Why Do Team Projects Progress Slowly?
A Model Based on Strategic Uncertainty

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Abstract

This paper analyzes the investment timing for team projects. Under demand uncertainty, it is valuable to maintain flexibility in future investment alternatives. However, one party's flexibility creates strategic uncertainty for another party, which causes the other party to choose a higher level of flexibility. This strategic complementarity leads to delays in investments in contrast to the case of accelerated investments for preemption. This strategic effect is also distinct from the free-rider problem because this study focuses on the second moment of payoffs. The model also provides a rational alternative to the status-quo bias in organizational decision-making.

JEL classification: G31, L14, L24.

Keywords: flexibility, non-cooperative games, strategic complementarity, real options, coordination failure.

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1. Introduction

Investments in a strategic environment is often studied in the context of preemption and entry deterrence. The standard result is that investments are accelerated in such strategic environments because early investments can limit competition by deterring potential entries (Dixit, 1979; Bulow et al., 1985a; Spencer and Brander, 1992; Allen et al., 2000). However, we often observe delays in team projects such as joint ventures and strategic alliances (Inkpen and Ross, 1998; Ertel and Gordon, 2007). For example, an alliance of a real estate developer and a redevelopment authority makes slow progress when both parties maintain many options to choose from. Alternatively, an alliance of firms for research and development tends to delay investments when each firm perceives uncertainty in partners' actions. Team projects are an essential element of an economy at all levels; e.g., a multi-divisional company, project-based labor contract, task force, joint venture, and public private partnership.

In this paper, I study the investment timing when two agents (e.g., firms) form a team to make joint investments. The initial agreement does not fully specify all state-contingent plans because of a high cost of writing a complete contract. Instead, as a common practice, the firms narrow down the action space by agreeing on a list of possible investment alternatives. In the terminology used by Hart and Moore (2004), firms "rule out". For example, a new computer product is often developed by an alliance of hardware and software firms. A hardware firm may consider improving graphics or a motion-detection function, but won't consider all possible improvements. Similarly, a real estate developer may consider a hotel or office, but won't consider all possible property types. After forming a team, the firms choose the best alternative and timing for investments while project values evolve stochastically. The team does not face a perfect competition with other teams and thus, the option to wait has a positive value (Dixit and Pindyck, 1994; Abel et al., 1996; Grenadier, 2002). This investment decision is strategic because one firm's choice of an investment alternative influences the payoff to the other firm through synergies. Firms make investment decisions by taking into consideration both exogenous demand uncertainty and a strategic effect.

I show that, in equilibrium, firms maintain greater flexibility in the initial list of investment alternatives and delay invest in this strategic environment than in a single entity environment even if the expected payoff is unchanged. A key insight is that more flexible plans for a firm create greater strategic uncertainty to the other firm because of the existence of multiple equilibria or changes in the equilibrium structure of the game. Given greater uncertainty, the other firm chooses as the best response a higher degree of flexibility in its initial list as Jones and Ostroy (1984) and Appelbaum and Lim (1985) demonstrate. Thus, the flexibility in investment alternatives is a strategic complement as defined by Bulow et al. (1985b). With this stratetgic complementarity, a positive feedback is created between flexibility and uncertainty. In equilibrium, uncertainty is greater and investments are delayed as a consequence of the maximization of firm value. This result based on the second moment of payoffs is contrasted with other results based on the first moment such as the war of attrition, the holdup problem (Che and Sakovics, 2004), the second-mover advantage in a sequential-move game (Chamley and Gale, 1994), and synchronization in a coordination game (Cooper and Haltiwanger, 1992; Cahuc and Kempf, 1997; Gale, 1995, 1996).

The delay in investments relative to the non-strategic case has an important implication. In an economy in which public private partnerships and joint ventures are widely used, investment activities can be stagnant even if the demand level is high and the demand uncertainty is low. The delay in investment also serves as a basis for a status-quo bias for a multi-divisional organization when the investment in this study is interpreted as a commitment for a change.

Specifically, I derive a perfect Nash equilibrium of a two-stage game, which embeds a continuous-time option model of investment in the second stage. In the second stage, the firms optimally exercise American call options on the basis of equilibrium payoffs, which are modeled as a jump-diffusion process. A geometric Wiener process represents stochastic demand and a Poisson process represents changing equilibrium structures. In the next section, I demonstrate that the equilibrium payoff exhibits jumps when the equilibrium structure of a product choice game changes.

In the first stage, the firms decide how many investment alternatives to include in the agreement. Maintaining multiple alternatives gives a firm flexibility to choose the best alternative later. A firm increases the number of alternatives until the additional value is greater than the additional cost of maintaining multiple alternatives.

