Modeling Sequential International R&D Alliances under Uncertainty

Elmar Lukas [a,*]

[a] *Department of Economics, University of Paderborn*

Abstract
Growth in the internationalization of R&D activity has increased in concert with the increasing use of strategic alliances. Typically, to date MNEs have preferred to internalize their R&D activities by setting up wholly owned subsidiaries or by acquiring a suitable target. By considering the sequential nature of market entry and the contingency for subsequent reorientation following an initial commitment for research collaboration, we use an option framework to derive a value for the overall flexibility. Given economic as well as technological uncertainty due to either incremental or radical innovation, this flexibility becomes increasingly important and offsets the losses incurred to possible knowledge dissipation. We present critical thresholds for timing and termination strategy selection and provide a novel perspective on existing empirical results, while generating a number of testable predictions.

Keywords international joint venture, research and development, foreign direct investment, merger and acquisition, real options, Levy process.

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* Corresponding author: Elmar Lukas, Warburger Str. 100, D-33098 Paderborn, Germany, tel.: +49 5251 60 2961; fax: +49 5251 60 3731. Email: ELukas@notes.uni-paderborn.de

1 Introduction

Due to an increasingly volatile and competitive environment, one of the main changes in the structure of multinational enterprises (MNEs) is related to the management of research and development (R&D). While these activities were traditionally located in the MNEs' home countries, they have become increasingly dispersed and internationalized since the mid 1980s (see, e.g. Pearce and Singh, 1992; Howells and Wood, 1993; Blanc and Sierra, 1999; Patel, 1996; Narula and Zanfei, 2005, among others). From 1993 to 2002, the worldwide R&D spending of foreign affiliates in host countries more than doubled to US$ 67 billion, which is equivalent to 16% of all global business R&D (UNCTAD, 2005, p. 125). Consequently, the choice of a market entry strategy is still one of the crucial decisions a firm has to make. This is especially true when a company opts for the internationalization path to relocate its R&D, and not only because the international terrain is much more uncertain than the national playground. Investments in R&D are fraught with issues of proprietary techniques and knowledge. Hence, their loss can dramatically alter the strategic competitive position of a firm.

Concurrently with this substantial increase in cross-border diffusion of R&D activity, MNEs are showing an increased propensity to perform such activities with overseas partners (Archibugi and Michie, 1995; Hagedoorn, 1996). A recent example of such cross-border R&D alliances is the joint venture between Samsung and Sony, S-LCD Corp., which focuses on the production and further development of liquid crystal displays (LCDs). The decline in worldwide foreign direct investment over the past few years has been accompanied by an increase in the number of strategic alliances. Between 1991 and 2001, the number of international technology alliances rose from 339 to 602 (UNCTAD, 2005). Increased competition due to the convergence of major technologies and the cross-fertilization of technology between sectors, coupled with the increased cost of developing new products, have increased the propensity to collaborate. The overall growth of strategic technology alliances, however, is somewhat odd since firms have hitherto preferred to internalize their R&D activities in order to secure any competitive advantage they may confer (Pisano, 1989; Dunning and Narula, 2004).

Given these developments, some important questions arise. Why do firms deviate from their internalization strategies and collaborate in knowledge-intensive sectors? Does R&D increase or decrease the propensity to collaborate, and how does the type of innovation impact the longevity of research and development joint ventures? Given the transitional nature of most collaborations, are there any generalizations regarding the choice and timing of the termination strategies, i.e., possible divestments or partner buyouts?

2 Literature Review

The term *alliance* has different meanings for different observers. In general, an alliance can be defined as any independently initiated cooperation between firms. It involves an exchange, sharing or co-development of capital, technology, or firm-specific assets, and is performed by either joint ventures, production, marketing and distribution agreements, or technology agreements (see, e.g. Gulati and Singh, 1998; Kale, Dyer, and Singh, 2005). One can broadly distinguish between two basic organizational modes: equity joint ventures and non-equity joint ventures. The former is created when each partner has an equity share in the new venture. Non-equity joint ventures, in contrast, are agreements to cooperate in some way but do not involve the creation of new firms. [1] An equity joint venture is considered international if at least one partner has its headquarters outside the venture's country of operation, or if the venture has a significant level of operation in more than one country (Geringer and Hebert, 1991; Glaister, Husan, and Buckley, 1998). In the context of this paper, the purpose of a strategic technological alliance (STA) is the generation, exchange and/or adoption of technical advances (Narula, 2001; Narula and Hagedoorn, 1999; Caloghirou, Ioannides, and Vonortas, 2003). Moreover, we will narrow our view and focus on international research joint ventures (RJVs), which are a subset of STAs, and which we define as organizations jointly controlled by at least two participating firms from different countries. [2] These are set up for the purpose of collaborative joint research and development and thus to generate innovations. An innovation is henceforth understood as any new or significantly improved product or process that results from new technological developments, combinations of existing technologies, or the utilization of acquired knowledge by the collaborative enterprises (EuroStat, 2004, p.7).

The search for factors that drive the use and success of international alliances has a long tradition in business and economics literature. Among the mo-

[1] Glaister, Husan, and Buckley (1998). However, in non-equity joint ventures, the sharing or exchange of equity may occur between partners (see *ibid* p. 170).

[2] However, we will use the term *alliance* and *joint venture* interchangeably throughout the paper.

tives that drive the formation of alliances are risk sharing, product rationalizing, economies of scale, transfer of complementary assets/exchange of patents, shaping competition, or facilitation of international expansion (see, e.g., Contractor and Lorange, 1988; Gatignon and Anderson, 1988, Blodgett, 1992; Kogut and Chang, 1996; Hennart, Kim and Zeng, 1998; Glaister, Husan, and Buckley, 1998; Veugelers, 1998). However, the joint R&D aspect has only recently been added to this mainly empirical-driven research canon. So far, the studies conducted in the domain of RJVs can be broadly classified into two groups. The first group focuses on the motivation for engaging in research and development collaboration. According to these studies, firms that cooperate on R&D tend to be relatively large, have a comparatively large share of R&D employees, and dedicate resources to monitoring external developments relevant to their innovation activities (see, e.g. Hladik, 1985; Tether, 2002; Negassi, 2004; Fritsch and Lukas, 2001). Moreover, a number of empirical research papers have found that firms prefer to exchange equity stakes when an alliance is technology intensive or is being established for the sake of joint R&D, and that the use of equity has a positive impact on innovation success (see, e.g. Pisano, 1989; Gulati and Singh, 1998; Oxley, 1997; Folta, 1998). Further, recent studies have highlighted the importance of an industry's overall technology intensity in promoting collaborations. Bayona, Garcia-Marco, and Huerta (2001) have found evidence that firms operating in high-tech industries have a higher probability of engaging in RJVs than those in low-tech industries. Of special interest are recent findings that suggest the type of innovation also has an impact on the propensity to collaborate on R&D (Bayona, Garcia-Marco, and Huerta, 2001; Miotti and Sachwald, 2003).

