Internal vs External R&D: A Real Options Approach

Sana Mrizak Baran Siyahhan* Donia Trabelsi†

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Abstract

This paper proposes a model that investigates firms' choice over internal R&D and corporate venture capital. Central to our model is an incumbent firm's ability to successfully deploy a startup firm's intellectual capital in the context of a corporate venture capital project and the degree of knowledge spillovers in the absence of a corporate venture capital engagement. Although a higher ability to integrate a startup's intellectual capital combined with a low degree of knowledge spillovers creates an incentive to engage in corporate venture capital, we show that this incentive is tempered by the future economic benefit the incumbent firm expects from the project.

Keywords: Corporate venture capital, Intellectual Capital, Absorptive Capacity, Knowledge Spillover, Real Options

JEL Classification: G24, D81, O32, O34

*Telecom School of Management, 9 rue Charles Fourier, 91011 Evry-Cedex, France, E-mail: baran.siyahhan@telecom-em.eu, Phone: +33160764359, ORCID ID: 0000-0002-2625-3861

†Telecom School of Management, 9 rue Charles Fourier, 91011 Evry-Cedex, France, E-mail: donia.trabelsi@telecom-em.eu, Phone: +33160764285

1 Introduction

Corporations need not only rely on their own organizational capabilities in order to bring out new and potentially groundbreaking innovations. In addition to their internal R&D activities, they can tap external sources of knowledge including, for instance, strategic alliances, acquisitions and corporate venture capital. Despite the ups and downs, the amount that firms have poured into corporate venture capital (CVC) deals has increased by about threefold from $11.0 billion in 2007 to $32.2 billion in 2016 (NVCA, 2017). In the same period, the number of deals concluded nearly doubled from 666 to 1204 (NVCA, 2017). The CVC arms of large firms such as Intel Capital and Microsoft Ventures continue to invest in the forefront of the latest technologies in autonomous machines, artificial intelligence and virtual reality.[1]

What induces such large corporations to set up CVC arms rather than relying solely on internal innovation? First, as opposed to independent venture capital (IVC) investments that focus mainly on financial returns, corporations that engage in CVC emphasize the strategic nature of their investments, often citing factors such as "gaining insight on innovative technologies", "increasing speed of innovation and reducing cost" and "identifying potential acquisitions" (Ernst & Young (2009)).[2]

Second, internal R&D can often be slow (Kim et al. (2016)) or may have deteriorated over time (Ma (2016)). Thus, corporations seeking faster and

[1] See the Forbes article and Microsoft Ventures website.

[2] MacMillan et al. (2008) and Dushnitsky and Lenox (2006) also emphasize the strategic orientation of CVC and their potential to create value and allow companies to acquire new knowledge. Dushnitsky and Lenox, 2005b find evidence that CVC investments are subsequently associated with higher innovation output as referenced by future patent citation levels.

more groundbreaking innovation can tap the external R&D opportunities, particularly in industries characterized by competition and high rates of obsolescence (Kim et al. (2016)).

In this paper, we investigate corporations' choice between internal R&D and CVC in a real options model that takes into account the strategic nature of CVC investments. In particular, the model emphasizes the information acquisition role that CVCs play in the innovation process.

In our model, the firm can either innovate internally or set up a CVC investment in a startup in order to realize an innovation that entitles the firm to a stream of cash flows whose value evolves stochastically over time. Once the innovation has been made, the firm decides whether it is optimal to market the product or not depending on the cash flows that it expects from the innovation.

The model features several crucial assumptions. First, the firm faces two sources of uncertainty. One source is the stochastic stream of cash flows, described above, that captures the market uncertainty. The second source emanates from the technological uncertainty represented by a fixed hazard rate. While market uncertainty is exogenous to both the firm and the startup, technological uncertainty is at the firm level and thus idiosyncratic. In particular, we allow the firm to partially control the technological uncertainty through its decision to carry out internal R&D or form a CVC partnership with the startup. This leads to the second crucial feature of the model: the hazard rates of individual firms depend on the stock of *intellectual capital* and knowledge spillovers.

Our choice to focus on knowledge spillovers and intellectual capital in the innovation process derives from the literature. Jaffe et al. (1993) and Bloom et al. (2013) emphasize the importance of knowledge spillovers. The latter find that the positive effect of knowledge spillovers dominates the negative effect from product market rivalry. In our model, we knowledge spillovers occur both with and without R&D cooperation. Firms can learn from each other even when they do not explicitly engage in a CVC.