2. An Illustration of Strategic Uncertainty

To demonstrate that strategic uncertainty can emerge as a result of changing equilibrium structures or multiple equilibria, I consider two firms that already formed a team. Each firm maintains two alternative product characteristics and determines the best alternative at each t by a simultaneous-move, non-repeated, non-cooperative game.[1] For example, an alliance of a computer hardware and software firms considers a better motion-detection technology or a better graphics. Although a good match between hardware and software will create synergies, the firms may not agree on the same alternative.

Fig. 1 depicts a path of Firm A's simulated project values, which are modeled as independent geometric random walks. When both firms choose the same type, the value is multiplied by a synergy ratio, which follows an AR(1) process around the value of one.[2] I report an equilibrium with the following priority: 1. a unique equilibrium, 2. the risk-dominant equilibrium among Pareto-ordered multiple equilibria (e.g., Carlsson and van Damme, 1993, demonstrate its robustness.), and 3. a realization of the mixed strategy equilibrium among non-Pareto-ordered multiple equilibria.

The equilibrium outcome exhibits jumps when the equilibrium structure changes from, say, Prisoners' Dilemma to the Battle of the Sexes. Jumps also occur when the players

[1] In a cooperative game, additional uncertainty on payoffs can be created because the ex post allocation of synergies is often undetermined and hence risky even if there is a unique Shapley value for each firm (Hart, 2008).

[2] The value of a Type-k investment for Firm i at time t is $V_{i,t}^k = V_{i,t-1}^k(1 + 0.07\varepsilon_{i,t})$ with $V_{i,0}^k = 1$, and the synergy ratio is $S_t^k = 1 + 0.9(S_{t-1}^k - 1) + 0.07\nu_t$, where $\varepsilon_{i,t}$ and ν_t are i.i.d. standard normal random variables.