The second group of studies focuses on performance for which duration is a dominant proxy.[3] The transitional phenomenon of JVs and choice of a termination strategy has been extensively examined in the literature (see Franko, 1971; Stopford and Wells, 1972; Killing, 1983; Hennart, Kim, and Zeng, 1998). Factors that have been identified as crucial are e.g. equity, cultural differences, cooperation and country experience and size, although the direction of their impact remains to a great extent ambiguous.[4] Moreover, only a few empirical analyses deal with the impact of R&D efforts on the longevity of JVs. Kogut (1989) hypothesise that R&D intensive joint ventures tend to be more stable because firms have strong incentives to create stable collaborations especially when the joint venture is larger and is associated with high R&D expenditures. In his study, R&D intensive joint ventures were found to be longer lived, indicating the aforementioned willingness of parents to create a stable collaboration. Park and Russo (1996) find a negative relationship between R&D activity and joint venture survival. Moreover, joint ventures that include R&D activity are less likely to lead to acquisition. The variable was found to be insignificant for dissolutions, a result that is consistent with the findings of Kogut (1991). The impact of technology transfer from the parents on stability

[3] Another proxy often used are abnormal returns (ARs). In general, studies on ARs have reported significant abnormal returns for companies engaging in joint ventures (see, e.g. Chan, Martin, and Kensinger, 1990; Allen and Phillips, 2000; Reuer, 2001). Notably, Zantout (1995) finds evidence that firms venturing RJVs earn statistically significantly greater positive abnormal returns than those resulting from the announcement of an increase in in-house R&D expenditures. Hence this provides a slight indication that financial markets price in contingent claim features, i.e. the option to defer or expand collaborations. See also Hackbarth and Morellec (2007).

[4] See e.g. Yan and Lou (2001) for a comprehensive survey.

was investigated by Park and Ungson (1997). The authors observed that joint ventures are less stable when they require technology transfer from the parent firms. The findings remain significant when termination options other than acquisition were excluded, indicating that the acquisition rate is higher than the dissolution rate for cases where technology transfer from the parents is an issue. Likewise, Lu and Hébert (2005) find empirical support that R&D intensive joint ventures are generally less stable. While investigating the interaction between R&D intensity and equity control the results also reveal that the effect is not valid for the whole spectrum of initial equity positions. Increased R&D intensity decreases the probability of dissolution in those cases where the foreign firm holds a majority equity share. In particular, if the foreign firm holds an initial equity share of 80% the risk of termination under high R&D intensity is half as great as under low R&D intensity. Once foreign equity portions of below 25% are considered, the effect reverses, i.e. an increase in R&D intensity increases the probability of the foreign partner to withdraw from the collaboration. By contrast, Dhanaraj and Beamish (2004) argue that intangible assets can be an effective barrier to failure. Their findings reveal a negative impact of R&D intensity on mortality of joint ventures, contradicting the previous discoveries of that R&D affects the longevity of JVs positively. Likewise, Vassolo, Anand and Folta (2004) found that technological uncertainty has a negative impact on RJV termination via divestment. Interestingly, the authors did not find significant support for the same relationship if the termination was triggered by a buyout. Notably, Folta and Ferrier (2000) found no positive effect of R&D on the likelihood of partner buyouts. As the remarks have highlighted these studies did not arrive at a clear pattern of variables or factors that appear to be conducive to the longevity of JVs and RJVs in particular.

Since the work of D'Aspremont and Jacquemin (1988), numerous theoretical models investigating the relative efficiency of competition and cooperation in the R&D domain have been proposed (see, e.g. Cohen and Levinthal, 1989; Vonortas, 1994; De Bondt, 1997; Kamien and Zang, 2000). These models, however, are to a large extent static and neglect timing in the presence of sunk costs and uncertainty leading to a suboptimal initiation of irreversible investments.[5] Moreover, too much emphasis is placed on the limiting downside risk rather than on the upside opportunities afforded by R&D collaborations.

Here we will draw upon recent advances in continuous time modeling in the domain of corporate finance for two reasons. First, for at least a decade, work on investment under uncertainty (summarized by the seminal book by Dixit and Pindyck (1994)) has significantly shaped the research on sequential investments and created a fruitful paradigm for its treatment. Thus, the initiation of a JV is just a first step, generating subsequent options in the next stages (Kogut, 1991). These real option rights have been successfully introduced into the R&D investment and foreign direct investment literature.[6] [7] Second, recent empirical studies have highlighted the fact that R&D alliances grant options to subsequently acquire the remaining stakes, and that their

[5] For a summary of major drawbacks of these approaches and a discussion why a radical departure in terms of formal theory, i.e. toward real option pricing methods, is necessary see e.g. Vonortas (1997, p. 111ff.).

[6] For real option models in R&D investments, see Huchzermeier and Loch (2001), Paxson (2003), Miltersen and Schwartz (2004), and Schwartz (2004). For a synopsis of real options in foreign direct investment, see Rugman and Li (2005).

[7] Real options highlight the option character of investment decisions, i.e. the right to initiate a project while not being obliged to do so. See, e.g., Dixit and Pindyck (1994) or Trigeorgis (1998).

abrupt ending is not a significant proxy for their failure, but an indicator of successful timing of subsequent opportunities (see, e.g. Kogut, 1983; Kogut, 1991; Hagedoorn and Sadowski, 1999; Folta, 1998; Folta and Miller, 2002; Villalonga and McGahan, 2005; Reuer and Zollo, 2005; Reuer and Tong, 2005). To conclude, these studies highlight the fact that option characteristics are of special importance for the formation and evolution of joint ventures. By contrast, there are a comparatively small number of papers that have considered theoretical modeling in the dynamic setting of collaborations (Chi and McGuire, 1996; Pennings and Sleuwaegen, 2004; Smit and Trigeorgis, 2004; Lukas, 2007; Habib-Mella and Barral, 2007).

Despite their potential to contribute to the analysis of the evolutionary sequence patterns of JVs the real option induced literature, however, has so far neglected the impact of R&D. Hagedoorn and Sadowski (1999, p. 90) state that "very little is known on the actual time-lag between establishing a [R&D driven] strategic alliance or a joint venture and its possible acquisition". It is precisely this apparent lacuna that has motivated the present work. Thus, the goal of this paper is to model a joint venture-induced market entry under economic and technological uncertainty in a continuous time setting. The remainder of the paper is structured as follows. In Section three, we will present the model: a three-phase market entry sequence. The main results are presented in Section four, while Section five summarizes the main findings and provides a synopsis of major comparative-static results. The conclusion and suggestions for further research follow in Section six.

The results confirm that innovation increases the probability of engaging in collaboration, however, they reveal that the results are also influenced by the type of innovation and the degree of uncertainty. Consequently, radical innovations have a higher probability of being initiated than incremental innovation-driven collaborations. Moreover, the results show that the longevity of radical innovation-driven RJVs is expected to be shorter than that of incremental-driven RJVs, assuming an optimal timing framework under investment uncertainty.