We define intellectual capital as the knowledge-based equity of a firm (Tan et al. 2007). Following the intellectual capital literature, the firm's intellectual capital is composed of human capital and structural capital. While human capital is the employee-specific competences, skills and education, structural capital is endemic to the firm and entails organizational infrastructure, networking system and corporate culture (Chen et al. 2005). Bascavusoglu-Moreau and Li (2013) report that organizational capital and training activities (i.e. investments in human capital) accounted for about a fifth of the total investments in intangibles in 2008, surpassing the investment in R&D activities. In our model, intellectual capital, together with knowledge spillovers, are related to the hazard rates of innovation through a production function. In the case of a CVC, the firm's ability to integrate the startup's intellectual capital (i.e. its *absorptive capacity*) also plays a crucial role in determining the hazard rate and thereby the technological uncertainty.

Our model is closest to that of Dockner and Siyahhan (2015). In their paper, they develop a real options model that analyzes the innovation cycle of a firm that employs its intellectual capital to develop a product. They then study the risk implications of different innovation phases. We extend their model to incorporate the external R&D decision and focus on the contrast between internal R&D and CVC.

Our model shows that the choice between internal R&D and CVC does not only depend on the level of technological uncertainty. Although a CVC can reduce technological uncertainty by increasing the hazard rate of innovation, this does not automatically induce the firm to engage in a CVC. In particular, we show that the incremental benefit of a CVC over internal R&D is U-shaped in the level of cash flows from marketing the innovation. For low levels of post-innovation cash flows, the firm prefers internal R&D over CVC even when the CVC potentially reduces techological uncertainty. Only when the cash flow prospects are sufficiently favorable does the firm engage in CVC. This result is in line with the observation that the CVC arms of large corporations typically pick startups that are in the forefront of technology that promise substantial rewards if successful.

Our paper makes several contributions to the literature. First, to the best of our knowledge, our model is first to explicitly link firms' intellectual capital to CVC investments in an analytical framework. The literature on firms' external R&D activities emphasize the role of competition and relatedness of technologies (Kim et al. 2016). We argue that intellectual capital is yet another factor that must be taken into account when outsourcing R&D. Moreover, although the real options nature of venture capital in general (Trigeorgis 1993, Li 2008) and corporate venture capital in particular (Tong and Li 2011 and van de Vrande and Vanhaverbeke 2013) is well recognized in the literature, we contribute to the literature by analyzing the compound options created through CVC in a theoretical model.

The rest of the paper is organized as follows. Section 2 presents our model. In Section 3, we demonstrate the model's implications through a numerical analysis. Section 4 concludes the paper.

2 The Model

2.1 Model Structure

Consider an incumbent firm like Google that would like to pioneer innovations in AI or robotics. If successful, the innovation entitles the firm to a future stream of cash flows. We assume that the present value of these cash flows follows a geometric Brownain motion:

$$dx_t = \mu x_t dt + \sigma x_t dz_t \tag{1}$$

where dz_t is the increments of a standard Brownian motion, σ denotes volatility parameter while μ is the drift parameter.

Both the incumbent firm and the startup carry out R&D in order to successfully innovate. The probability of successful innovation given that it has not yet been completed is given by:

$$\left.\begin{array}{l} \mathbb{P}\left\{\tau \in (t, t+dt] | \tau \geq t\right\} = \lambda_i dt \\ \mathbb{P}\left\{\tau \in (t, t+dt] | \tau \geq t\right\} = \lambda_e dt \end{array}\right\} \tag{2}$$

where λ_i and λ_e represent the innovation rates of the incumbent firm and the startup, respectively.

The incumbent firm has the option to innovate either internally within its R&D department or externally by spending an amount I_c to acquire a portion π in a startup as part of a CVC deal. The success of the innovation depends on how the incumbent uses its own intellectual capital in case of internal development and how well it is able to integrate the intellectual capital of the startup if it chooses to make a CVC investment. Similar to the incumbent firm, the startup also makes use of its intellectual capital to innovate. Based on the literature on intellectual capital, each firm's intellectual capital is composed of human capital and structural capital.

