 1$	1	1	×	1	1	1,2	1,2	1,2
$\epsilon = 2$		1	1	1	1	1	1	1,2
	$\bar{P}^1_{L1}$	$\bar{P}^1_{L2}$	$\bar{P}^2_{L1}$	$\tilde{P}^2_{L1}$	$\bar{P}^1_{F1}$	$\bar{P}^2_{F1}$	$\bar{P}^1_{F2}$	$\bar{P}^2_{F2}$

Table 4
Thresholds of the firms in case 2.

$\bar{P}^1_{L1}$	$\bar{P}^1_{L2}$	$\bar{P}^1_{F1}$	$\bar{P}^1_{F2}$	$\bar{P}_{S1}$	$\bar{P}_{S2}$
0.8812	1.1772	2.1706	3.4224	3.2558	5.1336
$\bar{P}^2_{L1}$	$\tilde{P}^2_{L1}$	$\bar{P}^2_{L2}$	$\tilde{P}^2_{L2}$	$\bar{P}^2_{F1}$	$\bar{P}^2_{F2}$
1.1121	2.0805	1.6371	3.2653	2.7549	4.3438

Table 5
Investment strategies of each firm in case 2.

$\epsilon = 1$	1	×	×	×	1	1	1,2	1,2	1,2	1,2
$\epsilon = 2$			1	×	×	×	×	1	1	1,2
	$\bar{P}^1_{L1}$	$\bar{P}^2_{L1}$	$\bar{P}^1_{L2}$	$\bar{P}^2_{L2}$	$\tilde{P}^2_{L1}$	$\bar{P}^1_{F1}$	$\bar{P}^2_{F1}$	$\tilde{P}^2_{L2}$	$\bar{P}^1_{F2}$	$\bar{P}^2_{F2}$

Numbers in the table represent the label of the investing firm, and a blank cell indicates that both firms wait for an investment. The situation where both firms have an incentive to invest and only one of them can become the leader is represented by × . For example, for $\bar{P}^1_{L1} \le P < \bar{P}^1_{L2}$, firm 1 can become the leader in regime 1 and firm 2 cannot, while both firms wait for investing in regime 2.[11] For $P \ge \bar{P}^2_{F2}$, both firms invest immediately and simultaneously.

In this case, firm 1 always has an incentive to become the leader for $P \ge \bar{P}^1_{L2}$. However, firm 2 has the incentive only for $\bar{P}^2_{L1} \le P < \tilde{P}^2_{L1}$ in regime 1 and can never become the leader in regime 2. We observe that in this parameter setting, only firm 1 can be the leader when the state variable starts at a lower level like previous theoretical papers.

4.2. Case 2: unknown winner

In this case, we choose $K^2 = 11$, $D^2_{10} = 1.5$ and assume that the other parameters remain the same. The thresholds under this parameter setting are calculated in Table 4. The primary difference between in case 1 and case 2 is that in case 2, firm 2 is partly disadvantaged in both regimes 1 and 2.

Table 5 presents the investment strategies of each firm in each regime.

A novel observation is as follows. Suppose that the current regime is a bust ($\epsilon = 2$) and the current level of demand P_0 lies in $[\bar{P}^2_{L1}, \bar{P}^1_{L2})$. Then both firms do not invest immediately and wait until the demand increases as long as the current regime continues. However, when the regime suddenly changes from 2 to 1, both firms have an incentive to invest as the leader.[12]

This result shows a stark contrast to Pawlina and Kort (2006). That is, in their model without regime switching in the economic condition, a firm that is more profitable than the other always becomes the leader and enters the market before the other when the initial value of P is low. On the contrary, our model produces a situation where a disadvantaged firm may be the leader in a newly developing market, by simply introducing a Markov chain in the exogenous parameters.

Table 6
Thresholds of the firms in case 3.

$\bar{P}^1_{L1}$	$\bar{P}^1_{L2}$	$\bar{P}^1_{F1}$	$\bar{P}^1_{F2}$	$\bar{P}_{S1}$	$\bar{P}_{S2}$
0.9872	1.3858	2.1706	3.4224	3.2558	5.1336
$\bar{P}^2_{L1}$	$\tilde{P}^2_{L1}$	$\bar{P}^2_{L2}$	$\tilde{P}^2_{L2}$	$\bar{P}^2_{F1}$	$\bar{P}^2_{F2}$
1.0810	2.1659	1.5622	3.4150	2.2791	3.5935

Table 7
Investment strategies of each firm in case 3.

$\epsilon = 1$	1	×	1	1	1,2	1,2
$\epsilon = 2$						1,2
	$\bar{P}^1_{L1}$	$\bar{P}^2_{L1}$	$\tilde{P}^2_{L1}$	$\bar{P}^1_{F1}$	$\bar{P}^2_{F1}$	$\bar{P}_{S2}$

4.3. Case 3: simultaneous investment

In this case, we choose $K^2 = 10.5$, $D^1_{10} = D^2_{10} = 1.45$, $D^2_{11} = 1$ and set the other parameters to be the same as the benchmark. With these parameter values, we obtain the investment thresholds as in Table 6. We verify from the calculation that firm 1 prefers simultaneous investment to preempt firm 2, and being the leader in regime 2 since $V^1_{S2} \ge G^1_{L2} - K^1$ for all $P < \bar{P}_{S2}$, while both firms have an incentive to become the leader in regime 1. An important difference from case 2 is that all thresholds except for $\bar{P}_{S2}$ are ignored in regime 2.

Table 7 presents the investment strategies that each firm adopts in each regime.

For $\bar{P}^2_{L1} \le P < \tilde{P}^2_{L1}$, we obtain the same situation as in case 1. Another novel observation is the following. Suppose that the current regime is a bust ($\epsilon = 2$) and that $\bar{P}^2_{F1} \le P < \bar{P}_{S2}$. Then, both firms wait for simultaneous investment until the state variable becomes higher. However, when the regime changes from 2 to 1, both firms do not care about the decision of the other and simultaneously invest in the project. The result is an extreme version of case 2. Such a simultaneous investment is not tacit collusion but caused by a sudden regime shift. In other words, there are two different types of simultaneous investment depending on the presence of tacit collusion. Recall again that the existing theoretical literature of the competitive real options approach cannot create such a scenario.

In summary, we have found from the numerical examples that our model is quite rich and flexible to explain many actual situations within a unified framework.

5. Equilibrium types

Pawlina and Kort (2006) examine the conditions for each type of equilibrium to occur, depending on the parameter setting. In

[11] Note that investment timing of firm 1 as a result is determined by optimization of firm 1 as the leader. See, for detail, Appendix C. We focus on the incentive to become the leader in this section.

[12] More formally, both firms adopt mixed strategies and optimally choose the probability of investment.

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their framework, a preemptive equilibrium occurs if one of the firms is partially disadvantaged and has the incentive to invest as the leader, and a sequential equilibrium occurs if one of the firms is fully disadvantaged and always becomes the follower. The other type of equilibrium is a simultaneous equilibrium, where both firms invest at the same point. In what follows, we follow their analysis and examine the conditions.