3 The Model

We focus on a representative equity-based joint venture initiated by a multinational enterprise (MNE) with a host country firm. The venture is initiated for the sake of R&D collaboration and joint production of high-tech products. It is assumed that the value of the chosen FDI mode $V(t)$ is ex ante unknown and follows a piecewise defined stochastic process.[8] The piecewise definition addresses the evolutionary sequence of RJVs, which will be discussed below.

Initially, the firm plans to initiate the market entry and has to choose the amount of equity ϵ it will contribute to the impending cooperation. This could either be a majority, minority, or equal equity stake. Moreover, the host country might dictate a restriction in the overall equity stake for foreign companies. We account for this by introducing a country-specific upper boundary $\bar{\epsilon}$. At that moment, the second critical parameter is the costs I_1 assigned to the market entry. We will assume that these costs cannot be recovered and thus represent sunk costs to the MNE.[9] As indicated earlier, uncertainty persists

[8] The choice of entry strategy has no influence upon the profit rates of other enterprises in the foreign market.

[9] The irreversibility of these costs can be justified by the high asset specificity of such an investment. Moreover, besides the set-up costs, the firm incurs trust-building

about the future value $V(t)$ of the RJV. Assuming a perfect capital market, the initial movements of $V(t)$ follow a geometric Brownian motion and can be expressed as:

$$\frac{dV}{V} = (r - \delta)dt + \sigma dZ^Q, \tag{1}$$

where $r \in \mathbb{R}^+$ is the risk-free interest rate, $\delta \in \mathbb{R}^+$ represents the opportunity cost of waiting, $\sigma^2 \in \mathbb{R}^+$ designates the variance of dV/V, and dZ^Q indicates a Wiener process with non-zero drift given a martingale measure Q. Having a planning horizon of length t_1, the value for the MNE at date $t = 0$ is then given by:

$$G = \sum_{n=0}^{\infty} \left(\mathbb{P}(n)\mathbb{E}^Q \left[\frac{[\epsilon V(t) + F(V(t), \lambda, m, \nu) - I_1]^+}{e^{rt_1}} | \mathcal{F}, \text{n jumps} \right] \right), \tag{2}$$

conditional on the filtration $\mathcal{F}$ and some future shocks n. Here, $F(V(t), \lambda, m, \nu)$ designates the value of subsequent flexibility, to be discussed below.

Once the MNE has exercised this option, it will form the R&D collaboration and perform joint research efforts. Thus, we will consider a time span in which the partners innovate and verify whether joint work is possible for the sake of the venture. We account for this by assuming that the MNE has a certain period $T = [t_1, t_2]$, in which it can decide how to continue with its market entry strategy. During this period, the partners perform innovation activities which

costs, monitoring costs, and adaptation costs (see, e.g. Oster, 1992; Hagedoorn and Sadowski, 1999). See Buckley and Casson (1998) for a summary of market entry-specific cost structures.

might generate either radical or incremental innovations.[10] [11] We will draw upon Henderson's (1993) dichotomy: radical innovations represent significant improvements along a single technical trajectory, while innovations that represent only moderate improvements are referred to as incremental. Consequently, the dynamics of $V(t)$ are also influenced by the success of such outcomes and, in addition to the aforementioned random movements of $V(t)$, we assume that the value during research collaboration also depends on the arrival of new innovations.[12] Let the probability of such an incident be Poisson distributed, i.e. $e^{-\lambda\tau}\lambda d\tau$. Consequently, the expected arrival time equals $\mathbb{E}(\tau) = 1/\lambda$ with λ designating the mean number of jumps per unit of time. Moreover, we will assume that the impact of the innovation is ex ante unknown and for simplicity, we will assume that the impact is log-normal distributed, i.e. the amplitude J is proportional to $me^{-\frac{1}{2}\nu+\nu^2 z_{0,1}}$, where z represents a normally distributed random variable.[13] Thus, the value dynamics can be formally expressed as:[14]

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[10] Likewise, we could have differentiated between joint R&D projects that are either more research-driven or more development-driven.

[11] As our paper focuses on the impact innovation has on output we do not differentiate between the sources that generate these effects, i.e. process and product innovation. Each of these types can feature attributes of incremental and radical innovations.

[12] Rare events such as innovation discoveries have been primarily described by stochastic processes such as Poisson processes (see Merton, 1976; Dasgupta and Stiglitz, 1980). For a study of R&D information influencing share prices, see, e.g. Chan, Martin, and Kensinger (1990).

[13] Such processes are typically used in modeling R&D projects. See, e.g. Brach and Paxson (2001). For more general applications, see Merton (1976) or Martzoukos and Trigeorgis (2002).

[14] Following Merton (1976, p. 318) we assume that the jump risk represents a non-systematic risk and that a compensation term is present in the jump-diffusion model

$$\frac{dV}{V} = (r - (J-1)\lambda - \delta)dt + \sigma dZ^Q + (J-1)dN(t) \forall \quad t \in [t_1, t_2], \tag{3}$$

where the additional factor $J \in \mathbb{R}^+$ indicates the jump amplitude with mean $m \in \mathbb{R}^+$ and variance $\nu^2 \in \mathbb{R}^+$, and $dN(t)$ designates the aforementioned Poisson process indicating that the probability of an innovation equals λdt and the probability of no event equals $(1-\lambda)dt$. From the above equation, it is obvious that if a new innovation occurs, the jump argument provokes an increase or decrease in the project value by JV. It is assumed that dZ^Q and dN do not correlate.

At the end of the period T, the MNE can decide whether it prefers to continue the collaboration with the host partner by obtaining the right to convert the RJV into a cross-border M&A, i.e. by acquiring the remaining shares $(\bar{\epsilon} - \epsilon)$ at a later date. Counterbalancing this, the MNE might prefer to have the right to dissolve the IJV over the growth option by selling its own interest ϵ to the local partner at a later date. We will assume that this phase is dedicated mainly to producing and marketing the improved product. Thus, jumps are neglected and the dynamics are again represented by equation (1). Figure (1) summarizes the dynamics of $V(t)$.

==========[INSERT FIGURE 1 HERE]===========

It can be demonstrated that for each stage there exists a threshold value at

to ensure that the expected return of the asset equals $(r-\delta)$. For a non-traded real option, this might not be the case and the compensation term could be absent. Consequently, rare events might also influence the expected growth rate of the asset. See Dixit and Pindyck (1994) for a discussion.

which it is optimal for an MNE to initiate the investment.[15] The following section briefly summarizes the trigger values that illustrate when it is optimal for an MNE to trigger the first, second, and third stage of the cooperative market entry.

4 Results

In the following, the main findings resulting from the previously introduced model framework are summarized. The initial decision whether to enter the foreign market and perform joint research can be interpreted as having a compound option to invest/divest, contingent not only on the immediate gain but also on subsequent asymmetric managerial actions and uncertainties. Thus, the value of flexibility assigned to such a situation at time $t = 0$ is summarized by Proposition 1.