In addition to the intellectual capital, each firm may also benefit from positive externalities in the form of knowledge spillovers (see Griliches 1979 and Bloom et al. 2013). To the extent observable, these spillovers may arise from the success or failures of other firms' R&D efforts or imitation of other firms' innovations (Bascavusoglu-Moreau and Li 2013).

As in Dockner and Siyahhan (2015), a Cobb-Douglas function captures the relation between intellectual capital, knowledge spillovers and the innovation rate:[3]

$$\left.\begin{aligned} \lambda_i(H_i, S_i, K) &= H_i^{\eta_1} S_i^{\eta_2} K^{\eta_3} \\ \lambda_e(H_e, S_e, K) &= H_e^{\nu_1} S_e^{\nu_2} K^{\nu_3} \end{aligned}\right\} \tag{3}$$

where H_i and H_e denote the respective human capitals while S_i and S_e represent each firm's structural capital and K is the knowledge spillover. We assume that $\eta_j < 1$, $j \in \{1, 2, 3\}$ and $\sum_j \eta_j < 1$. Similar conditions apply to ν_j, $j \in \{1, 2, 3\}$

Our modeling of innovation success rests on the literature on the role of intellectual capital in pioneering innovations. For instance, Zingales (2000) notes that skilled human capital is more crucial to generating innovation than physical capital. More recently, Chen and Wang (2014) find that human capital and structural capital are associated with a higher likelihood of pioneering innovation. Equation (3) also captures the idea that the components of intellectual capital and knowledge spillovers are complementary.

If the incumbent invests in the startup as a corporate VC, then the

[3]The Cobb-Douglas function belongs to the family of constant elasticity of substitution (CES) functions which nest several interesting cases other than the Cobb-Douglas fuction including linear function with perfect factor substitution and Leontief function with perfect complementarity.

innovation rate depends on how well it can integrate the startup's intellectual capital. We capture this ability by $\omega \in [0, 1]$:

$$\lambda_c(H_i, S_i, H_e, S_e) = (H_i + \omega H_e)^{\eta_1} (S_i + \omega S_e)^{\eta_2} \tag{4}$$

where, for exposition, we have maintained the incumbent firm's elasticity η_1 and η_2 on human capital and structural capital. A higher ω in equation (4) means that the incumbent firm has a higher absorbing capacity and can put a comparatively higher portion of the startup's intellectual capital to innovative use. Put differently, the parameter ω captures how well interorganizational learning takes place.

Turning to the cost side, we assume that each firm incurs a fixed cost per unit of time to maintain its internal R&D denoted by $f_i dt$ and $f_e dt$ while a CVC leads to a fixed cost of $f_c dt$. These costs may include salaries paid for scientists and expenditures made to maintain and upgrade organizational systems to bring them amenable to the current research activity.

Given the structure on innovation rates and costs, Figure 1 summarizes the decisions faced by the incumbent. The incumbent firm decides whether to carry out its R&D internally or make a CVC investment in the startup. Upon successful completion of the innovation, the incumbent has to decide whether to bring the product to the market. In an internally conducted R&D, this amounts to deciding whether to market the product immediately if market conditions are favorable or postpone the launch if they are unfavorable. In the case of the CVC, the incumbent firm has an additional option: whether to acquire the startup or sell its shares. The acquisition of the remaining portion of the startupm $1 - \pi$ comes at a cost I_m if the product is in the marketing region and at $I_p \leq I_m$ if it is optimal to postpone the product launch.