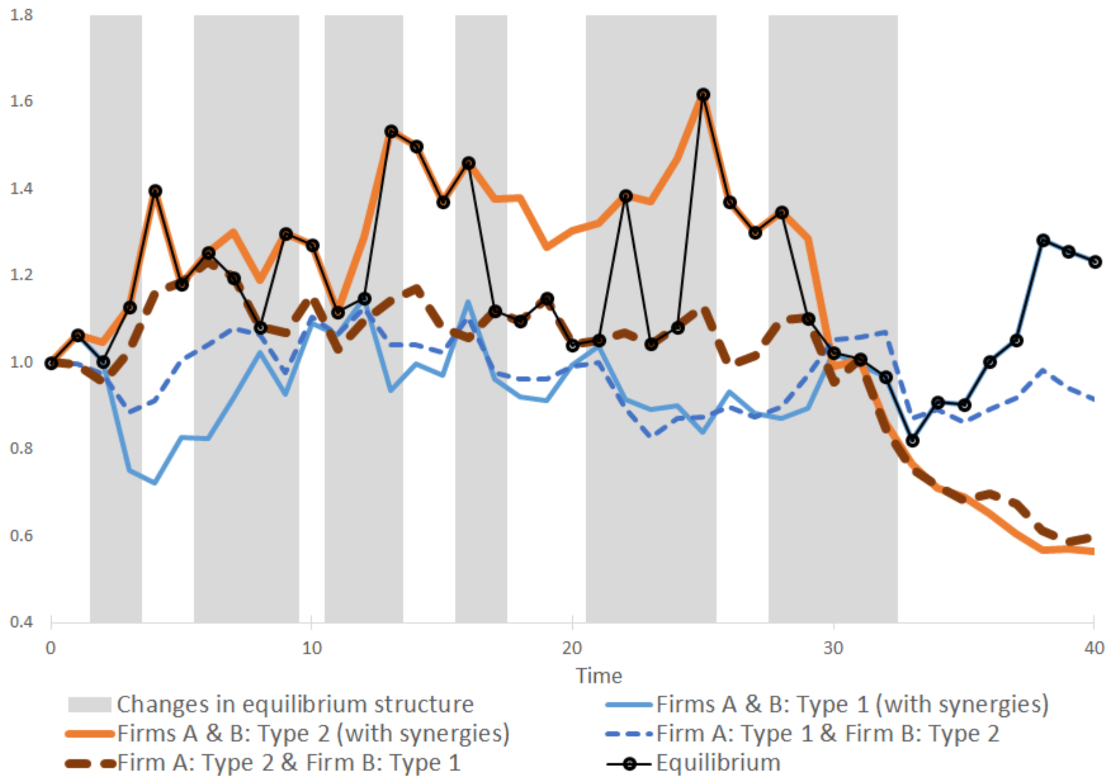

Fig. 1. Simulated project value for Firm A

may have divergent preferences across multiple equilibria (e.g., in the Battle of the Sexes) or they cannot eliminate Pareto-dominated equilibria (e.g., see Crawford, 1995, for a Pure Coordination Game).[3] For example, Firm A's value exhibits jumps from 1.15 to 1.53 at $t = 13$ and from 1.46 to 1.12 at $t = 17$. Firm A's equilibrium choices change between two types at times $2, 3, 12, 13, 30, 31,$ and 32, and Firm B's choices change at times $7, 9, 17, 22, 23,$ and 25.

[3]A growing number of experimental studies show that actual equilibria change over time (e.g., Van Huyck et al., 1990, 1991; Cooper et al., 1990; Ochs, 1992; Duffy and Feltovich, 2006; Blume and Ortmann, 2007; Riechmann and Weimann, 2008; Cason et al., 2012). In a cooperative game, strategic uncertainty can emerge from the ex post allocation of synergies.

3. The Model and Results

Two risk-neutral firms, labeled $i \in \{A, B\}$, form a team for joint investments. The team does not face a perfect competition for the investment opportunity and thus, an option to wait has a positive value. There are two phases: an initial phase of team formation and the second phase of investments. In the initial team formation phase, firms agree on a list of investment alternatives that can be carried out in the investment phase, but they cannot contract on every potential contingency; i.e., the contract is incomplete. Firms could narrow the list down to a single alternative, but it is not optimal because an initially optimal alternative may turn out to be ex-post suboptimal due to exogenous demand uncertainty.

The number of alternatives is a measure of flexibility of the project. It is a discrete number in principle, but for analytical convenience, I formulate the flexibility as a continuous variable $F_i \in (0, \infty)$. An alternative is indexed by $k \in (0, F_i]$. Maintaining more alternatives increases the firm's ability to react to changes in market conditions, but incurs costs L_i to keep all alternatives up-to-date (e.g., expenses for planning, feasibility studies, and regulatory processes). L_i is assumed to be an increasing convex function of $F_i : L_i'(F_i) > 0$ and $L_i''(F_i) > 0$. The firms determine F_A and F_B in the initial agreement at time $t = 0$, and make their investments by the end of the investment phase, time T.

In the investment phase, the fundamental value of an alternative k evolves as a geometric Wiener process on a filtered probability space $(\Omega, \mathcal{F}, P)$, with filtration $\{\mathcal{F}_t\}$ on $t \in [0, T]$. The value process is expressed as: $dV_{i,t}^k = V_{i,t}^k \left[\left(r - \mu_i^k \right) dt + \sigma_i^k dW_{i,t}^k \right]$, where $r \in (0, \infty)$ is the constant risk-free rate, and $\mu_i^k \in [0, \infty)$ is the instantaneous rate of reduction in the project value due to competitions with other teams. If the team is a monopoly, $\mu_i^k = 0$ and the team invests only at the end of the investment phase. σ_i^k is the volatility of the asset value, and $dW_{i,t}^k$ is a one-dimensional standard Wiener process adapted to filtration $\mathcal{F}_t$. Let $\bar{V}_{i,t}$ denote the value of the best alternative for Firm i: $\bar{V}_{i,t} \equiv \max_{k \in (0, F_i]} \left\{ V_{i,t}^k \right\}$. This is a Wiener process with regime-switching. Let m denote the index for the best alternative at each point in time. Then, the drift is $(r - \mu_i^{m_i})$ and the volatility is $\sigma_i^{m_i}$. It is important to note that $\bar{V}_{i,t}$ is non-decreasing in F_i because adding more alternatives won't harm:

$$\partial \bar{V}_{i,t} / \partial F_i \geq 0 \tag{1}$$

In addition to the fundamental value, firm i's payoff is influenced by the strategic uncertainty that stems from a game with firm j. As illustrated in Section 2, payoffs exhibit infrequent jumps due to changing equilibrium structures or the existence of multiple equilibria. Let a mean-zero Poisson process $q_{i,t}$ characterize the strategic uncertainty for firm i:

$$dq_{i,t} = \begin{cases} 0 & \text{with probability } 1 - \lambda_i dt \\ -\varepsilon_{i,t} + \tilde{\varepsilon}_i & \text{with probability } \lambda_i dt \end{cases} \tag{2}$$