Proposition 1 *The flexibility for an individual MNE to perform an international R&D joint venture in the host country is determined by:*

$$
\begin{aligned}
G = {} & \epsilon V_0 e^{-\delta t_1} N(d_9) - I_1 e^{-rt_1} N(d_9 - \sigma\sqrt{t_1}) + \sum_{n=0}^{\infty} e^{-\lambda T} \left(\frac{(\lambda T)^n}{n!} \right) \\
& \kappa I_0 e^{-rt_2} M(h_1, k_1; -\tilde{\rho}) - \epsilon V_0 m^n e^{-\delta t_2} e^{-(m-1)\lambda T} M(h_1 + \sigma\sqrt{t_1}, k_4; -\tilde{\rho}) \\
& + B V_0^{\beta_2} m^{n\beta_2} e^{(\Omega_2 - r)T} \left(M(h_2, k_7; -\tilde{\rho}) - M(h_2, k_8; -\tilde{\rho}) \right) \\
& + A V_0^{\beta_1} m^{n\beta_1} e^{(\Omega_1 - r)T} \left(M(h_3, k_5; -\tilde{\rho}) - M(h_3, k_6; -\tilde{\rho}) \right) \\
& + (\bar{\epsilon} - \epsilon) V_0 m^n e^{-\delta t_2} e^{-(m-1)\lambda T} M(h_1 + \sigma\sqrt{t_1}, k_3; \tilde{\rho}) - I_2 e^{-rt_2} M(h_1, k_2; \tilde{\rho}) \Big] ,
\end{aligned}
\tag{4}
$$

where V_0 states the value of the project at time $t = 0$, $M(\ldots)$ and $N(\ldots)$ designate the bivariate and univariate cumulative standard normal distribution,

[15] A derivation of the threshold values is given in the Appendix.

respectively, and $\tilde{\rho} = \Gamma\sqrt{t_1/t_2}$ *and the remaining parameters are defined as follows:*

$$\begin{aligned}
\Omega_i &= (r-\delta-(m-1)\lambda)\beta_i - \frac{1}{2}\beta_i\tilde{\sigma}^2 + \frac{1}{2}\beta_i^2\tilde{\sigma}^2, \quad \forall i = 1,2\\
\Lambda_i &= (m-1)\lambda\beta_i - \frac{1}{2}\frac{\nu^2 n}{T}\beta_i(2\beta_i - 1), \quad \forall i = 1,2\\
\Delta_1 &= (m-1)\lambda + \frac{1}{2}\frac{\nu^2 n}{T},\\
\Delta_2 &= \Delta_1 - \frac{\nu^2 n}{T},\\
\Gamma &= \frac{\sigma}{\tilde{\sigma}\sqrt{1+((\frac{\sigma}{\tilde{\sigma}})^2-1)(t_1/t_2)}},
\end{aligned}$$

and

$$\begin{aligned}
k_1 &= \Gamma\left(\frac{\ln\left(\frac{V_\infty}{V_0 m^n}\right)-(r-\delta-\frac{1}{2}\sigma^2)t_2+\Delta_1 T}{\sigma\sqrt{t_2}}\right), \quad k_7 = \Gamma\left(\frac{\beta_2\ln\left(\frac{\zeta}{V_0 m^n}\right)-(r+\frac{1}{2}\sigma^2\beta_2^2)t_2+\Lambda_2 T}{\sigma\beta_2\sqrt{t_2}}\right),\\
k_2 &= \Gamma\left(\frac{\ln\left(\frac{V_0 m^n}{V^\infty}\right)+(r-\delta-\frac{1}{2}\sigma^2)t_2-\Delta_1 T}{\sigma\sqrt{t_2}}\right), \quad k_8 = \Gamma\left(\frac{\beta_2\ln\left(\frac{V_\infty}{V_0 m^n}\right)-(r+\frac{1}{2}\sigma^2\beta_2^2)t_2+\Lambda_2 T}{\sigma\beta_2\sqrt{t_2}}\right),\\
k_3 &= \Gamma\left(\frac{\ln\left(\frac{V_0 m^n}{V^\infty}\right)+(r-\delta+\frac{1}{2}\sigma^2)t_2-\Delta_2 T}{\sigma\sqrt{t_2}}\right), \quad h_1 = \frac{\ln\left(\frac{V_0}{V_1^*}\right)+(r-\delta-\frac{1}{2}\sigma^2)t_1}{\sigma\sqrt{t_1}},\\
k_4 &= \Gamma\left(\frac{\ln\left(\frac{V_\infty}{V_0 m^n}\right)-(r-\delta+\frac{1}{2}\sigma^2)t_2-\Delta_2 T}{\sigma\sqrt{t_2}}\right), \quad h_2 = \frac{\beta_2\ln\left(\frac{V_0}{V_1^*}\right)+(r+\frac{1}{2}\sigma^2\beta_2^2)t_1}{\sigma\beta_2\sqrt{t_1}},\\
k_5 &= \Gamma\left(\frac{\beta_1\ln\left(\frac{V^\infty}{V_0 m^n}\right)-(r+\frac{1}{2}\sigma^2\beta_1^2)t_2+\Lambda_1 T}{\sigma\beta_1\sqrt{t_2}}\right), \quad h_3 = \frac{\beta_1\ln\left(\frac{V_0}{V_1^*}\right)+(r+\frac{1}{2}\sigma^2\beta_1^2)t_1}{\sigma\beta_1\sqrt{t_1}},\\
k_6 &= \Gamma\left(\frac{\beta_1\ln\left(\frac{\zeta}{V_0 m^n}\right)-(r+\frac{1}{2}\sigma^2\beta_1^2)t_2+\Lambda_1 T}{\sigma\beta_1\sqrt{t_2}}\right), \quad d_9 = \frac{\ln\left(\frac{V_0}{V_1^*}\right)+(r-\delta+\frac{1}{2}\sigma^2)t_1}{\sigma\sqrt{t_1}}.
\end{aligned}$$

Proof 1 *See Appendix.*

From the above equation, it is apparent that the first two terms in the equation emphasize the value of waiting to invest. Apart from these well known Black-Scholes results, however, a substantial contribution to the value of the RJV entry strategy stems from the third term, which designates the subsequent flexibility. Thus, Proposition 1 formulates what has become a crucial point of interest for the empirical market-entry driven literature, namely, the joint impetus of the deferral and subsequent growth options, commonly referred to as dueling options (see Folta and O'Brien, 2004).

In general, host countries only benefit from real options if firms are willing to exercise them. Consequently, the MNE will actually perform the market entry at date $t = t_1$ if a certain threshold value V^* is surpassed.