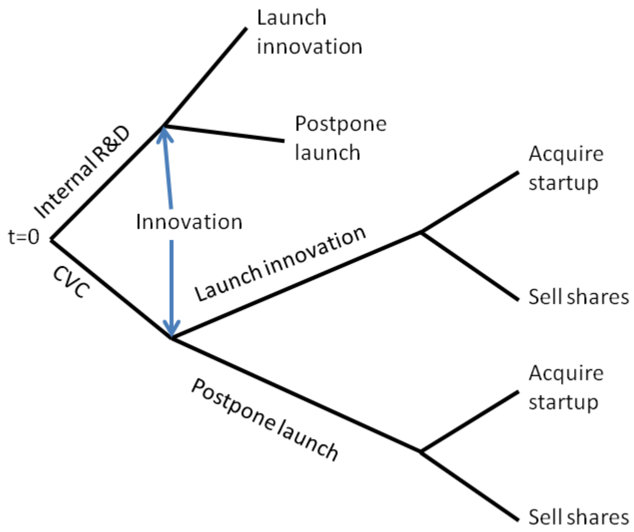

Figure 1: *Model structure*

2.2 Solving the Firm's Problem

Let $V_i(x)$ and $V_e(x)$ denote the value of the innovation project carried out internally by the incumbent firm and the startup, respectively. We also let $V_c(x)$ represent the value of the project to the incumbent firm in a CVC investment. In the subsequent two sections, we derive the expressions for these value functions. In order to formulate the problem, however, we first need to obtain an expression for the option value to market the product in the postponement region. Once the innovation is completed, the incumbent will market the product only if the present value of the cash flows is greater than any costs to launch the product. These costs could include any regulatory permissions to be obtained prior to the product launch, advertising costs and/or construction of production sites. We let M capture these expenditures.

Using standard arguments,[4] one can show that the value of the option to market the product is given by:

$$F(x) = (x_m - M)\left(\frac{x}{x_m}\right)^{\gamma} \tag{5}$$

where $\gamma > 1$ is a constant and x_m denotes the trigger value of the patent at which the firm optimally markets the product:

$$x_m = \frac{\gamma}{\gamma - 1} M \tag{6}$$

Thus, if the value of patent, x_t is lower than x_m at the time of innovation, the firm holds an option to launch the product later with value $F(x)$. Otherwise, the firm markets the product and obtains $x - M$. Given these two possibilities, we now formulate the optimal decision problem.

2.2.1 Internal R&D

When the incumbent firm develops internally, its innovation rate is $\lambda_i(H_i, S_i, K)$ specified in equation (3). Correspondingly, we denote by τ_i the random time at which innovation occurs. We also allow the incumbent firm to abandon the project at any time and denote the abandonment time by τ_a. For simplicity, we assume no inflow or outflow as a result of abandonment. Thus the incumbent continues to pay a fixed cost of f_i until either it makes a breakthrough or abandons the development. The incumbent solves

[4] See Dixit and Pindyck (1994).

equation (7) subject to the state equation in (1):

$$max\ \mathbb{E}_0 \left\{ -\int_0^{\tau_i \wedge \tau_a} f_i e^{-rt} dt + \mathbb{I}_{\tau_m \leq \tau_i} e^{-r\tau_i}(x - M) + \mathbb{I}_{\tau_m > \tau_i} e^{-r\tau_i} F(x) \right\} \quad (7)$$

where τ_m is the optimal time to market the product once the innovation is completed and $\mathbb{I}_{\tau_m \leq \tau_i}$ and $\mathbb{I}_{\tau_m > \tau_i}$ are indicator functions taking the value 1 if the condition in the subscript is satisfied. Finally, r denotes the risk-free rate. Equation (7) makes clear that the incumbent's payoff is $x - M$ when market conditions are favorable upon the completion of the innovation project and $F(x)$ if they are unfavorable.

Proposition 1 summarizes the value of the internal R&D to the incumbent.

Proposition 1. *When the firm innovates through internal R&D, its value is given by:*

$$V_i(x) = \begin{cases} 0 & x < x_a \\ \Psi_i F(x) - \dfrac{f_i}{r+\lambda_i} + A_1 x^{\beta_1} + A_2 x^{\beta_2} & x_a < x < x_m \\ \dfrac{\lambda_i x}{r+\lambda_i-\mu} - \dfrac{f_i+\lambda_i M}{r+\lambda_i} + B_2 x^{\beta_2} & x > x_m \end{cases} \quad (8)$$

where $\Psi_i(\lambda_i), A_1(\lambda_i), A_2(\lambda_i)$ *and* $B_2(\lambda_i)$ *are constants,* $\beta_1(\lambda_i) > 1$ *and* $\beta_2(\lambda_i) < 0$ *are exponents determined through the solution of the homogeneous part of the ordinary differential equations laid out in the appendix and* x_a *is the optimal abandonment trigger to be determined numerically.*

Proof: See Appendix.

The value function in equation (8) depends critically on the firm's innovation rate, which, in turn, is a function of the firm's intellectual capital and any knowledge spillovers. The corporate VC thus allows the incumbent to potentially increase its innovation rate and thus its value. Before turning to the CVC in the next section, the following corollary establishes the stand-alone value of the innovation project to the startup.