To compare our result to Pawlina and Kort (2006), we suppose that $D_{N_iN_j} := D^1_{N_iN_j} = D^2_{N_iN_j}$, which means that asymmetry lies only in the investment cost.[13] We define

$$u = \frac{D_{10} - D_{00}}{D_{11} - D_{00}},$$
$$v = \frac{D_{11} - D_{01}}{D_{11} - D_{00}}$$

and

$$w = \frac{D_{10} - D_{01}}{D_{11} - D_{01}}.$$

The first-mover advantage and cost asymmetry are defined by D_{10}/D_{11} and $\kappa = K^2/K^1$, respectively. Pawlina and Kort (2006) show in their model with constant (μ, σ) that a simultaneous equilibrium happens if $\kappa < \kappa^{**}$, where

$$\kappa^{**} = \max\left\{ v\left(\frac{\theta(u-1)}{u^\theta - 1}\right)^{\frac{1}{\theta-1}}, 1\right\},$$
$$\theta = \frac{1}{2} - \frac{\mu}{\sigma^2} + \sqrt{\left(\frac{\mu}{\sigma^2} - \frac{1}{2}\right)^2 + \frac{2r}{\sigma^2}}.$$

A sequential equilibrium occurs if $\kappa > \kappa^*$, where

$$\kappa^* = \left(\frac{w^\theta - 1}{\theta(w-1)}\right)^{\frac{1}{\theta-1}}.$$

Otherwise, a preemptive equilibrium occurs and a disadvantaged firm can be the leader. While closed-form expressions of κ^* and κ^{**} are obtained in the one-regime case, κ^*_ϵ and κ^{**}_ϵ in our model need to be evaluated numerically.[14] We use the base case parameter set in Table 1 again, except for $D^1_{10} = D^2_{10}$ and $D^1_{11} = D^2_{11} = 1$.

Fig. 3 depicts the regions of equilibria as a function of the first-mover advantage D_{10}/D_{11} and the investment cost asymmetry κ in our model. To simplify the analysis, we only investigate the case $\lambda_1 = \lambda_2$.[15]

Our calculation shows that the κ^*s in regime 1 are higher than in the one regime case, while the κ^*s in regime 2 are lower than those in the one regime case. On the other hand, the κ^{**}s in regime 1 are lower than in the one regime case, while the κ^{**}s in regime 2 are higher than those in the one regime case. In other words, a preemptive equilibrium is more likely to occur in a boom than in a bust. Intuitively, the booms create large investment opportunities, which make firms' preemption strategy relatively more attractive. In contrast, investment opportunities decrease in busts, making firms prefer sequential or simultaneous investments. This corresponds to the result of Pawlina and Kort (2006), that is, market uncertainty delays investment by making the firms switch across equilibria. However, in this work, the equilibria also depend on the switching intensity, that is, the regime uncertainty.

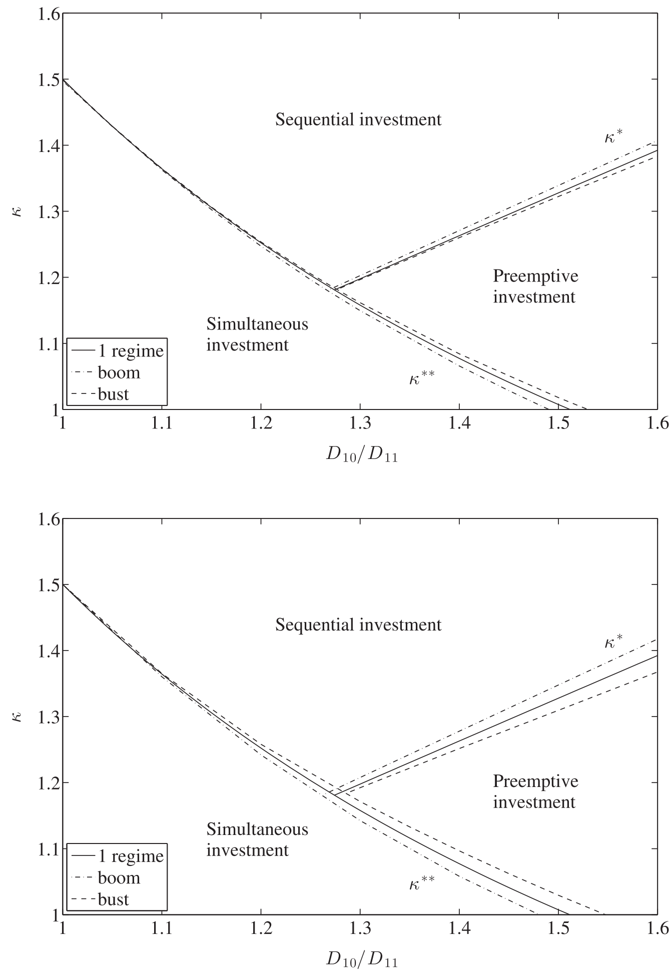

Fig. 3. Regions of sequential, preemptive, and simultaneous investment for the benchmark case except for $D^1_{10} = D^2_{10}$ and $D^1_{11} = D^2_{11} = 1$. The intensities are $\lambda_1 = \lambda_2 = 0.2$ in the upper and $\lambda_1 = \lambda_2 = 0.8$ in the lower.

Note in Fig. 3 that the above mentioned result is more remarkable especially when λ_1 and λ_2 are higher. Intuitively, we would conjecture that the line of κ^*_1 in regime 1 is located farther from the line of κ^*_2 in regime 2 when λ is low, and then converges to that of κ^* in a one-regime case as λ goes to infinity. A similar argument can be made for κ^{**}. But the numerical result shows that the conjecture is not true.

To examine the observation in more depth, we present Fig. 4, plotting κ^* and κ^{**} in both regimes for different values of λ with other parameter values fixed.[16]

The above figure show that in regime 1, κ^*_1 (κ^*_2 in regime 2) is increasing (decreasing) for a small λ, and subsequently decreases (increases). The opposite shapes can be found for the κ^{**}s.

Regarding the observation in Fig. 4, we can provide the following theoretical explanation. Suppose first that λ is small. In this situation, the probability of a regime change is negligible and both firms do not need to take a regime change into account for the investment decision. Therefore, an equilibrium type should

[13] In this analysis, as in Pawlina and Kort (2006), we consider an asymmetric situation in which each firm has different investment costs. For example, in the power industry there exist some cases where firms invest power generations of distinct technologies for same capacities such as peaking and base load technologies.

[14] We numerically calculate the functions $V^i_{S\epsilon}$ and $G^i_{L\epsilon}$ to check the magnitude of the relationship.

[15] We use

$$\mu \equiv \frac{\lambda_1\mu_1 + \lambda_2\mu_2}{\lambda_1 + \lambda_2} = \frac{\mu_1 + \mu_2}{2},$$
$$\sigma \equiv \frac{\lambda_1\sigma_1 + \lambda_2\sigma_2}{\lambda_1 + \lambda_2} = \frac{\sigma_1 + \sigma_2}{2},$$

for the expected growth rate and the volatility in the one-regime model, respectively.

[16] Unfortunately, numerical calculations for $\lambda > 3$ are unstable and cannot be presented.

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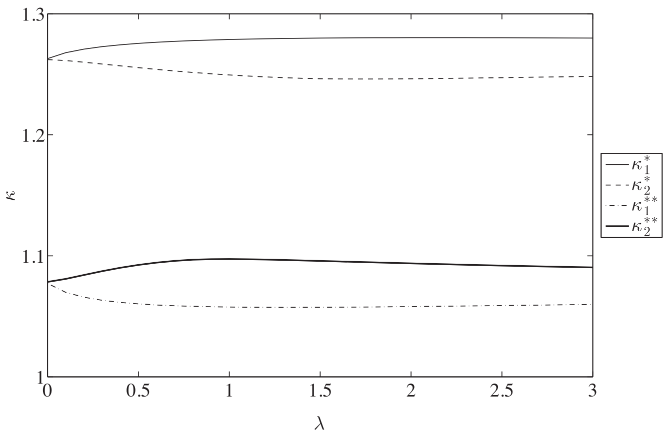

Fig. 4. Comparative statics of κ's with respect to λ for the benchmark case except for $D^1_{10} = D^2_{10} = 1.4$ and $D^1_{11} = D^2_{11} = 1$.