Proposition 2 *The MNE will initiate the R&D collaboration in the host country if $V(t)$ reaches at least an optimal trigger value V^* determined by:*

$$\epsilon V^*(t) + F(V^*(t)) - I_1 \stackrel{!}{=} 0. \tag{5}$$

$F(V^*(t))$ represents the value of the flexibility stemming from the bidirectional IJV evolutionary path and is given by:

$$\begin{aligned} F(V^*(t)) = \sum_{n=0}^{\infty} e^{-(r+\lambda)T} \left(\frac{(\lambda T)^n}{n!} \right) \Big[& \kappa N(d_1) - \epsilon V^* m^n e^{(r-\delta-(m-1)\lambda)T} N(d_2) \\ & + e^{\Omega_2 T} B(V^* m^n)^{\beta_2} (N(d_3) - N(d_4)) + e^{\Omega_1 T} A(V^* m^n)^{\beta_1} (N(d_5) - N(d_6)) \\ & + (\bar{\epsilon} - \epsilon) V^* m^n e^{(r-\delta-(m-1)\lambda)T} N(d_7) - I N(d_8) \, \Big], \end{aligned} \tag{6}$$

with $N(\ldots)$ as the cumulative normal distribution, and

$$d_1 = \frac{\ln\left(\frac{V_\infty}{(V^* m^n)}\right) - (r - \delta - (m-1)\lambda - \frac{1}{2}\tilde{\sigma}^2)T}{\tilde{\sigma}\sqrt{T}}, \quad d_2 = d_1 - \tilde{\sigma}\sqrt{T},$$

$$d_3 = \frac{\beta_2 \ln\left(\frac{\zeta}{(V^* m^n)}\right) - (\Omega_2 + \frac{1}{2}\tilde{\sigma}^2 \beta_2^2)T}{\tilde{\sigma}\beta_2\sqrt{T}}, \qquad d_4 = d_3 + \frac{\ln\left(\frac{V_\infty}{\zeta}\right)}{\tilde{\sigma}\sqrt{T}},$$

$$d_5 = \frac{\beta_1 \ln\left(\frac{V^\infty}{(V^* m^n)}\right) - (\Omega_1 + \frac{1}{2}\tilde{\sigma}^2 \beta_1^2)T}{\tilde{\sigma}\beta_1\sqrt{T}}, \qquad d_6 = d_5 + \frac{\ln\left(\frac{\zeta}{V^\infty}\right)}{\tilde{\sigma}\sqrt{T}},$$

$$d_7 = \frac{\ln\left(\frac{(V^* m^n)}{V^\infty}\right) + (r - \delta - (m-1)\lambda + \frac{1}{2}\tilde{\sigma}^2)T}{\tilde{\sigma}\sqrt{T}}, \; d_8 = d_7 - \tilde{\sigma}\sqrt{T},$$

as well as $\tilde{\sigma} = \sqrt{\sigma^2 + \frac{\nu^2 n}{T}}$.

Proof 2 *See Appendix.*

It is important to note here that the market entry depends not only on the costs and environmental uncertainty linked to $V(t)$, but also on the technological uncertainty and type of innovation assigned to the project. Once the firm initiates the market entry, it receives a JV with value ϵV and the right to perform subsequent actions. In line with the demands of recent literature, this proposition stresses the importance of future investment opportunities as a key driver in evaluating initial foreign direct investment moves (see Buckley and Casson, 1998).

Research JVs are mostly performed until some pre-specified objective is met (see Pennings and Lint, 1997). Thus, they are very transitional in nature. In order to better capture this feature, the subsequent evolution of a RJV is linked to two possible courses of action. The first relates to the acquisition of the remaining stakes and the MNE's commitment to staying in the host country. This buyout strategy also addresses the internationalization theory aspects of foreign direct investment, stating that firms choose low commitment entry strategies at the outset and penetrate gradually into foreign markets as time elapses. However, just recently, the majority of MNEs have withdrawn from some host countries by performing divestment strategies. An example is Lucent Technologies' withdrawal from Netherlands-based Philips Consumer Communications, a JV formed with Philips Electronics NV.[16] Thus, divest-

[16] In early 1999, Lucent chose to divest its 40 percent stake in the venture to Philips Electronics NV and to abandon its activities in the European consumer communications market.

ments also have to be treated as serious strategies, which is captured by the fact that the MNE can sell the initial stake to the partnering firm and withdraw from the foreign market. The criteria determining which route of action is chosen by the MNE are given by the following proposition:

Proposition 3 *Subsequent to the R&D collaboration, the MNE will choose to buy out the host country partner if* $V(t_2)$ *reaches at least the optimal trigger value* ζ *given by:*

$$\zeta = \left[-\frac{\epsilon}{(\bar{\epsilon} - \epsilon)} \frac{\beta_1}{\beta_2} \frac{(V_\infty)^{1-\beta_2}}{(V^\infty)^{1-\beta_1}} \right]^{1/\gamma}, \tag{7}$$

with $\gamma = \beta_1 - \beta_2$. *Otherwise, the MNE prepares to withdraw from the foreign market.*

Proof 3 *See Appendix.*

To opt for the buyout strategy at time t_2 is equivalent to possessing a perpetual call option. More precisely, it grants the right to acquire the remaining stake, i.e. $(\bar{\epsilon} - \epsilon)$, in exchange for the assigned costs I. Consequently, the following proposition specifies when it is optimal for the MNE to perform the buyout.

Proposition 4 *The MNE will end the R&D collaboration by performing the buyout if* V *reaches at least the optimal trigger value* V^∞*, determined by:*

$$V^\infty = \frac{1}{(\bar{\epsilon} - \epsilon)} \frac{\beta_1}{\beta_1 - 1} I, \tag{8}$$

with $\beta_1 = \frac{1}{2} - \frac{(r-\delta)}{\sigma^2} + \left(\left[\frac{(r-\delta)}{\sigma^2} - \frac{1}{2} \right]^2 + \frac{2r}{\sigma^2} \right)^{1/2}$.

Proof 4 *See Appendix.*

In contrast, choosing to exit the foreign market at date $t = t_2$ is equivalent to a perpetual put option. Thus, upon exercising the option, the MNE gives up a project with value ϵV and receives its abandonment value κ expressed in units of initial cost outlay I_1. The optimal timing for divestment is indicated by the following proposition.

Proposition 5 *The MNE will end the R&D collaboration by performing the divestment if V reaches at least the optimal trigger value V_∞ determined by:*

$$V_\infty = \frac{\beta_2}{\beta_2 - 1}\frac{\kappa}{\epsilon}, \tag{9}$$

with $\beta_2 = \frac{1}{2} - \frac{(r-\delta)}{\sigma^2} - \left(\left[\frac{(r-\delta)}{\sigma^2} - \frac{1}{2}\right]^2 + \frac{2r}{\sigma^2}\right)^{1/2}$.