Corollary 1. *The value of the innovation project to the startup is given by:*

$$V_e(x) = \begin{cases} 0 & x < x_e \\ \Psi_e F(x) - \dfrac{f_e}{r+\lambda_e} + C_1 x^{\alpha_1} + C_2 y^{\alpha_2} & x_e < x < x_m \\ \dfrac{\lambda_e x}{r+\lambda_e-\mu} - \dfrac{f_e+\lambda_e M}{r+\lambda_e} + D_2 x^{\alpha_2} & x > x_m \end{cases} \tag{9}$$

where $\Psi_e(\lambda_e), C_1(\lambda_e), C_2(\lambda_e), D_2(\lambda_e), \alpha_1(\lambda_e) > 1$ *and* $\alpha_2(\lambda_2) < 0$ *are defined analogous to Proposition 1 and* x_e *is the optimal abandonment trigger to be determined numerically.*

2.2.2 Corporate VC

The CVC benefits the incumbent firm in two ways: first, it potentially increases the rate of innovation by employing the startup's intellectual capital to the extent it is able to integrate it in its organizational structure. Second, the CVC allows the incumbent to obtain a toehold in a startup that it may later on choose to acquire.

Regarding the first objective, we note that two factors determine whether a CVC allows the innovation rate to increase: the degree of knowledge spillovers and the ability of the incumbent to integrate the startup's intellectual capital in its R&D. When the incumbent firm's ability integrate the startup's intellectual capital into its R&D process, ω is high while the extent of knowledge spillovers, K, is low, a CVC investment becomes a viable route to pursue to increase the innovation rate. The following proposition formalizes this intutition.

Proposition 2. *Given the innovation rates in equations (3) and (4), there exists a level of knowledge spillover, denoted by* $\bar{K}(\omega)$ *such that* $\lambda_c(H_i, S_i, H_e, S_e) \geq \lambda_i(H_i, S_i, K)$ *if* $K \leq \bar{K}(\omega)$ *and* $\lambda_c(H_i, S_i, H_e, S_e) < \lambda_i(H_i, S_i, K)$ *otherwise. The critical knowledge spillover value is given by:*

$$\bar{K}(\omega) = \left[\left(\frac{H_i + \omega H_e}{H_i} \right)^{\eta_1} \left(\frac{S_i + \omega S_e}{S_i} \right)^{\eta_2} \right]^{1/\eta_3} \tag{10}$$

Proof: The proposition follows directly from the inequality $\lambda_c(H_i, S_i, H_e, S_e) \geq \lambda_i(H_i, S_i, K)$ using equations (3) and (4).

It is straightforward to show that $\frac{d\bar{K}(\omega)}{d\omega} > 0$. This implies that a higher absorptive capacity enlarges the region in which CVC becomes an attractive route of R&D for the incumbent firm. Figure 2 graphically illustrates this point. For low values of ω, even low levels of knowledge spillovers would justify internal R&D. As the incumbent firm's absorptive capacity increases, however, significantly higher levels of spillover effects must be present to make internal R&D the more attractive avenue for development.

Although a higher absorptive capacity relative to the flow of positive externalities from knowledge spillovers makes a CVC more attractive, Figure 2 does not imply that the incumbent engages in CVC whenever $\lambda_c \geq \lambda_i$. This latter decision will depend also on the cost of engaging in a CVC investment. Put differently, the cost of the second benefit (i.e. obtaining a toehold in the startup and the potential subsequent acquisition of the startup) must be weighed against the incremental gain in value emanating from a higher innovation rate as a consequence of the CVC. With this intuition, we now characterize the decision problem that the incumbent faces in a CVC.