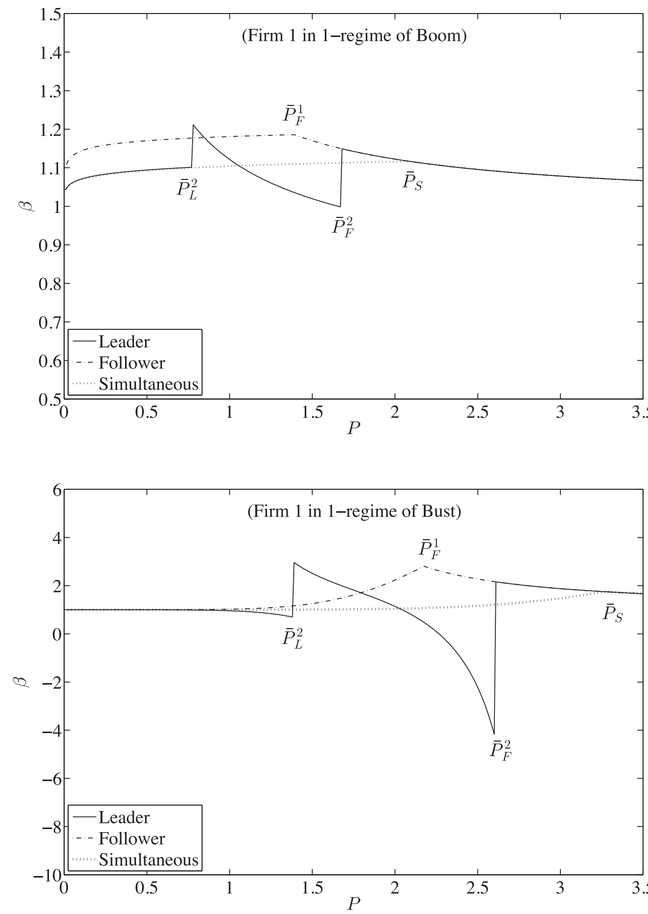

Fig. 5. Betas of the leader, the follower, and simultaneous investment for firm 1 in boom (upper) and bust (lower) without a regime shift.

be the same as in the one-regime case. In the case where λ is moderately high, both firms actually consider the effect of regime change, and hasten to invest in a boom, but hesitate to invest in a bust, leading to the situation where a preemptive equilibrium is more likely to occur in a boom and it is less likely to occur in a bust. If λ is extremely high, then the regime easily switches from one to another and both firms regard the economic condition as a one-regime setting with $\mu \equiv (\lambda_2\mu_1 + \lambda_1\mu_2)/(\lambda_1 + \lambda_2)$ and $\sigma \equiv (\lambda_2\sigma_1 + \lambda_1\sigma_2)/(\lambda_1 + \lambda_2)$. The above explanation effectively describes how regime uncertainty affects the investment decision of both firms.

In other words, both firms take the option value to wait and see the future evolution of a regime into account, especially when the regime is bad for investment and the intensity of a sudden regime shift is moderate. In the real options literature, the option value of wait is extensively studied by many papers but is usually related to the volatility of demand. The effect of regime uncertainty is analyzed by Guo et al. (2005) and other papers, but the option value of a regime change is not discussed extensively in the literature. The current study sheds new light on the investment theory by presenting the importance of regime uncertainty in a way that is different from other theoretical studies.

6. Equity risk premium

In this section, we present a numerical analysis on the equity risk premium. To this end, $G^i_{L\epsilon}$ is not appropriate and we should calculate $V^i_{L\epsilon}$, the value function of the leader firm including the option value of the follower. We derive $V^i_{L\epsilon}$ in Appendix C.

Following Carlson et al. (2004) and Aguerrevere (2009), we define the beta of the leader firm i's equity in regime ϵ to be

$$\beta^i_{L\epsilon}(P) = \frac{\mathbb{C}_{P,\epsilon}[(\mathrm{d}P/P),(\mathrm{d}V^i_{L\epsilon}/V^i_{L\epsilon})]}{\mathbb{V}_{P,\epsilon}[(\mathrm{d}P/P)]} = \frac{P}{G^i_{L\epsilon}(P)}V^{i\,\prime}_{L\epsilon}(P). \tag{19}$$

The beta of the follower firm is

$$\beta^i_{F\epsilon}(P) = \frac{\mathbb{C}_{P,\epsilon}[(\mathrm{d}P/P),(\mathrm{d}V^i_{F\epsilon}/V^i_{F\epsilon})]}{\mathbb{V}_{P,\epsilon}[(\mathrm{d}P/P)]} = \frac{P}{V^i_{F\epsilon}(P)}V^{i\,\prime}_{F\epsilon}(P) \tag{20}$$

and that in simultaneous investment to be

$$\beta^i_{S\epsilon}(P) = \frac{\mathbb{C}_{P,\epsilon}[(\mathrm{d}P/P),(\mathrm{d}V^i_{S\epsilon}/V^i_{S\epsilon})]}{\mathbb{V}_{P,\epsilon}[(\mathrm{d}P/P)]} = \frac{P}{V^i_{S\epsilon}(P)}V^{i\,\prime}_{S\epsilon}(P), \tag{21}$$

where $\mathbb{V}_{P,\epsilon}$ and $\mathbb{C}_{P,\epsilon}$ are the variance and covariance operators conditional on (P, ϵ), respectively.

In this analysis, the parameter values are chosen based on Bhamra et al. (2009) except for K^i and $D_{N_iN_j}$, which are chosen to match the actual economic environment. Table 8 presents the values of exogenous parameters. Note that firm 1 is advantaged in cost.

The thresholds of both firms as the leader and follower under this setup are given in Table 9.[17] As conjectured, the thresholds of firm 1 in regimes 1 and 2 are lower than the thresholds of firm 2.

First we present Figs. 5 and 6 depicting the relationship between β and P in a one-regime case as a benchmark.

Figs. 5 and 6 plot betas of the leader, the follower, and the simultaneous investment for firms 1 and 2, respectively. Both figures almost reproduce the results of Carlson et al. (2014). The beta for the leader discontinuously increases when P is equal to the investment thresholds, and subsequently decreases for a larger value of P. On the other hand, the beta for the follower increases when P is smaller than the follower's thresholds and decreases afterwards. The beta for the simultaneous investment is similar to that for the follower except that the beta of firm 2 discontinuously increases at the investment threshold. This is because firm 1 invests simultaneously and optimally, while firm 2 reluctantly invests simultaneously at the same point.

The difference from Carlson et al. (2014) is seen at the leader's investment threshold. Figs. 5 and 6 show that the beta for the leader (follower) discontinuously increases (does not change) at that point, while the beta for the leader (follower) discontinuously decreases (increases) in Carlson et al. (2014). This difference is caused by the difference in the model setting, that is, the leader's

[17] $\bar{P}^{1*}_{L\epsilon}$ is defined in Appendix C and necessary to calculate the leader's value functions.

Table 8
Parameter values. We follow Bhamra et al. (2009) except for K and D.

μ_1	μ_2	σ_1	σ_2	r	λ_1	λ_2	K^1	K^2	D_{00}	D_{01}	D_{10}	D_{11}
0.0782	-0.0401	0.0834	0.1334	0.1	0.2718	0.4928	10	12	0.5	0.25	1.5	1

Table 9
Thresholds of the firms.