Proof 5 *See Appendix.*

5 Comparative-static Analysis

This section presents a summary of a comparative-static analysis of the derived flexibility and individual stage trigger points. First we discuss the value of the flexibility the MNE has to consider while planning to implement the IJV. From Proposition 1 it is apparent that the first two terms in the equation emphasize the value of waiting to invest. Thus, the sensitivities of these terms are identical to those of the Black Scholes (BS) formula, e.g. the longer the possibility to defer the decision, the more valuable the flexibility. Apart from these well known BS results, however, a substantial contribution to the value of the IJV entry strategy stems from its subsequent flexibility. As the result indicates, the overall value G of the entry strategy increases with the size of the initial equity share, the uncertainty, and the value of the RJV, while it decreases for high initial market entry costs I_1 and lower levels of divestiture price κ. Figure 2 summarizes the results graphically.[17]

==========[INSERT FIGURE 2 HERE]===========

To what extent does innovation influence the overall value of the pending RJV? In general, the results show that if the number of innovations relative to the collaboration time increases, the value of flexibility decreases. An increase in the mean amplitude m decreases the overall option value, however, the effect becomes less crucial the later the arrival time and the lower the initial equity. In order to differentiate between incremental and radical innovation, we choose values similar to those of Brach and Paxson (2001).[18] First, we will assume that radical innovation is less frequent than incremental innovation, i.e. $\lambda_i > \lambda_r$. Moreover, if an innovation occurs, we will assume that the impact on the project value is positive on average and higher for radical innovation than for incremental innovation, which is modeled by assuming that $1 < \mu_i < \mu_r$. In order to capture the risk of failure, however, we will assume that the variance parameter of the jump amplitude distribution is greater for radical than for incremental innovations, i.e. $\nu_i < \nu_r$. Consequently, we account for the fact that jumps can significantly alter the radical innovation-driven project value during the collaboration period, and that complete loss is possible. Table 1 summarizes the parameters used hereafter.

[17] All option values have been calculated for $n = 0..15$ with an option premium accurate to the fourth decimal point.

[18] As an example, Apple's first iPod (2001) reflects a radical innovation in the consumer electronics industry, whereas all other generations thereafter (such as the iPod video or the iPod nano) are only incremental innovations.

==========[INSERT Table 1 HERE]===========

To what extent does this affect the entry decision? To answer this question we have to refer to Proposition 2 and analyze the sensitivity of the critical threshold and the probability of a market entry. For simplicity, we assume risk neutrality hereafter, so that all assets are priced so as to yield an expected rate of return equal to the risk-free rate, r.[19] The risk-neutral probability of initiating an R&D collaboration $\mathbb{P}[V^*(t) \leq V(t)]$, i.e. exercising the first stage, becomes more certain the higher the economic uncertainty and less certain the higher the associated costs I_1 and I are. *Ceteris paribus*, higher initial equity stakes as well as higher recovery values for possible later divestment have an enhancing effect on R&D collaboration. Two more results are notable. Because of the higher growth option value, the critical threshold for radical innovation is much lower than that for incremental innovation. Thus, all else being equal, R&D collaborations intended to perform radical innovation have a higher probability of being initiated than those initiated for the sake of incremental innovation, which is in agreement with recent empirical findings (see Tether, 2002; Fritsch and Lukas, 2001). Moreover, while this is less significant for very high uncertainties, the effect becomes more pronounced if environmental uncertainty is moderate (see Figure 3 and Figure 4 below). Another fact that becomes evident from the graphs is that if one neglects environmental as well as technological uncertainty, classical valuation would result in an

[19] This restrictive assumption, however, can easily be relaxed by adjusting the real drift rate α to account for a risk premium. See, e.g. Grenadier and Weiss (1997) and Martzoukos (2003). Schwartz (2004) suggests using the returns of successful R&D projects to estimate a proper risk premium.

underinvestment in both incremental and radical-driven RJVs.[20]

==========[INSERT FIGURE 3 and 4 HERE]===========

So far, we have analyzed the formation of R&D collaborations. With the critical threshold delimiting both termination strategies at hand, we are also able to specify the probability of buyouts and divestments choices (Proposition 3). Hence, once the MNE enters the host country, a decision in favor of a divestment becomes more probable the higher the chosen initial equity stake. Conversely, opting for buyouts is more likely if less equity was put into the initial R&D collaboration. Interestingly, environmental uncertainty influences the termination strategy of majority and minority equity RJVs differentially. The termination choice of majority equity RJVs is very sensitive with respect to changes in uncertainty when low environmental uncertainty is present. Given this seemingly concave dependence, an increase in uncertainty significantly increases the probability of choosing a divestment, while this effect dampens for situations subject to high uncertainty. For minority RJVs, the preference probability to divest the RJV seems to be a convex function with respect to uncertainty. Thus, changes in uncertainty increase the probability to decide in favor of a final divestment as overall uncertainty rises. Taking technological uncertainty into account, an overall increase in the propensity to perform a future divestment is observed. Moreover, given low environmental uncertainty, maximum buyout preferences are no longer observed for low equity partnerships. Instead, MNEs participating in partnerships around the 50:50 split will most likely be inclined to buy out the partner. However, this effect

[20] Comparison is based upon setting the environmental uncertainty and technical uncertainty equal to zero. See Schwartz (2004).

is dampened when environmental uncertainty increases. Figure 5 depicts the influences of initial equity stake and uncertainty on the choice of termination strategy of RJVs by plotting the risk-neutral probability $\mathbb{P}(V^*(t) \leq V(t) \leq \zeta)$ at time t_1 of deciding in favor of a subsequent divestment.

==========[INSERT FIGURE 5 HERE]===========

Two more results stand out. First, the model predicts that MNEs initiating R&D collaborations for the purpose of conducting incremental research decide more likely in favor of buying out the local partner in the host country. This is the case because there is little difference between the optimal market entry threshold and the threshold separating the termination strategies. Contrary to the above, MNEs participating in collaborations aimed at radical innovation tend to choose a subsequent divestment instead. These findings are in line with the empirical results provided by Hagedoorn and Sadowski (1999), who found evidence that the share of strategic technology alliances transformed into a M&A is smaller if performed in new core technologies and high-tech sectors than in mature industries.[21] Moreover, while this difference is more pronounced for low and moderate uncertainties, assimilation for high uncertainties is observed.

Since the value dynamics of the termination stage period are no longer explicitly influenced by innovation and concentrate on the marketing and production of the output, the comparative-static results for the remaining Propositions 4 and 5 are straightforward. We briefly summarize them here. *Ceteris paribus*, uncertainty increases the opportunity costs of waiting and, as a consequence, the gap between the classical NPV threshold and the derived optimal threshold

[21] See also Reuer and Zollo (2005).

for both scenarios increases, indicating the MNE's preference to wait before initiating the corresponding termination strategy. Increasing costs I and decreasing resale values κ further increase the propensity to wait before committing to terminating an R&D collaboration. Furthermore, if the MNE prefers to buy out the partner, this is less probable the higher the initial equity stake. In contrast, the optimal timing of a divestment increases if the MNE initially favored a majority share in the joint research collaboration.