Once it acquires a portion π in the startup at a cost of I_c, the incumbent can either choose to sell its stake in the startup or acquire the remain-

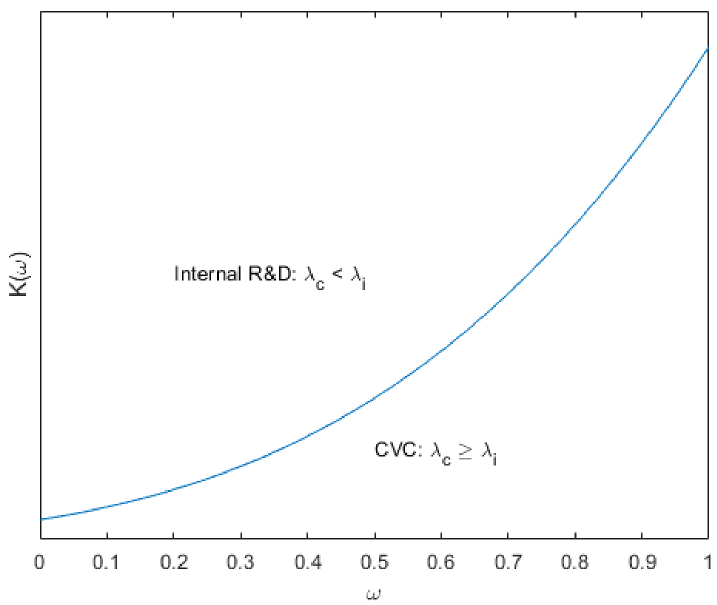

Figure 2: *The figure shows the regions in which $\lambda_c > \lambda_i$ for various degrees for knowledge spillover and the incumbent's absorptive capacity.*

ing portion $1 - \pi$ after the innovation is completed. Since the innovation can be completed either under favorable or unfavorable market conditions, the strategy space of the incumbent consists of a pair of actions characterizing which policy the firm should follow when the innovation is in the marketing region and in the postponement region. For instance, the strategy $(Acquire, Sell)$ would lead the incumbent to acquire the startup if the project ends in the marketing region while selling its shares in the postponement region. Figure 1 indicates that the incumbent has four such actions in its strategy space. Because CVC is also frequently considered a means to identify future potential targets for acquisition, we focus in the rest of the paper on the case in which the incumbent acquires the startup in both the marketing and the postponement regions. Extension of the model to the other strategies, however, is straightforward.

Equation (11) characterizes the incumbent's decision problem in a CVC investment:

$$max\ \mathbb{E}_0 \left\{ - \int_0^{\tau_c \wedge \tau_l} f_c e^{-rt} dt + \mathbb{I}_{\tau_m \leq \tau_c} e^{-r\tau_c} (x - M - I_m) + \mathbb{I}_{\tau_m > \tau_c} e^{-r\tau_c} [F(x) - I_a] \right\} \quad (11)$$

where I_m and I_a denote the cost of acquisition of the remaining portion of the firm. The random stopping times τ_c and τ_l represent the innovation time and the abandonment trigger.[5] It is reasonable to assume that $I_a \leq I_m$.

Proposition 3 characterizes the firm value under CVC.

Proposition 3. *When the firm innovates through CVC, its value is given by:*

$$V_c(x) = \begin{cases} 0 & x < x_c \\ \Psi_c F(x) - \dfrac{f_c + \lambda_c I_a}{r + \lambda_c} + P_1 x^{\theta_1} + P_2 y^{\theta_2} & x_c < x < x_m \\ \dfrac{\lambda_c x}{r + \lambda_c - \mu} - \dfrac{f_c + \lambda_c (M + I_m)}{r + \lambda_c} + Q_2 x^{\theta_2} & x > x_m \end{cases} \quad (12)$$

where $\Psi_c(\lambda_c), P_1(\lambda_c), P_2(\lambda_c), Q_2(\lambda_c)$ *are constants,* $\theta_1(\lambda_c) > 1$ *and* $\theta_2(\lambda_c) < 0$ *are exponents derived analogous to Proposition 1.*

Proof: See Appendix.

Given value functions in Proposition 1 and Proposition 3, the incumbent's optimal decision consists of choosing the R&D strategy that would create the higher value: $\max[V_i(x), V_c(x) - I_c]$. Thus, the incumbent would be better off with a CVC if the value of the project net of the initial acquisition cost for the stake in the startup is higher than the value of the project with internal R&D. In the following section, we inspect the incumbent's decision through numerical analysis.

[5] Note that τ_c is a random arrival time with arrival rate λ_c while τ_l is an optimal stopping time determined by the firm.