$\bar{P}^1_{L1}$	$\bar{P}^{1*}_{L1}$	$\bar{P}^1_{L2}$	$\bar{P}^{1*}_{L2}$	$\bar{P}^1_{F1}$	$\bar{P}^1_{F2}$	$\bar{P}_{S1}$	$\bar{P}_{S2}$
0.6050	1.1067	0.6964	1.1609	1.4934	1.6980	2.2401	2.5470
$\bar{P}^2_{L1}$	$\bar{P}^2_{L1}$	$\bar{P}^2_{L2}$	$\bar{P}^2_{L2}$	$\bar{P}^2_{F1}$	$\bar{P}^2_{F2}$		
0.8599	1.4398	0.9908	1.6522	1.7921	2.0376		

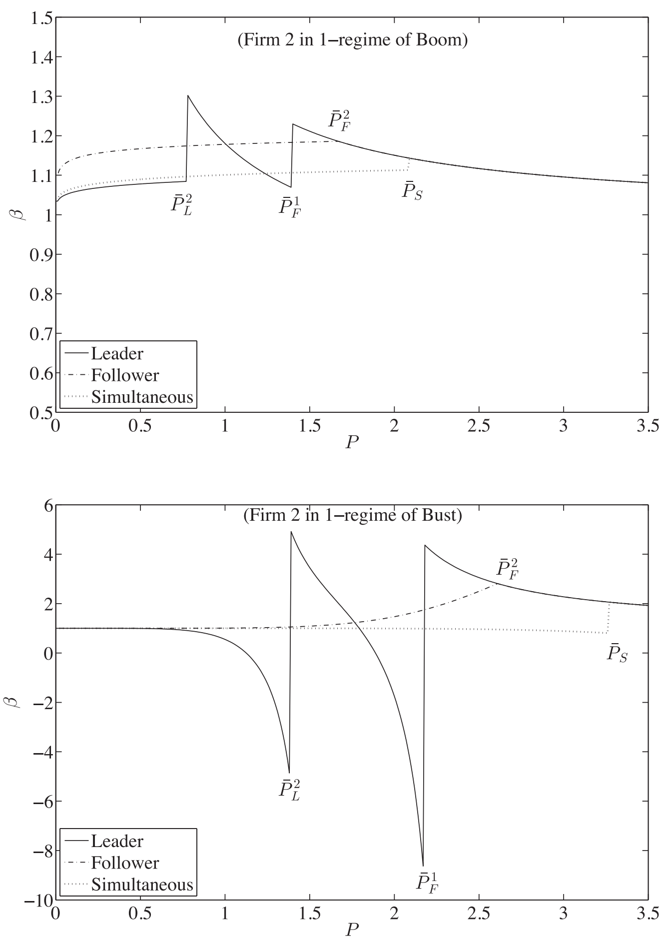

Fig. 6. Betas of the leader, the follower, and simultaneous investment for firm 2 in boom (upper) and bust (lower) without a regime shift.

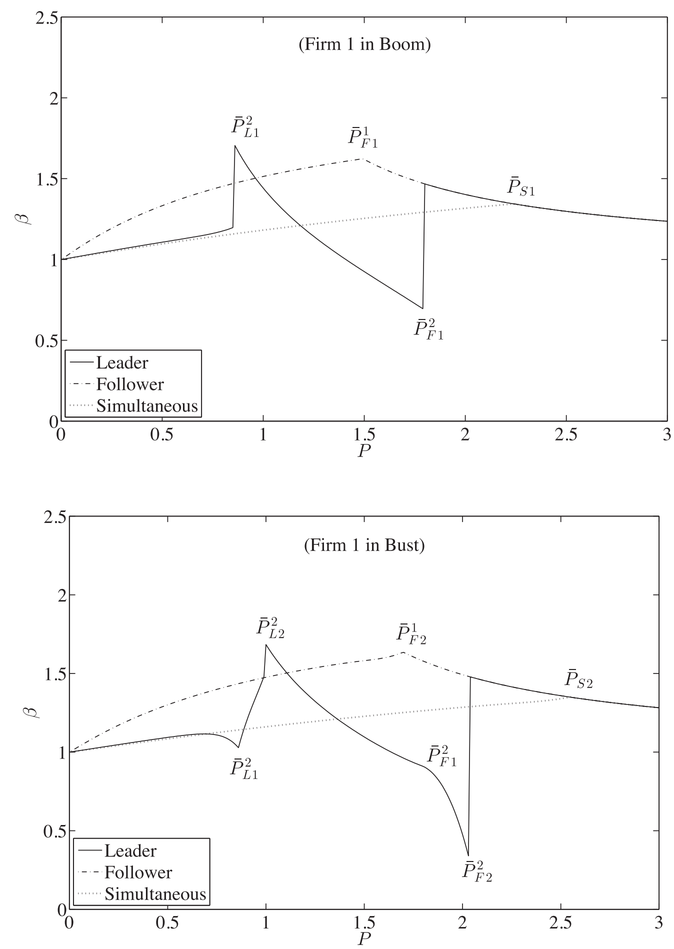

Fig. 7. Betas of the leader, the follower, and simultaneous investment for firm 1 in boom (upper) and bust (lower) with a regime shift.

investment is not optimal due to preemption and the follower's option value is independent from the leader's investment in our setting. We also observe that the leader's beta is more volatile than the follower's. The reason is that an actual investment is irreversible and a decrease of P after investment has a big impact on the leader's value. Note finally that the betas in a bust are more volatile than in a boom. This is due to the fact that the volatility of P is higher in a bust.

Now we show the betas in our regime-switching model. Figs. 7 and 8 plot the betas of the advantaged and disadvantaged firms in the two regimes under the benchmark parameters, respectively.

We observe that the difference of the beta between two regimes in Figs. 7 and 8 is much less than that in Figs. 5 and 6, which means that introducing the regime switch can prevent the underestimation of the beta in a boom, and the overestimation of the beta in a bust. An important observation from Figs. 7 and 8 is that the graph of beta in regime 1 is similar to Figs. 5 and 6 but the graph in regime 2 is different. More concretely, the beta for the leader in regime 2 is not monotonic for a small P and has a kink at $P = \bar{P}^2_{L1}$. The reason is that the beta in regime 2 reflects the possibility of a sudden change to regime 1, which leads to an immediate investment and makes the decision irreversible. And then, the option value of the leader vanishes and the value of the leader includes only the NPV of an immediate investment. Therefore, the beta for the leader in regime 2 changes the shape drastically at

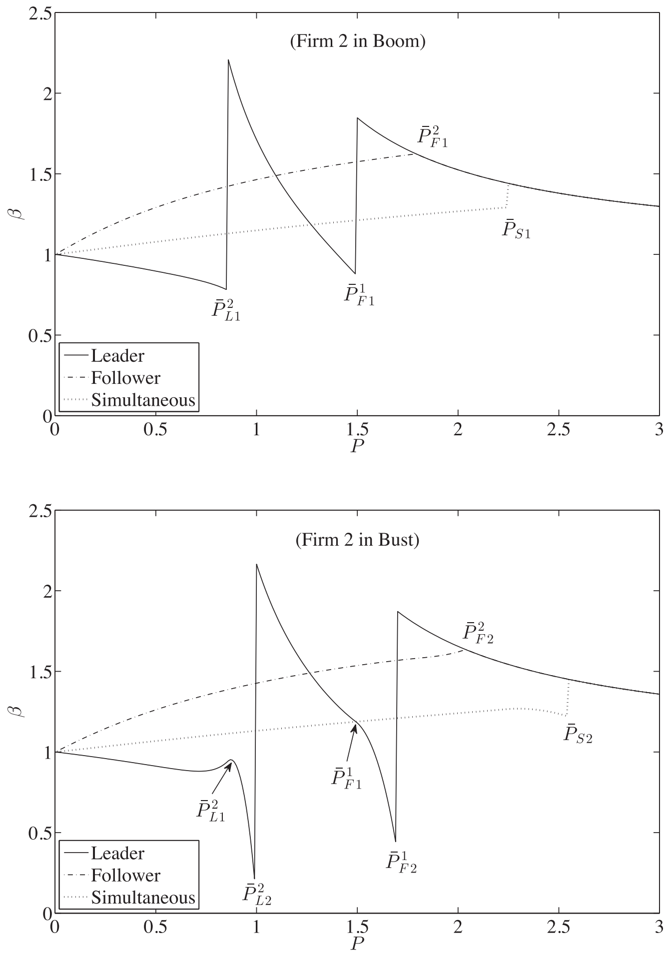

Fig. 8. Betas of the leader, the follower, and simultaneous investment for firm 2 in boom (upper) and bust (lower) with a regime shift.