where $\lambda_i \in (0,1)$ is the intensity, and a random variable $\tilde{\varepsilon}_i \in \mathbb{R}$ is the size of a jump, $\varepsilon_{i,t} \in \mathbb{R}$ is the current level of $q_{i,t}$, or the size of the previous jump. The term $-\varepsilon_{i,t}$ cancels the previous jump and makes the jump process stationary around zero. This is contrasted with the model of a level effect studied by Appelbaum and Lim (1985) and Vives (1989). $\tilde{\varepsilon}_i$ can be drawn from any symmetric distribution, but for concreteness I assume $Uniform\left(-\sigma_i^s, \sigma_i^s\right),\ \sigma_i^s > 0$. I assume $E\left(dW_{i,t}^k\ dq_{i,t}\right) = 0$ for any t, k, i. The volatility of $\tilde{\varepsilon}_i$, σ_i^s is a measure of strategic uncertainty for Firm i. Because a lager strategy space of firm j creates a greater variation in equilibrium outcomes for firm i (Crawford, 1995), strategic uncertainty is assumed to be an increasing function of F_j :

$$d\sigma_i^s / dF_j > 0, \tag{3}$$

The project value for Firm i, denoted by $V_{i,t}$, evolves as a jump-diffusion process:

$$V_{i,t} = \bar{V}_{i,t} + q_{i,t}, \tag{4}$$

By investing $K_i^{m_i}$, Firm i obtains the payoff $\Pi_i\left(V_{i,t}; K_i^{m_i}\right) \equiv \max\left(V_{i,t} - K_i^{m_i}, 0\right)$. With a stopping time τ, the no-arbitrage value process for the investment opportunity $C_{i,t}$ is:

$$C_{i,t} = E_t \left[e^{-r(\tau - t)} \Pi_i \left(V_{i,\tau}; K_i^{m_i} \right) \right], \tag{5}$$

$$\tau = \inf \left\{ t : \forall i, \Pi_i \left(V_{i,t}; K_i^{m_i} \right) - C_{i,t} \geq 0 \right\}. \tag{6}$$

The firms simultaneously invest when both projects satisfy (6). This investment rule that includes the opportunity cost of discarding an option is contrasted with Tobin's q criterion under perfect competition (Abel et al., 1996). The standard solution method is to divide the range of the underlying asset value into the continuation and stopping regions. By applying Ito's lemma to $C_{i,t}$ in the continuation region, I obtain:

$$\begin{aligned} C\left(V_{i,t}\right) rdt = &\left\{ \frac{\partial C\left(V_{i,t}\right)}{\partial V_{i,t}} V_{i,t} \left(r - \mu_{i,t}^{m_i} \right) + \frac{1}{2} \frac{\partial^2 C\left(V_{i,t}\right)}{\partial {V_{i,t}}^2} \left(\sigma_{i,t}^{m_i} V_{i,t} \right)^2 \right\} dt \\ &+ \left\{ E^{\varepsilon} \left[C\left(\bar{V}_{i,t} + \tilde{\varepsilon}_i \right) \right] - C\left(\bar{V}_{i,t} + \varepsilon_{i,t_-} \right) \right\} \lambda dt, \end{aligned} \tag{7}$$

where $E^{\varepsilon}[\bullet]$ is the expectation over $\tilde{\varepsilon}_i$. The expected return on $C_{i,t}$ equals the sum of the expected change in fundamental value (the first term) and the expected change due to strategic uncertainty (the second term). In Appendix A, I derive an analytical expression for $C_{i,t}$ by using the formula proposed by Gukhal (2001). Although $C_{i,t}$ can be numerically analyzed, for the purpose of this study, it suffices to use the following standard properties of an American call option:

$$\partial C_{i,t} / \partial V_{i,t} \in (0, 1], \tag{8}$$

$$\partial C_{i,t} / \partial \sigma_i^s > 0. \tag{9}$$

From (3) and (9), $C_{i,t}$ is increasing in F_j. Eqs. (1), (4), and (8) imply that $C_{i,t}$ is non-decreasing in F_i as demonstrated by Triantis and Hodder (1990). Furthermore, it is natural to assume that marginal benefit of flexibility is diminishing but increasing in uncertainty:

$$\partial C_{i,t}/\partial F_i \geq 0. \tag{10}$$

$$\partial^2 C_{i,t}/\partial F_i^2 < 0. \tag{11}$$

$$\partial^2 C_{i,t}/\partial F_i \partial \sigma_i^s > 0. \tag{12}$$

In the team formation phase, a firm solves:

$$\max_{F_i} I_i \equiv C_{i,0}\left(V_{i,0}, K_i^{m_i}, F_i, T, \sigma_{i,t}^{m_i}, \sigma_i^s\right) - L_i\left(F_i\right).$$