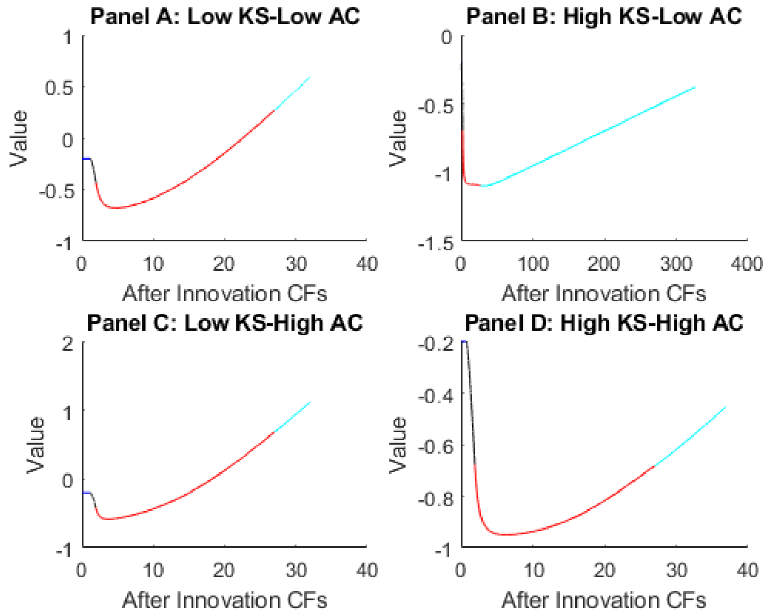

Figure 3: *The figure shows the difference between value of the CVC net of the initial acquisition cost and the value of internal R&D to the incumbent.*

3 Numerical Analysis

Recall that Proposition 2 posits that when knowledge spillover between firms is below a certain level and the absorptive capacity of the incumbent firm is sufficiently high, the innovation rate of a CVC between the incumbent and the startup is higher than that of internal R&D. Would a higher innovation rate lead the incumbent to always prefer a CVC over internal R&D? To this end, we define the following difference function:

$$V_d(x) = V_c(x) - V_i(x) - I_c \tag{13}$$

When the difference function is greater than zero, the incumbent would be better off to acquire a stake in the startup for a CVC project. Figure

3 plots the difference function $V_d(x)$. In each panel, we vary the extent of knowledge spillover in the market and the incumbent's ability to integrate the startup's intellectual capital in the CVC. For instance, Panel A depicts a case in which both knowledge spillovers (KS) and the incumbent's absorptive capacity (AC) are low. All the panels indicate that the incumbent's decision depends crucially on the present value of expected cash flows from the project. For low levels of cash flows, the incumbent would opt for internal R&D while for sufficiently large cash flows, a CVC becomes more attractive.

4 Conclusion

This paper has developed a model that takes on a real options approach to analyze the decision to carry out internal R&D or invest in a startup through a CVC. Our model is the first to combine knowledge spillovers, intellectual capital and absorptive capacity in a theoretical model of decision problem.

The model shows that the decision between internal R&D and CVC depends crucially on the level of eceonomic rewards firms would expect from the innovation. The U-shaped relation between the incremental benefit from CVC and post-innovation economic rewards captures the manner in which the CVC arms of large firms invest in startups preferring those with the potential to provide a signficant cash flow or market share base after the innovation has been marketed.

Appendix

Proof of Proposition 1: Following the arguments in Dixit and Pindyck (1994), the firm's problem in equation (7) satisfies:

$$rVdt = -f_i dt + \mathbb{E}(dV) \tag{A-1}$$

where $V(x)$ is the value function. Recall that the value of the firm after the innovation is completed depends on whether or not the market conditions are favorable for an immediate launch of the product. If they are, as is the case when $x > x_m$ then the incumbent's payoff is $x - M$. Otherwise, the firm's value is $F(x)$ as specified in equation (5). Thus, we distinguish between value functions $V_{ib}(x)$ in the region $x_a < x < x_m$ and $V_{ia}(x)$ in the region $x > x_m$. Applying Itô's lemma in equation (A-1), we end up with the following system of ordinary differential equations:

$$\left.\begin{array}{l} \frac{1}{2}\sigma^2 x^2 V_{ib}^{''} + \mu x V_{ib}^{'} - (r+\lambda_i)V_{ib} - f_i + \lambda_i F(x) = 0, \quad x_a < x \leq x_m \\ \frac{1}{2}\sigma^2 x^2 V_{ia}^{''} + \mu x V_{ia}^{'} - (r+\lambda_i)V_{ia} - f_i + \lambda_i (x - M) = 0, \quad x_m < x \end{array}\right\} \tag{A-2}$$