$\bar{P}^2_{L1}$. Similarly, the beta for the leader i in regime 2 has an inflection point at $\bar{P}^j_{F1}$. This is because follower j will invest at $\bar{P}^j_{F1}$ when the regime changes from 2 to 1. However, the impact of the possibility of a regime change at this point is less than that at $\bar{P}^2_{L1}$ since the option value of the leader has already vanished at $\bar{P}^2_{L1}$. These theoretical findings are new in the literature and can be obtained only in our regime-switching model.

We also verify from Figs. 7 and 8 that the risk premium in regime 1 tends to be lower than the one in regime 2. Our study replicates the result of Aguerrevere (2009) that describes the business cycle by the level of the state variable. However many empirical papers such as Chen (1991) and Hoberg and Phillips (2010) report that the time-varying beta is negatively associated with the economic growth rate or the market return, not the absolute level of demand or the market size. By considering changes in the expected growth rate, this study provides explanations for empirical facts about the relationship between the economic cycle and risk premium that are not possible in previous studies that proxy economic conditions by the level of demand or otherstate variables.

7. Conclusion

In this study, we introduce a Markov switching regime as Driffill et al. (2013) into the model of Pawlina and Kort (2006) to consider the investment problem of asymmetric firms with regime uncertainty. In the case of no regime switch, a profitable firm always becomes the leader in the investment, and a disadvantaged firm never has an incentive to become the leader in a newly developing market. However, if there is uncertainty in the regime, there are some parameter settings in which both firms can be the leader even when the initial state variable is at a lower level. This finding shows a stark contrast to Pawlina and Kort (2006) as our model can provide richer results within a unified framework.

From the numerical calculations, we conclude that regime uncertainty can have a big impact on the investment decision and the market equilibrium. When there is a regime switching structure in the economy, each firm needs to take the probability and effect of a regime change into account, which can cause a shift of the equilibrium type. In addition, the equity risk premium tends to be higher when the expected growth rate is low. This theoretical result describes previous empirical findings in a more precise way than other extant studies.

For future study, it is important to consider the changes of profitability and cost invoked by the regime. It is natural that the firm's profitability and cost are better in a boom than in a bust. By doing this, we will be able to explain more complicated economic behavior of firms facing the entry race under uncertainty.

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Appendix A. Glossary.

The glossary of the notation used in the paper is presented for the reader's convenience.

P_t	the level of demand at time t
μ_ϵ	expected growth rate of P in regime ϵ
σ_ϵ	volatility of P in regime ϵ
r	discount rate to calculate the net present value
λ_ϵ	transition intensity from regime ϵ to the other regime
$D^i_{N_iN_j}$	contribution parameter to the profit of firm i, where $N_k = 1$ if firm $k \in \{i, j\}$ has invested and $N_k = 0$ otherwise
K^i	firm i's investment cost
τ^i_L (τ^i_F)	firm i's investment timing if it is the leader (follower)
$\bar{P}^i_{L\epsilon}$ ($\bar{P}^i_{F\epsilon}$)	firm i's investment threshold in regime ϵ if it is the leader (follower)
$\bar{P}^{1*}_{L\epsilon}$	firm 1's optimal investment threshold in regime ϵ if it is the leader
$\tilde{P}^2_{L\epsilon}$	the value which relates the incentive to be the leader for firm 2 in regime ϵ
$\bar{P}_{S\epsilon}$	both firm's investment threshold in regime ϵ for the case of a simultaneous equilibrium
$G^i_{L\epsilon}$ ($G^i_{F\epsilon}$)	firm i's net present value for an immediate investment in regime ϵ if it is the leader (follower)
$V^i_{L\epsilon}$ ($V^i_{F\epsilon}$)	firm i's value including the option value in regime ϵ if it is the leader (follower)
$V^i_{S\epsilon}$	firm i's value function including the option value of the future investment in regime ϵ for the case of a simultaneous equilibrium
κ^*_ϵ	parameter determining if a sequential equilibrium occurs in regime ϵ
κ^{**}_ϵ	parameter determining if a simultaneous equilibrium occurs in regime ϵ

Appendix B. Boundary conditions in Propositions.

In this appendix, we provide boundary conditions in Propositions 2–4. First, boundary conditions for the follower in Proposition 2 are as follows:

$$\pi_2 D^i_{11}\bar{P}^i_{F2} - K^i = b^i_{21}(\bar{P}^i_{F2})^{\alpha_1} + b^i_{22}(\bar{P}^i_{F2})^{\alpha_2} + \frac{D^i_{01}+\lambda_2\pi_1 D^i_{11}}{r+\lambda_2-\mu_2}\bar{P}^i_{F2} - \frac{\lambda_2}{r+\lambda_2}K^i, \quad (B.1)$$

$$\pi_2 D^i_{11} = \alpha_1 b^i_{21}(\bar{P}^i_{F2})^{\alpha_1-1} + \alpha_2 b^i_{22}(\bar{P}^i_{F2})^{\alpha_2-1} + \frac{D^i_{01}+\lambda_2\pi_1 D^i_{11}}{r+\lambda_2-\mu_2}, \quad (B.2)$$

$$c^i_{11}(\bar{P}^i_{F1})^{\gamma_1} + c^i_{12}(\bar{P}^i_{F1})^{\gamma_2} + \pi_1 D^i_{01}P = \pi_1 D^i_{11}\bar{P}^i_{F1} - K^i, \quad (B.3)$$

$$\gamma_1 c^i_{11}(\bar{P}^i_{F1})^{\gamma_1-1} + \gamma_2 c^i_{12}(\bar{P}^i_{F1})^{\gamma_2-1} + \pi_1 D^i_{01} = \pi_1 D^i_{11}, \quad (B.4)$$

$$\ell_1 c^i_{11}(\bar{P}^i_{F1})^{\gamma_1} + \ell_2 c^i_{12}(\bar{P}^i_{F1})^{\gamma_2} + \pi_2 D^i_{01}P = b^i_{21}(\bar{P}^i_{F1})^{\alpha_1} + b^i_{22}(\bar{P}^i_{F1})^{\alpha_2} + \frac{D^i_{01}+\lambda_2\pi_1 D^i_{11}}{r+\lambda_2-\mu_2}\bar{P}^i_{F1} - \frac{\lambda_2}{r+\lambda_2}K^i, \quad (B.5)$$

$$\gamma_1\ell_1 c^i_{11}(\bar{P}^i_{F1})^{\gamma_1-1} + \gamma_2\ell_2 c^i_{12}(\bar{P}^i_{F1})^{\gamma_2-1} + \pi_2 D^i_{01} = \alpha_1 b^i_{21}(\bar{P}^i_{F1})^{\alpha_1-1} + \alpha_2 b^i_{22}(\bar{P}^i_{F1})^{\alpha_2-1} + \frac{D^i_{01}+\lambda_2\pi_1 D^i_{11}}{r+\lambda_2-\mu_2}. \quad (B.6)$$

(B.1) and (B.2) ((B.3) and (B.4)) are the value-matching and the smooth-pasting conditions at $\bar{P}^i_{F2}$ ($\bar{P}^i_{F1}$), respectively. (B.5) and (B.6) are the continuity and high-contact conditions, respectively.