Before concluding, it is useful to mention the duration of a RJV. As mentioned previously, the MNE has to decide at date $t = t_2$ which termination strategy it will choose. So far, the research collaboration has existed for a length of T. From then on, termination is performed once the corresponding threshold is reached. We can express the first hitting times $\tilde{t}$ formally as $\tilde{t}_B = \inf\{t \geq 0; V(t) \geq V_\infty\}$ and $\tilde{t}_D = \inf\{t \geq 0; V(t) \leq V_\infty\}$, where B and D denote the buyout and divestment strategies. While these stopping times are themselves random variables, it is possible to estimate their expected value, i.e. $\mathbb{E}[\tilde{t}]$. For geometric Brownian motion, we get:

$$\mathbb{E}[\tilde{t_B}] = Z^{-1} \ln\left(\frac{V^\infty}{V(t_2)}\right), \tag{10}$$

$$\mathbb{E}[\tilde{t_D}] = (-Z)^{-1} \ln\left(\frac{V(t_2)}{V_\infty}\right), \tag{11}$$

with $Z = (r - \delta) - 0.5\sigma^2 > 0.$[22] If the condition $Z > 0$ does not hold, the termination is never optimal and the collaboration remains active. Consider, for example, an environment where the initial equity equals 0.5 and uncertainty equals 0.4. Assuming V^* as the best predictor for the value at date t_2, i.e.

[22] For a detailed discussion on optimal stopping times for perpetual options, see Wilmott, Dewynne, and Howison (1993, p. 368ff.).

$\mathbb{E}[V(t_2)] = V^*$, we can specify the expected overall duration, i.e. $T + \mathbb{E}[\tilde{t_D}]$, of non-innovative collaboration as being 12.3 years before the MNE will divest its stake and withdraw from the host country.[23] Ceteris paribus, RJVs performing radical innovation will observe an expected overall duration of 11.4 years while the longevity of RJVs performing incremental innovation is expected to equal 11.9 years. Given these stylized facts, radical innovation driven joint ventures exhibit the lowest stability.

6 Summary

The increasing similarity of technologies across countries and cross-fertilization of technology between sectors, coupled with the increasing costs and risks, have increased the volatility of worldwide economic activity. While this has amplified the pressure to internationalize, it has also improved the possibility to source complementary assets abroad, i.e. technology-intensive assets or competencies. Thus, there is a perceived trend toward an era of alliance capitalism in R&D, where firms seek to exploit and acquire assets and technology that may be specific to particular locations. While R&D alliances have formed as a first-best option in many instances, we suggest modeling them accordingly, in order to examine, inter alia, the factors that determine the value of immanent flexibility, timing aspects, as well as their duration and termination strategies. Given the resulting evolutionary pattern, the model derives results in a dynamic context. The presence of R&D activity can significantly

[23] The parameters used are: $r = 0.05$, $\delta = 0.03$, $I = 1$, $I_1 = 1$, $\kappa = 0.7$ and $T = 3$. Given these parameters the critical market entry threshold is below the optimal trigger value ζ indicating a preference for subsequent divestments in all cases.

enhance investment option value and affect critical decision thresholds. The results show that conducting R&D increases the propensity to co-operate. As the findings indicate, however, the impact is sensitive to the type of innovation and degree of environmental uncertainty. Hence, radical innovations have a higher probability of being initiated than incremental innovation-driven collaborations. Moreover, the results suggest new and complementary insights: that the evolutionary sequence of international RJVs is not only driven by the growth option, as commonly modeled in the literature, but is also driven by the flexibility to dissolve the joint venture. Consequently, the model complements recent results emphasizing the importance of divestment options in the setup of JVs (see, e.g. Habib and Mella-Barral, 2007). While it has been commonly acknowledged that IJVs are a transitional form of foreign market expansion, less emphasis has been placed on what triggers the choice of termination form. Consequently, the model provides an endogenous solution that allows it to reveal which kind of termination is chosen by the MNE, given the initial equity stake in the venture and the economic and technological uncertainty parameters. The results indicate that MNEs initiating R&D collaborations intended to perform incremental R&D, e.g. in the steel industry, are more prone to buy out the JVs than MNEs that have initiated RJVs for the sake of radical innovation. In the latter case, the outcomes foreshadow that these R&D collaborations will be divested, which is in line with the findings of recent empirical studies. Moreover, implications for governmental policies in order to attract R&D-induced FDI can also be deduced from the model.

Generating recommendations for managerial actions of international operating firms was not a primary concern of the study. However, with the findings at hand, managers can use the presented structural option attributes and their corresponding valuation as an argumentative backing of certain - in the light of NPV based valuations - critical investment decisions. Further, less explicit option clauses have been observed in the IJV context due to the aforementioned problems involving real option complexities and their valuations. Thus, the derived closed form solutions can help MNEs' managers to structure and deploy these explicit option clauses more efficiently.

While this study provides new opportunities for further empirical research under an option framework, it is not without its own limitations. The model builds upon the assumption that a RJV is either active perpetually or is terminated via buyout or divestment at some point in time. Some R&D alliances, however, are abandoned suddenly and neither of the above exit strategies are chosen (see, e.g. Reuer and Zollo, 2005). This unilateral withdrawal could be due to cultural differences in management or to another technological innovation external to the firms that makes current research efforts obsolete. Thus, one direction for future research could be to implement multiple hazard rates. Moreover, while it has been widely acknowledged that learning is an important parameter for IJVs' formation and their sustainability, the model neglects the impact of learning. One way to circumvent this would be to treat the environmental uncertainty as a time-varying parameter (see, e.g. Majd and Pindyck, 1989 and Martzoukos, 2003). For example, once initiated, joint R&D collaboration can reduce this uncertainty over time. Clearly, the resulting evolutionary pattern is markedly more complex than those in this article. An analysis that addresses these limitations is important but is best left for future investigations.

7 Appendix

7.1 Optimal Timing of Buyout or Divestment Strategy

From the standard literature the results of a perpetual call option and a perpetual put option are commonly known.[24] Thus they are just summarized briefly. Departing from the Bellman principal of optimality, any perpetual real option value $f(V)$ has to satisfy:

$$\frac{1}{2}\sigma^2 V^2 \frac{\partial^2 f}{\partial V^2} + (r-\delta)V\frac{\partial f}{\partial V} - rf = 0, \tag{12}$$

subject to some specific boundary conditions. For this Euler PDE the general solution is $AV^{\beta_1} + BV^{\beta_2}$ where the βs are the positive and negative solution of the following nonlinear equation:

$$\frac{1}{2}\sigma^2\beta(\beta-1) + (r-\delta)\beta - r = 0. \tag{13}$$

Given the proper boundary conditions for the buyout strategy,

$$\lim_{V\to 0^+} f_1(0) = 0, \tag{14}$$
$$\lim_{V\to V^\infty} f_1(V^\infty) = (\bar{\epsilon}-\epsilon)V^\infty - I, \tag{15}$$
$$\lim_{V\to V^\infty} f_1(V^\infty) = (\bar{\epsilon}-\epsilon), \tag{16}$$

i.e. the value matching and smooth pasting condition, as well as fact that $V = 0$ serves as an absorbing barrier, the value of the corresponding strategy $f_1(V)$ results in:

$$f_1(V) = AV^{\beta_1} \quad \text{for} \quad V < V^\infty, \tag{17}$$

[24] See, e.g. Dixit and Pindyck (1994) as well as Merton (1973).