Note that $I_i(F_i)$ is concave in F_i by $L_i''(F_i) > 0$ and (11). In the benchmark case in which σ_i^s is independent of F_i, the necessary and sufficient condition that characterizes the optimal F_i^* would be:

$$\frac{\partial I_i}{\partial F_i} = \frac{\partial C_{i,0}}{\partial F_i} - \frac{\partial L_i}{\partial F_i} = 0. \tag{13}$$

This equation implicitly defines the reaction function of firm i, $F_i\left(\sigma_i^s\left(F_j\right); V_{i,0}, K_i^{m_i}, T\right)$. Without strategic uncertainty, $dC_{i,0}/dF_i$ is equivalent to the direct effect $\partial C_{i,0}/\partial F_i$. In this case, the optinal F_i is not influenced by Firm j's decision. By contrast, in the presence of strategic uncertainty, F_i is shown to influences its own σ_i^s. I call this effect a strategic uncertainty effect. To see that the strategic uncertainty effect is positive, I first show that the choice of flexibility is a strategic complement.

Proposition 1. *When there is a strategic uncertainty, F_i and F_j are strategic complements. That is, a more flexible strategy of firm i results in firm j's reacting with a more flexible strategy:*

$$\left.\frac{\partial F_j\left(F_i\right)}{\partial F_i}\right|_{\frac{\partial I_j}{\partial F_j}=0} > 0. \tag{14}$$

Proof. Firm j's choice of flexibility is determined by the optimality condition (13), where $dC_{j,0}/dF_j$ is decreasing in F_j from (11) and dL_i/dF_i is increasing in F_j by $L_i''(F_i) > 0$.

If Firm i increases the degree of flexibility F_i, Firm j faces larger σ_j^S from (3), and thus $dC_{j,0}/dF_j$ is larger for any F_j by (12). Then, a larger value of F_j satisfies (13); i.e., (14) is derived. □

The next proposition shows that the strategic uncertainty effect is positive.

Proposition 2. *The strategic uncertainty effect is positive. That is, a firm's increased degree of flexibility increases the uncertainty that the firm itself faces:*

$$\frac{\partial \sigma_i^s}{\partial F_i} > 0. \tag{15}$$

.

Proof. From (3), σ_i^s is strictly increasing in F_j. From (14), $\partial F_j/\partial F_i$ is strictly positive at the optimum. Hence, $\frac{\partial \sigma_i^s}{\partial F_i} = \frac{\partial \sigma_i^s}{\partial F_j}\frac{\partial F_j}{\partial F_i} > 0$. □

With the strategic uncertainty effect, the optimality condition for i becomes:

$$\frac{\partial I_i}{\partial F_i} = \left(\frac{\partial C_{i,0}}{\partial F_i} + \frac{\partial C_{i,0}}{\partial \sigma_i^s}\frac{\partial \sigma_i^s}{\partial F_i}\right) - \frac{\partial L_i}{\partial F_i} = 0. \tag{16}$$

The reaction function is higher everywhere in (16) than in (13). In other words, a positive strategic uncertainty effect shifts the reaction function outward. To see this, note that the additional term $\frac{\partial C_{i,0}}{\partial \sigma_i^s}\frac{\partial \sigma_i^s}{\partial F_i}$ is positive from Eqs. (9) and (15). Then, $\frac{dC_{i,0}}{dF_i}$ (i.e., the terms in parentheses) is higher for any level of F_i because there are two channels, through which F_i positively affect $C_{i,0}$. On the other hand, $\partial L_i/\partial F_i$ is increasing in F_i. Thus, for any given level of F_j, the optimal level of flexibility for firm i is higher with the strategic uncertainty effect than without. From this discussion, I obtain one of the main results of this study.

Proposition 3. *The equilibrium degree of flexibility F_i^* for $i = 1, 2$ is higher when the strategic uncertainty effect exists.*

Proof. With the strategic uncertainty effect, each firm must satisfy (16) at the optimum. Therefore, the reaction curve of each firm is shifted outward as explained in the discussion above. Because the strategic complementarity (14) implies upward sloping reaction curves, an outward shift of a reaction curve results in a higher equilibrium level of flexibility for each firm. □

Fig. 2 depicts a symmetric case. $F_i\,(F_j)$ is the reaction function of firm i to the strategy of firm j. Non-decreasing reaction functions represent strategic complementarity in (14). With a positive strategic uncertainty effect ($\partial\sigma_i/\partial F_i > 0$), the reaction function shifts higher everywhere, and as a result, the equilibrium degree of flexibility F_i^* is higher.