Second, we provide boundary conditions for a leader in Proposition 3:

$$e^i_{21}(\bar{P}^j_{F2})^{\alpha_1} + e^i_{22}(\bar{P}^j_{F2})^{\alpha_2} + \frac{D^i_{10}+\lambda_2\pi_1 D^i_{11}}{r+\lambda_2-\mu_2}\bar{P}^j_{F2} = \pi_2 D^i_{11}\bar{P}^j_{F2}, \quad (B.7)$$

$$h^i_{11}(\bar{P}^j_{F1})^{\gamma_1} + h^i_{12}(\bar{P}^j_{F1})^{\gamma_2} + \pi_1 D^i_{10}\bar{P}^j_{F1} = \pi_1 D^i_{11}\bar{P}^j_{F1}, \quad (B.8)$$

$$\ell_1 h^i_{11}(\bar{P}^j_{F1})^{\gamma_1} + \ell_2 h^i_{12}(\bar{P}^j_{F1})^{\gamma_2} + \pi_2 D^i_{10}\bar{P}^j_{F1} = e^i_{21}(\bar{P}^j_{F1})^{\alpha_1} + e^i_{22}(\bar{P}^j_{F1})^{\alpha_2} + \frac{D^i_{10}+\lambda_2\pi_1 D^i_{11}}{r+\lambda_2-\mu_2}P^j_{F1}, \quad (B.9)$$

$$\gamma_1\ell_1 h^i_{11}(\bar{P}^j_{F1})^{\gamma_1-1} + \gamma_2\ell_2 h^i_{12}(\bar{P}^j_{F1})^{\gamma_2-1} + \pi_2 D^i_{10} = \alpha_1 e^i_{21}(\bar{P}^j_{F1})^{\alpha_1-1} + \alpha_2 e^i_{22}(\bar{P}^j_{F1})^{\alpha_2-1} + \frac{D^i_{10}+\lambda_2\pi_1 D^i_{11}}{r+\lambda_2-\mu_2}. \quad (B.10)$$

(B.7) and (B.8) are the value-matching conditions at $\bar{P}^i_{F2}$ and $\bar{P}^i_{F1}$, respectively. (B.9) and (B.10) are the continuity and high-contact conditions, respectively. Note that smooth-pasting conditions do not exist for the leader's problem.

Finally, boundary conditions for simultaneous investment in Proposition 4 are given by

$$\pi_2 D^i_{11}\bar{P}_{S2} - K^i = m^i_{21}(\bar{P}_{S2})^{\alpha_1} + m^i_{22}(\bar{P}_{S2})^{\alpha_2} + \frac{D^i_{00}+\lambda_2\pi_1 D^i_{11}}{r+\lambda_2-\mu_2}\bar{P}_{S2} - \frac{\lambda_2}{r+\lambda_2}K^i, \quad (B.11)$$

$$q^i_{11}(\bar{P}_{S1})^{\gamma_1} + q^i_{12}(\bar{P}_{S1})^{\gamma_2} + \pi_1 D^i_{00}P = \pi_1 D^i_{11}\bar{P}_{S1} - K^i, \quad (B.12)$$

$$\ell_1 q^i_{11}(\bar{P}_{S1})^{\gamma_1} + \ell_2 q^i_{12}(\bar{P}_{S1})^{\gamma_2} + \pi_2 D^i_{00}P = m^i_{21}(\bar{P}_{S1})^{\alpha_1} + m^i_{22}(\bar{P}_{S1})^{\alpha_2} + \frac{D^i_{00}+\lambda_2\pi_1 D^i_{11}}{r+\lambda_2-\mu_2}\bar{P}_{S1} - \frac{\lambda_2}{r+\lambda_2}K^i, \quad (B.13)$$

$$\gamma_1\ell_1 q^i_{11}(\bar{P}_{S1})^{\gamma_1-1} + \gamma_2\ell_2 q^i_{12}(\bar{P}_{S1})^{\gamma_2-1} + \pi_2 D^i_{00} = \alpha_1 m^i_{21}(\bar{P}_{S1})^{\alpha_1-1} + \alpha_2 m^i_{22}(\bar{P}_{S1})^{\alpha_2-1} + \frac{D^i_{00}+\lambda_2\pi_1 D^i_{11}}{r+\lambda_2-\mu_2}, \quad (B.14)$$

$$\pi_2 D^1_{11} = \alpha_1 m^1_{21}(\bar{P}_{S2})^{\alpha_1-1} + \alpha_2 m^1_{22}(\bar{P}_{S2})^{\alpha_2-1} + \frac{D^1_{00}+\lambda_2\pi_1 D^1_{11}}{r+\lambda_2-\mu_2}, \quad (B.15)$$

$$\gamma_1 q^1_{11}(\bar{P}_{S1})^{\gamma_1-1} + \gamma_2 q^1_{12}(\bar{P}_{S1})^{\gamma_2-1} + \pi_1 D^1_{00} = \pi_1 D^1_{11}. \quad (B.16)$$

(B.11) and (B.12) ((B.15) and (B.16)) are the value-matching and the smooth-pasting conditions at $\bar{P}_{S2}$ ($\bar{P}_{S1}$), respectively. (B.13) and (B.14) are the continuity and high-contact conditions, respectively. Note that the smooth-pasting conditions hold for only firm 1 because of its advantage.

Appendix C. Derivation of the leader's value function.

In this appendix, we drive the value function of both firms as the leader for investment, to calculate their βs. To this end, we need to consider the magnitude of the relationship between the leader's optimal investment threshold of firm 1 and the leader's investment threshold of firm 2.

C1. The case of firm 1's optimization

First, we consider the case where firm 1 can surely become the leader, and let $\bar{P}^{1*}_{L\epsilon}$ denote the leader's optimal investment threshold of firm 1 in regime ϵ. If $\epsilon(t)=\epsilon$ and $P \geq \bar{P}^{1*}_{L\epsilon}$, the optimal decision of firm 1 is to invest immediately and $V^1_{L\epsilon} = G^1_{L\epsilon} - K^1$.

Suppose that $\bar{P}^{1*}_{L1} \leq P < \bar{P}^{1*}_{L2}$ and $\epsilon(t)=2$. In this situation, firm 1 invests in the new project immediately after the regime changes from 2 to 1. Therefore, the value function V^1_{L2} satisfies the ODE given by

$$\frac{\sigma_2^2}{2}P^2\frac{\mathrm{d}^2 V^1_{L2}}{\mathrm{d}P^2} + \mu_2 P\frac{\mathrm{d}V^1_{L2}}{\mathrm{d}P} - rV^1_{L2} + \lambda_2(G^1_{L1} - K^1 - V^1_{L2}) + D^1_{00}P = 0 \quad (C.1)$$

where G^1_{L1} appears in Proposition 3, and the boundary condition is given by

$$\lim_{P\uparrow \bar{P}^{1*}_{L2}} V^1_{L2}(P) = \lim_{P\downarrow \bar{P}^{1*}_{L2}} G^1_{L2}(P) - K^1.$$

We conjecture that the functional form of (C.1) is

$$V^1_{L2}(P) = e^{L1}_{21}P^{\alpha_1} + e^{L1}_{22}P^{\alpha_2} + \hat{e}^{L1}_{23}P^{\gamma_1} + \hat{e}^{L1}_{24}P^{\gamma_2} + \hat{e}^{L1}_{25}P + \hat{e}^{L1}_{26}, \quad (C.2)$$

where γ_1 and γ_2 are the positive roots of (12) and α_1 and α_2 are the roots of the quadratic Eq. (9). Plugging (C.2) into (C.1), we obtain

$$\hat{e}^{L1}_{23} = \frac{\lambda_2 h^1_{11}}{r+\lambda_2-\mu_2\gamma_1-\frac{\sigma_2^2}{2}\gamma_1(\gamma_1-1)}, \quad (C.3)$$

$$\hat{e}^{L1}_{24} = \frac{\lambda_2 h^1_{12}}{r+\lambda_2-\mu_2\gamma_2-\frac{\sigma_2^2}{2}\gamma_2(\gamma_2-1)}, \quad (C.4)$$

$$\hat{e}^{L1}_{25} = \frac{D^1_{00}+\lambda_2\pi_1 D^1_{10}}{r+\lambda_2-\mu_2} \quad (C.5)$$

and

$$\hat{e}^{L1}_{26} = -\frac{\lambda_2}{r+\lambda_2}K^1, \quad (C.6)$$

where h^1_{11} and h^1_{12} are given in Proposition 3. The coefficients e^{L1}_{21} and e^{L1}_{22} are derived later.