In order to solve the system in (A-2), we impose the following boundary conditions:

$$\left.\begin{array}{l} V_{ib}(x_a) = 0 \\ V_{ib}^{'}(x_a) = 0 \\ V_{ib}(x_m) = V_{ia}(x_m) \\ V_{ib}^{'}(x_m) = V_{ia}^{'}(x_m) \\ lim_{x\to\infty} V_{ia}(x) < \infty \end{array}\right\} \tag{A-3}$$

The first two boundary conditions in (A-3) regulate firm value at the exit trigger, x_a assuming that the firm value is 0 when the incumbent abandons the project. The subsequent two boundary conditions ensure that firm value below and above the exit trigger match. The final boundary condition is imposed to guarantee finite firm values.

The boundary conditions in (A-3) imply a general solution of the form:

$$\left.\begin{array}{l} V_{ib}(x) = \Psi_i F(x) - \frac{f_i}{r+\lambda_i} + A_1 x^{\beta_1} + A_2 x^{\beta_2} \\ V_{ia}(x) = \frac{\lambda_i x}{r+\lambda_i-\mu} - \frac{f_i + \lambda_i M}{r+\lambda_i} + B_1 x^{\beta_1} + B_2 x^{\beta_2} \end{array}\right\} \tag{A-4}$$

where

$$\Psi_i = \frac{\lambda_i}{r + \lambda_i - \mu\gamma - 0.5\sigma^2\gamma(\gamma - 1)}$$

and $\beta_1 > 1$, $\beta_2 < 0$ roots of the characteristic equation:[6]

$$\frac{1}{2}\sigma^2\beta(\beta - 1) + \mu\beta - (r + \lambda_i) = 0 \tag{A-5}$$

We determine the constants $\{A_1, A_2, B_1, B_2\}$ and the optimal exit trigger x_a by imposing the boundary conditions in (A-3) on the general solution in (A-4). We thus end up with:

$$\left.\begin{array}{l} A_1 = -\dfrac{1}{\beta_1 - \beta_2}\left[\Omega_i x_a^{\gamma-\beta_1}(\gamma - \beta_2) + \dfrac{\beta_2 f_i}{(r + \lambda_i)x_a^{\beta_1}}\right] \\ A_2 = \dfrac{1}{\beta_1 - \beta_2}\left[\Omega_i x_a^{\gamma-\beta_2}(\gamma - \beta_1) + \dfrac{\beta_1 f_i}{(r + \lambda_i)x_a^{\beta_2}}\right] \\ B_1 = 0 \\ B_2 = \dfrac{1}{x_m^{\beta_2}}\left[\Omega_i x_m^{\gamma} + A_1 x_m^{\beta_1} + A_2 x_m^{\beta_2} - \dfrac{\lambda_i x_m}{r + \lambda_i - \mu} + \dfrac{\lambda_i M}{r + \lambda_i}\right] \end{array}\right\} \tag{A-6}$$

where

$$\Omega_i = \frac{\lambda_i (x_m - M) x_m^{-\gamma}}{r + \lambda_i - \mu\gamma - 0.5\sigma^2\gamma(\gamma - 1)} \tag{A-7}$$

The optimal exit trigger x_a is obtained numerically by solving:

$$(\gamma - \beta_2)\Omega_i x_m^{\gamma-1} - \frac{x_m^{\beta_1 - 1}}{x_a^{\beta_1}}\left[\Omega_i x_a^{\gamma}(\gamma - \beta_2) + \frac{\beta_2 f_i}{r + \lambda_i}\right] - \frac{\lambda_i(1 - \beta_2)}{r + \lambda_i - \mu} - \frac{\beta_2 \lambda_i M}{x_m(r + \lambda_i)} = 0 \tag{A-8}$$

Solving the system (A-2) subject to the boundary conditions in (A-3) yields Proposition 1.

Proof of Proposition 3: The proof follows the same line of reasoning as the proof of Proposition 1 with the appropriate changes in the innovation rate and the cost parameters.

[6] See Dixit and Pindyck (1994).

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