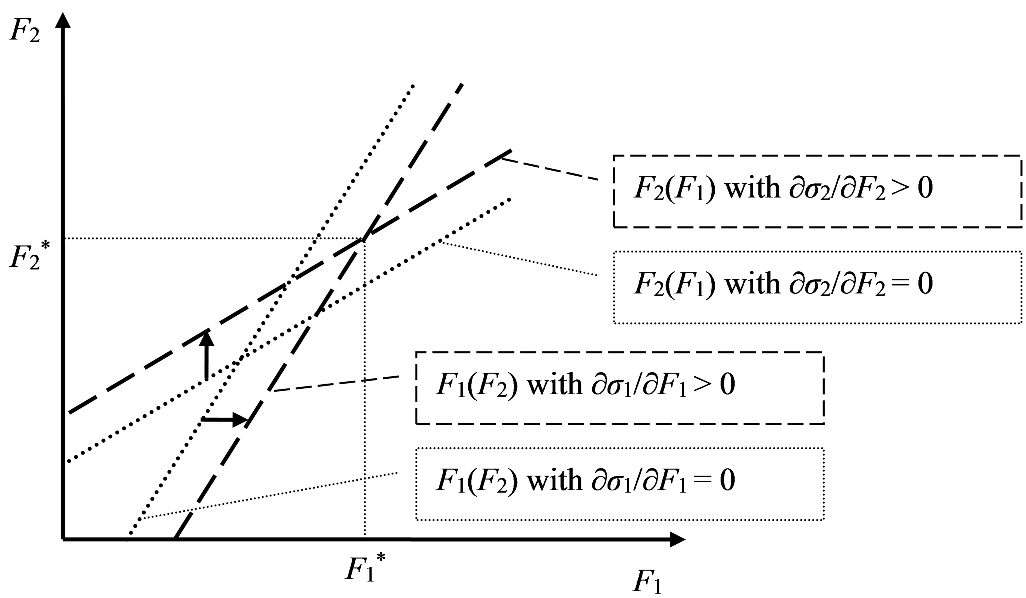

Fig. 2. Reaction Functions.

Note that there must be at least one equilibrium level of flexibility, provided that the agreement is reached in the initial phase. If the reaction curves are linear, globally convex, or globally concave, then there exists a unique equilibrium. In general, uniqueness cannot be obtained without identifying the functional form of the reaction curves. The level of flexibility in the initial contract should represent either a unique equilibrium or one of multiple equilibria. Although I do not model the process of choosing one of the multiple equilibria, that two firms have reached an agreement indicates that they have chosen a particular level of flexibility.

Now I consider the equilibrium timing of investment. After deciding the degree of flexibility of the investment plan, the firms choose the optimal timing of investment, as observed in (6). At each point in time until the expiration of the project, the firms follow the optimal investment rule: Invest if $V_{i,t} - K_i^{m_i} - C_{i,t} \geq 0$. Note that Tobin's q criterion under perfect competition is $V_{i,t} - K_i^{m_i} \geq 0$. Under imperfect competition, the rule includes the opportunity cost of discarding options when a firm makes an investment. By incorporating Proposition 3 into this investment rule, I obtain the second main result of this study about the equilibrium investment timing:

Proposition 4. *Investment is delayed when there is a positive strategic uncertainty effect,* $\frac{\partial \sigma_i^s}{\partial F_i} > 0$.

Proof. By Proposition 3, the equilibrium degree of flexibility is higher when there is an strategic uncertainty effect. The resulting level of uncertainty is higher for both firms. Therefore, the equilibrium value of investment opportunity $C_{i,t}^*$ is higher for all t for two reasons. First, a higher equilibrium level of flexibility weakly increases the value of investment opportunity through the direct effect of (10). Second, a higher equilibrium level of flexibility increases uncertainty through the strategic uncertainty effect (15), and the greater uncertainty increases the value of the investment opportunity through (9). The firm requires a higher level of $V_{i,t}$ to make the investment. As a result, the investment is delayed under the strategic uncertainty effect. □

4. Conclusion

Previous studies have shown that exogenous uncertainty makes agents want to maintain greater flexibility and delay investment. The innovation of this paper is to incorporate the reverse effect: the effect of flexibility on uncertainty. With the strategic uncertainty effect, the equilibrium degree of flexibility is even greater, and the investment is more delayed. This self-reinforcing effect is important because individually optimal decision-making results in stagnant economic activities.

This economics applies not only to investment decisions but also to a variety of joint projects that require the commitment of agents. An example is a multinational negotiation among international organizations when forming a joint multinational project. The model of the strategic uncertainty effect sheds light on this wide range of strategic activities.