Next we suppose that $P < \bar{P}^{1*}_{L1}$. In this situation, firm 1 does not invest at the time of a regime change. Therefore $\{V^1_{L\epsilon}\}_{\epsilon=1,2}$ must satisfy the simultaneous ODEs

$$\frac{\sigma_\epsilon^2}{2}P^2\frac{\mathrm{d}^2 V^1_{L\epsilon}}{\mathrm{d}P^2} + \mu_\epsilon P\frac{\mathrm{d}V^1_{L\epsilon}}{\mathrm{d}P} - rV^1_{L\epsilon} + \lambda_\epsilon(V^1_{L\hat{\epsilon}} - V^1_{L\epsilon}) + D^1_{00}P \quad (C.7)$$

for $\epsilon = 1, 2$. The boundary conditions are

$$\lim_{P\uparrow\bar{P}^{1*}_{L1}} V^1_{L1}(P) = \lim_{P\downarrow\bar{P}^{1*}_{L1}} G^1_{L1}(P) - K^1$$

and

$$\lim_{P\uparrow\bar{P}^{1*}_{L1}} V^1_{L2}(P) = \lim_{P\downarrow\bar{P}^{1*}_{L1}} V^1_{L2}(P),$$
$$\lim_{P\uparrow\bar{P}^{1*}_{L1}} V^{1\prime}_{L2}(P) = \lim_{P\downarrow\bar{P}^{1*}_{L1}} V^{1\prime}_{L2}(P). \tag{C.8}$$

The function V^1_{L2} is of C^1 except for $P = \bar{P}^{1*}_{L2}$, implying that the high contact condition (C.8) holds. The conjectured functions of (C.7) are

$$V^1_{L\epsilon}(P) = h^{L1}_{\epsilon 1}P^{\gamma_1} + h^{L1}_{\epsilon 2}P^{\gamma_2} + \pi_\epsilon D^1_{00}P. \tag{C.9}$$

The unknown parameters are given in the following proposition.

Proposition C.1. *Suppose that $\bar{P}^{1*}_{L\epsilon} < \bar{P}^2_{L\epsilon}$. Then firm 1 can surely become the leader and the value function of firm 1 for regime 1 is given by*

$$V^1_{L1}(P) = \begin{cases} G^1_{F1}(P) - K^1, & \text{for } P \geq \bar{P}^2_{F1}, \\ G^1_{L1}(P) - K^1, & \text{for } \bar{P}^{1*}_{L1} \leq P < \bar{P}^2_{F1}, \\ h^{L1}_{11}P^{\gamma_1} + h^{L1}_{12}P^{\gamma_2} + \pi_1 D^1_{00}P, & \text{for } P < \bar{P}^{1*}_{L1} \end{cases} \tag{C.10}$$

and the function for regime 2 is

$$V^1_{L2}(P) = \begin{cases} G^1_{F2}(P) - K^1, & \text{for } P \geq \bar{P}^2_{F2}, \\ G^1_{L2}(P) - K^1, & \text{for } \bar{P}^{1*}_{L2} \leq P < \bar{P}^2_{F2}, \\ e^{L1}_{21}P^{\alpha_1} + e^{L1}_{22}P^{\alpha_2} + \hat{e}^{L1}_{23}P^{\gamma_1} + \hat{e}^{L1}_{24}P^{\gamma_2} & \\ \quad + \hat{e}^{L1}_{25}P + \hat{e}^{L1}_{26}, & \text{for } \bar{P}^{1*}_{L1} \leq P < \bar{P}^{1*}_{L2}, \\ \ell_1 h^{L1}_{11}P^{\gamma_1} + \ell_2 h^{L1}_{12}P^{\gamma_2} + \pi_2 D^1_{00}P, & \text{for } P < \bar{P}^{1*}_{L1}, \end{cases} \tag{C.11}$$

where $\hat{e}^{L1}_{23}$, $\hat{e}^{L1}_{24}$, $\hat{e}^{L1}_{25}$ and $\hat{e}^{L1}_{26}$ are given in (C.3)–(C.6). The unknown parameters $(\bar{P}^{1*}_{L1}, \bar{P}^{1*}_{L2}, e^{L1}_{21}, e^{L1}_{22}, h^{L1}_{11}, c^{L1}_{12})$ are the solution of the simultaneous equation

$$h^1_{11}(\bar{P}^{1*}_{L1})^{\gamma_1} + c^{L1}_{12}(\bar{P}^{1*}_{L1})^{\gamma_2} + \hat{c}^{L1}_{13}\bar{P}^{1*}_{L1} - K^1 = h^{L1}_{11}(\bar{P}^{1*}_{L1})^{\gamma_1}$$
$$\quad + h^{L1}_{12}(\bar{P}^{1*}_{L1})^{\gamma_2} + \hat{h}^{L1}_{13}\bar{P}^{1*}_{L1},$$
$$\gamma_1 h^1_{11}(\bar{P}^{1*}_{L1})^{\gamma_1 - 1} + \gamma_2 c^{L1}_{12}(\bar{P}^{1*}_{L1})^{\gamma_2 - 1} + \hat{c}^{L1}_{13}$$
$$= \gamma_1 h^{L1}_{11}(\bar{P}^{1*}_{L1})^{\gamma_1 - 1} + \gamma_2 h^{L1}_{12}(\bar{P}^{1*}_{L1})^{\gamma_2 - 1} + \hat{h}^{L1}_{13}, \tag{C.12}$$

$$c^{L1}_{21}(\bar{P}^{1*}_{L2})^{\gamma_1} + c^{L1}_{22}(\bar{P}^{1*}_{L2})^{\gamma_2} + \hat{c}^{L1}_{23}\bar{P}^{1*}_{L2} - K^1 = e^{L1}_{21}(\bar{P}^{1*}_{L2})^{\alpha_1} + e^{L1}_{22}(\bar{P}^{1*}_{L2})^{\alpha_2}$$
$$\quad + \hat{e}^{L1}_{23}(\bar{P}^{1*}_{L2})^{\gamma_1} + \hat{e}^{L1}_{24}(\bar{P}^{1*}_{L2})^{\gamma_2} + \hat{e}^{L1}_{25}\bar{P}^{1*}_{L2} + \hat{e}^{L1}_{26},$$
$$\gamma_1 c^{L1}_{21}(\bar{P}^{1*}_{L2})^{\gamma_1 - 1} + \gamma_2 c^{L1}_{22}(\bar{P}^{1*}_{L2})^{\gamma_2 - 1} + \hat{c}^{L1}_{23} = \alpha_1 e^{L1}_{21}(\bar{P}^{1*}_{L2})^{\alpha_1 - 1}$$
$$\quad + \alpha_2 e^{L1}_{22}(\bar{P}^{1*}_{L2})^{\alpha_2 - 1} + \gamma_1 \hat{e}^{L1}_{23}(\bar{P}^{1*}_{L2})^{\gamma_1 - 1}$$
$$\quad + \gamma_2 \hat{e}^{L1}_{24}(\bar{P}^{1*}_{L2})^{\gamma_2 - 1} + \hat{e}^{L1}_{25},$$
$$e^{L1}_{21}(\bar{P}^{1*}_{L1})^{\alpha_1} + e^{L1}_{22}(\bar{P}^{1*}_{L1})^{\alpha_2} + \hat{e}^{L1}_{23}(\bar{P}^{1*}_{L1})^{\gamma_1} + \hat{e}^{L1}_{24}(\bar{P}^{1*}_{L1})^{\gamma_2} + \hat{e}^{L1}_{25}\bar{P}^{1*}_{L1} + \hat{e}^{L1}_{26}$$
$$= \ell_1 h^{L1}_{11}(\bar{P}^{1*}_{L1})^{\gamma} + \ell_2 h^{L1}_{12}(\bar{P}^{1*}_{L1})^{\gamma_2} + \pi_2 D^1_{00}\bar{P}^{1*}_{L1},$$
$$e^{L1}_{21}\alpha_1(\bar{P}^{1*}_{L1})^{\alpha_1 - 1} + e^{L1}_{22}\alpha_2(\bar{P}^{1*}_{L1})^{\alpha_2 - 1} + \hat{e}^{L1}_{23}\gamma_1(\bar{P}^{1*}_{L1})^{\gamma_1 - 1}$$
$$\quad + \hat{e}^{L1}_{24}\gamma_2(\bar{P}^{1*}_{L1})^{\gamma_2 - 1} + \hat{e}^{L1}_{25}$$
$$= \ell_1 h^{L1}_{11}\gamma_1(\bar{P}^{1*}_{L1})^{\gamma_1 - 1} + \ell_2 h^{L1}_{12}\gamma_2(\bar{P}^{1*}_{L1})^{\gamma_2 - 1} + \pi_2 D^1_{00}. \tag{C.13}$$