Appendix A.

In this appendix, I present an analytical formula for the value of the investment opportunity $C_{i,t}$ after characterizing the value by a second-order partial differential equation. In (7), by retaining leading terms in dt, I obtain the second-order partial differential equation for $C_{i,t}$:

$$0 = -rC_{i,t} + \frac{\partial C_{i,t}}{\partial \bar{V}_{i,t}} V_{i,t} \left(r - \mu_i^{m_i}\right) + \frac{1}{2} \frac{\partial^2 C_{i,t}}{\partial \bar{V}_{i,t}^{\;2}} \left(\sigma^{m_i} V_{i,t}\right)^2 + \lambda E^{\varepsilon} \left[C\left(\bar{V}_{i,t} + \tilde{\varepsilon}_i\right)\right] - \lambda C\left(\bar{V}_{i,t} + \varepsilon_{i,t}\right). \tag{A.1}$$

If a jump takes the asset value into the stopping region, $C\left(\bar{V}_{i,t} + \tilde{\varepsilon}_i\right)$ in (A.1) is replaced by $\Pi\left(\bar{V}_{i,t} + \tilde{\varepsilon}_i; K^{m_i}\right)$. The problem is a free boundary problem with the following boundary conditions:

$$\begin{aligned} C\left(V_{i,t}\right) &= \max\left\{0, \Pi\left(V_{i,t}; K^{m_i}\right)\right\}, \\ C_{i,t}\left(0\right) &= 0, \\ C_{\tau}\left(V_{\tau}\right) &= \Pi\left(V_{\tau}; K^{m_i}\right), \quad \text{(Value matching condition)} \\ \frac{\partial C_{\tau}\left(V_{\tau}\right)}{\partial V_{\tau}} &= 1. \quad \text{(Smooth pasting condition).} \end{aligned}$$

Gukhal (2001) derives a formula for the value of American call option when the underlying asset follows a jump-diffusion process. The value of an investment opportunity can be expressed as:

$$\begin{aligned} C_0 &= b_0 + \int_{u=0}^{T} e^{-ru} E\left[\left\{ \mu^{m_i} V_u - rK^{m_i} \right\} \mathbf{1}_{\{V_u \in \mathbf{S}\}} \middle| \mathcal{F}_0 \right] du \\ & -\lambda \int_{u=0_+}^{T} e^{-ru} E\left[\begin{array}{c} \left\{ C_u - \Pi\left(V_u; K^{m_i}\right) \right\} \\ \times \mathbf{1}_{\left\{V_{u_-} \in \mathbf{S}\right\}} \mathbf{1}_{\{V_u \in \mathbf{C}\}} \mathbf{1}_{\{u<\tau\}} \end{array} \middle| \mathcal{F}_0 \right] du, \end{aligned} \tag{A.2}$$

where b_0 is the value of the corresponding European call option, $\mathbf{1}_{\{\bullet\}}$ is an indicator function, $0_+ \equiv 0 + du$, and $u_- \equiv u - du$. $\mathbf{S}$, $\mathbf{C} \subset \mathbb{R}$ represent the stopping and continuation regions, respectively. The critical asset value $X_{i,t}$ that divides $V_{i,t}$ into $\mathbf{S}$ and $\mathbf{C}$ is obtained by solving $X_{i,t} - K^{m_i} = C_{i,t}$.

The sum of the two integral terms is called the early exercise premium. The first integral is the benefit from the stopped reduction in asset value $(+\mu^{m_i} V_u)$ less the cost of foregone interest $(-rK^{m_i})$ in cases of early exercise. The second integral is another "cost" of early exercise that is associated with jumps from the stopping region back to the continuation region. Even if the asset value is in the stopping region and the option is exercised at time u_-, subsequent Poisson jumps may bring the asset value back to the continuation region after the exercise. In that case, $C_u - \Pi\left(V_u, q_u; K\right)$ becomes positive. The optimal exercise policy requires that the stopped reduction in asset value be greater than the combined cost of foregone interest and missed chances of continuation.

References

Abel, A. B., Dixit, A. K., Eberly, J. C., Pindyck, R. S., 1996. Options, the value of capital, and investment. The Quarterly Journal of Economics 111, 753–77.

Allen, B., Deneckere, R., Faith, T., Kovenock, D., 2000. Capacity precommitment as a barrier to entry: A bertrand-edgeworth approach. Economic Theory 15, 501–530.

Appelbaum, E., Lim, C., 1985. Contestable markets under uncertainty. Rand Journal of Economics 16, 28–40.

Blume, A., Ortmann, A., 2007. The effects of costless pre-play communication: Experimental evidence from games with pareto-ranked equilibria. Journal of Economic Theory 132, 274 – 290.

Bulow, J., Geanakoplos, J., Klemperer, P., 1985a. Holding idle capacity to deter entry. The Economic Journal 95, pp. 178–182.

Bulow, J. I., Geanakoplos, J. D., Klemperer, P. D., 1985b. Multimarket oligopoly: Strategic substitutes and complements. The Journal of Political Economy 93, 488–511.

Cahuc, P., Kempf, H., 1997. Alternative time patterns of decisions and dynamic strategic interactions. Economic Journal 107, 1728–41.

Carlsson, H., van Damme, E., 1993. Global games and equilibrium selection. Econometrica 61, pp. 989–1018.

Cason, T. N., Sheremeta, R. M., Zhang, J., 2012. Communication and efficiency in competitive coordination games. Games and Economic Behavior 76, 26 – 43.

Chamley, C., Gale, D., 1994. Information revelation and strategic delay in a model of investment. Econometrica 62, 1065–85.

Che, Y.-K., Sakovics, J., 2004. A dynamic theory of holdup. Econometrica 72, 1063–1103.

Cooper, R. W., DeJong, D. V., Forsythe, R., Ross, T. W., 1990. Selection criteria in coordination games: Some experimental results. The American Economic Review 80, pp. 218–233.

Cooper, R. W., Haltiwanger, J. J., 1992. Macroeconomic implications of production bunching : Factor demand linkages. Journal of Monetary Economics 30, 107–127.

Crawford, V. P., 1995. Adaptive dynamics in coordination games. Econometrica 63, 103–43.

Dixit, A. K., 1979. A model of duopoly suggesting a theory of entry barriers. Bell Journal of Economics 10, 20–32.

Dixit, A. K., Pindyck, R. S., 1994. Investment Under Uncertainty. Princeton University Press, Princeton, NJ.

Duffy, J., Feltovich, N., 2006. Words, deeds, and lies: Strategic behaviour in games with multiple signals. The Review of Economic Studies 73, 669–688.

Ertel, D., Gordon, M., 2007. The Point of the Deal: How to Negotiate When Yes Is Not Enough. Harvard Business School Press, first ed.

Gale, D., 1995. Dynamic coordination games. Economic Theory 5, 1–18.

Gale, D., 1996. Delay and cycles. The Review of Economic Studies 63, pp. 169–198.

Grenadier, S. R., 2002. Option exercise games: An application to the equilibrium investment strategies of firms. The Review of Financial Studies 15, 691–721.

Gukhal, C. R., 2001. Analytical valuation of american options on jump-diffusion processes. Mathematical Finance 11, 97–115.

Hart, O. D., Moore, J., 2004. Agreeing now to agree later: Contracts that rule out but do not rule in. NBER Working Paper 10397 .

Hart, S., 2008. Shapley value. In: Durlauf, S. N., Blume, L. E. (eds.), *The New Palgrave Dictionary of Economics*, Palgrave Macmillan, Basingstoke.

Inkpen, A. C., Ross, J., 1998. Why do some strategic alliances persist beyond their useful life? Organization Science 9, 306–325.

Jones, R. A., Ostroy, J. M., 1984. Flexibility and uncertainty. Review of Economic Studies 51, 13–32.

Ochs, J., 1992. Coordination problems. In: Kagel, J. H., Roth, A. E. (eds.), *The Handbook of Experimental Economics*, Princeton University Press, Princeton, pp. 195–252.

Riechmann, T., Weimann, J., 2008. Competition as a coordination device: Experimental evidence from a minimum effort coordination game. European Journal of Political Economy 24, 437–454.

Spencer, B. J., Brander, J. A., 1992. Pre-commitment and flexibility: Applications to oligopoly theory. European Economic Review 36, 1601–26.

Triantis, A. J., Hodder, J. E., 1990. Valuing flexibility as a complex option. The Journal of Finance 45, 549–565.

Van Huyck, J. B., Battalio, R. C., Beil, R. O., 1990. Tacit coordination games, strategic uncertainty, and coordination failure. American Economic Review 80, 234–48.

Van Huyck, J. B., Battalio, R. C., Beil, R. O., 1991. Strategic uncertainty, equilibrium selection, and coordination failure in average opinion games. Quarterly Journal of Economics 106, 885–910.

Vives, X., 1989. Technological competition, uncertainty, and oligopoly. Journal of Economic Theory 48, 386–415.