If $P < \bar{P}^2_{L\epsilon}$, firm 2 does not have incentive to become the leader. Therefore, firm 1 can surely become the leader optimally at $\bar{P}^{1*}_{L\epsilon}$ in this case. Smooth-pasting conditions (C.12) and (C.13) reflect firm 1's optimization.

C2. The case of firm 1's preemption

Second, we consider the case of $\bar{P}^2_{L\epsilon} \leq \bar{P}^{1*}_{L\epsilon}$. In this case, firm 2 has an incentive to become the leader before firm 1's optimal investment threshold. Therefore, firm 1 reluctantly invests at $\bar{P}^2_{L\epsilon}$ in order to preempt firm 2. We can summarize the result in case of $\bar{P}^2_{L\epsilon} \leq \bar{P}^{1*}_{L\epsilon}$ by replacing $\bar{P}^{1*}_{L\epsilon}$ with $\bar{P}^2_{L\epsilon}$ and omitting smooth-pasting conditions in Proposition C.1.

Proposition C.2. *Suppose that $\bar{P}^2_{L\epsilon} \leq \bar{P}^{1*}_{L\epsilon}$. Then firm 1 preempts firm 2 and becomes a leader at $\bar{P}^2_{L\epsilon}$. The value function of firm 1 for regime 1 is given by*

$$V^1_{L1}(P) = \begin{cases} G^1_{F1}(P) - K^1, & \text{for } P \geq \bar{P}^2_{F1}, \\ G^1_{L1}(P) - K^1, & \text{for } P^2_{L1} \leq P < \bar{P}^2_{F1}, \\ h^{L1}_{11}P^{\gamma_1} + h^{L1}_{12}P^{\gamma_2} + \pi_1 D^1_{00}P, & \text{for } P < \bar{P}^2_{L1} \end{cases} \tag{C.14}$$

and the function for regime 2 is

$$V^1_{L2}(P) = \begin{cases} G^1_{F2}(P) - K^1, & \text{for } P \geq \bar{P}^2_{F2}, \\ G^1_{L2}(P) - K^1, & \text{for } \bar{P}^2_{L2} \leq P < \bar{P}^2_{F2}, \\ e^{L1}_{21}P^{\alpha_1} + e^{L1}_{22}P^{\alpha_2} + \hat{e}^{L1}_{23}P^{\gamma_1} + \hat{e}^{L1}_{24}P^{\gamma_2} & \\ \quad + \hat{e}^{L1}_{25}P + \hat{e}^{L1}_{26}, & \text{for } \bar{P}^2_{L1} \leq P < \bar{P}^2_{L2}, \\ \ell_1 h^{L1}_{11}P^{\gamma_1} + \ell_2 h^{L1}_{12}P^{\gamma_2} + \pi_2 D^1_{00}P, & \text{for } P < \bar{P}^2_{L1}, \end{cases} \tag{C.15}$$

The unknown parameters $(e^{L1}_{21}, e^{L1}_{22}, h^{L1}_{11}, c^{L1}_{12})$ are the solution of the simultaneous equation

$$h^1_{11}(\bar{P}^2_{L1})^{\gamma_1} + c^{L1}_{12}(\bar{P}^2_{L1})^{\gamma_2} + \hat{c}^{L1}_{13}\bar{P}^2_{L1} - K^1 = h^{L1}_{11}(\bar{P}^2_{L1})^{\gamma_1}$$
$$\quad + h^{L1}_{12}(\bar{P}^2_{L1})^{\gamma_2} + \hat{h}^{L1}_{13}\bar{P}^2_{L1},$$
$$c^{L1}_{21}(\bar{P}^2_{L2})^{\gamma_1} + c^{L1}_{22}(\bar{P}^2_{L2})^{\gamma_2} + \hat{c}^{L1}_{23}\bar{P}^2_{L2} - K^1 = e^{L1}_{21}(\bar{P}^2_{L2})^{\alpha_1} + e^{L1}_{22}(\bar{P}^2_{L2})^{\alpha_2}$$
$$\quad + \hat{e}^{L1}_{23}(\bar{P}^2_{L2})^{\gamma_1} + \hat{e}^{L1}_{24}(\bar{P}^2_{L2})^{\gamma_2} + \hat{e}^{L1}_{25}\bar{P}^2_{L2} + \hat{e}^{L1}_{26},$$
$$e^{L1}_{21}(\bar{P}^2_{L1})^{\alpha_1} + e^{L1}_{22}(\bar{P}^2_{L1})^{\alpha_2} + \hat{e}^{L1}_{23}(\bar{P}^2_{L1})^{\gamma_1} + \hat{e}^{L1}_{24}(\bar{P}^2_{L1})^{\gamma_2} + \hat{e}^{L1}_{25}\bar{P}^2_{L1} + \hat{e}^{L1}_{26}$$
$$= \ell_1 h^{L1}_{11}(\bar{P}^2_{L1})^{\gamma} + \ell_2 h^{L1}_{12}(\bar{P}^2_{L1})^{\gamma_2} + \pi_2 D^1_{00}\bar{P}^2_{L1},$$
$$e^{L1}_{21}\alpha_1(\bar{P}^2_{L1})^{\alpha_1 - 1} + e^{L1}_{22}\alpha_2(\bar{P}^2_{L1})^{\alpha_2 - 1} + \hat{e}^{L1}_{23}\gamma_1(\bar{P}^2_{L1})^{\gamma_1 - 1}$$
$$\quad + \hat{e}^{L1}_{24}\gamma_2(\bar{P}^2_{L1})^{\gamma_2 - 1} + \hat{e}^{L1}_{25}$$
$$= \ell_1 h^{L1}_{11}\gamma_1(\bar{P}^2_{L1})^{\gamma_1 - 1} + \ell_2 h^{L1}_{12}\gamma_2(\bar{P}^2_{L1})^{\gamma_2 - 1} + \pi_2 D^1_{00}.$$

The value function of firm 2 as the leader for investment is given in Proposition C.2 regardless of the magnitude relationship between $\bar{P}^{1*}_{L\epsilon}$ and $\bar{P}^2_{L\epsilon}$ as long as $\bar{P}^2_{L\epsilon}$ exists. In case of $\bar{P}^{1*}_{L\epsilon} < \bar{P}^2_{L\epsilon}$ and $\bar{P}^2_{L\hat{\epsilon}} \leq \bar{P}^{1*}_{L\hat{\epsilon}}$, the result can be given as the mix of Propositions C.1 and C.2.

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