with I designating the cost of acquiring the rest of the equity stake $(\bar{\epsilon}-\epsilon)$.[25] Here, A and β_1 are the usual constants which are defined by

$$\beta_1 = \frac{1}{2} - \frac{(r-\delta)}{\sigma^2} + \left(\left[\frac{(r-\delta)}{\sigma^2} - \frac{1}{2}\right]^2 + \frac{2r}{\sigma^2}\right)^{1/2}, \tag{18}$$

$$A = \left[(\bar{\epsilon}-\epsilon)\frac{1}{\beta_1}\left[\frac{1}{(\bar{\epsilon}-\epsilon)}\frac{\beta_1}{\beta_1-1}I\right]^{(1-\beta_1)}\right]. \tag{19}$$

From this, the optimal trigger value V^∞ for the buyout strategy can be deduced which results in:

$$V^\infty = \frac{1}{(\bar{\epsilon}-\epsilon)}\frac{\beta_1}{\beta_1-1}I. \tag{20}$$

In contrast, if the MNE prefers to exit the foreign market it will obtain a perpetual divestment option. Upon exercising the second stage, the MNE forsakes the existing project with value ϵV and subsequently realizes its abandonment value κ (See, e.g. Chi (2000)). Let V_∞ designate the optimal threshold value, then the boundary conditions result in:

$$\lim_{V\to 0^+} f_2(0) = 0, \tag{21}$$

$$\lim_{V\to V_\infty} f_2(V_\infty) = \kappa - \epsilon V_\infty, \tag{22}$$

$$\lim_{V\to V_\infty} f_2(V_\infty) = -\epsilon. \tag{23}$$

The strategic flexibility value results in:

$$f_2(V) = BV^{\beta_2} \quad \text{for} \quad V > V_\infty, \tag{24}$$

with

[25] It is assumed that the acquisition price is fixed right from the start. For a justification of this assumption refer to e.g. Chi and McGuire (1996).

$$\beta_2 = \frac{1}{2} - \frac{(r-\delta)}{\sigma^2} - \left(\left[\frac{(r-\delta)}{\sigma^2} - \frac{1}{2} \right]^2 + \frac{2r}{\sigma^2} \right)^{1/2}, \tag{25}$$

$$B = \left[-\frac{1}{\beta_2} \epsilon \left(\frac{\beta_2 \kappa}{(\beta_2 - 1)\epsilon} \right)^{1-\beta_2} \right]. \tag{26}$$

The corresponding optimal threshold value V_∞ for initiating a divestment strategy results in:

$$V_\infty = \frac{\beta_2}{\beta_2 - 1} \frac{\kappa}{\epsilon}. \tag{27}$$

7.2 Choice of Strategy

The aforementioned optimal threshold ζ separating both strategies is determined by the intersection of $f_2(\zeta)$ and $f_1(\zeta)$. From $A\zeta^{\beta_1} = B\zeta^{\beta_2}$ we get:

$$\zeta = \left[-\frac{\epsilon}{(\bar{\epsilon} - \epsilon)} \frac{\beta_1}{\beta_2} \frac{(V_\infty)^{1-\beta_2}}{(V^\infty)^{1-\beta_1}} \right]^{1/\gamma}, \tag{28}$$

with $\gamma = \beta_1 - \beta_2$. Consequently, for project values V below ζ the divestment option is preferred while for project values above ζ the MNE will choose the cross-border buyout strategy.

We are now ready to determine the value of the chooser option at time t_1. For the sake of convenience, we deviate from the Bellman Principle of Optimality and compute the subsequent values using the risk neutral valuation technique.[26] [27] The value of the chooser option at the time of choice is determined by $\max\{f_2(V), f_1(V)\}$.

In order to determine the actual value of the chooser option one has to take account of the fact that jumps with probability $\mathbb{P}(n)$ might occur. Thus the value at time t_1 is given by:

$$
\begin{aligned}
F &= \sum_{n=0}^{\infty}\left(\mathbb{P}(n)\mathbb{E}^{Q}\left[\frac{\max\{f_2(V), f_1(V)\}}{e^{rT}}|\text{n jumps}\right]\right), \qquad (29)\\
&= \sum_{n=0}^{\infty}\left(e^{-\lambda T}\left(\frac{(\lambda T)^n}{n!}\right)\mathbb{E}^{Q}\left[\frac{\max\{f_2(V), f_1(V)\}}{e^{rT}}|\text{n jumps}\right]\right).
\end{aligned}
$$

Simplifying the above equation results in:

$$
\begin{aligned}
F &= \sum_{n=0}^{\infty} e^{-\lambda T}\left(\frac{(\lambda T)^n}{n!}\right)e^{-rT}\Bigg[\int_{0}^{V_\infty}(\kappa - \epsilon V)dP + \int_{V_\infty}^{\zeta} BV^{\beta_2}d\tilde{P} + \int_{\zeta}^{V^\infty} AV^{\beta_1}d\tilde{P}\\
&+ \int_{V^\infty}^{\infty}((\bar{\epsilon} - \epsilon)V - I)dP\Bigg], \qquad (30)
\end{aligned}
$$

with $\mathbb{E}^{Q}[\ldots]$ as the expectations operator under the martingale measure Q, and $dP, d\tilde{P}$ denoting the implied probability measures. The first and last two integrals of equation (30) lead to the Black-Scholes solutions for jumps as presented by Merton (1976). The solution to the remaining integrals is derived in a similar manner, i.e. substitute $V = Vm^n e^{((r-\delta-(m-1)\lambda-1/2\tilde{\sigma}^2)T+\tilde{\sigma}Z^Q\sqrt{T})}$ into

[26] The solution to the perpetual option rights could have been performed in a similar fashion as for the chooser option. This calls for computing the expectations of all stopping times since the option rights are of an American type, i.e. they can be exercised during their time to maturity. For a martingale approach to value American perpetual options see, e.g. Gerber and Shiu (1994).

[27] We draw on risk-neutral valuation as established in Constantinides (1978), Harrison and Pliska (1981), and Cox, Ingersoll, and Ross (1985).

equation (30). By applying the symmetry features of the normal distribution, i.e. $\int_a^b f(x)dx = \int_{-\infty}^b f(x)dx - \int_{-\infty}^a f(x)dx$ to the intermediate solution the integral can easily be solved. Finally, we get:

$$
\begin{aligned}
F = \sum_{n=0}^{\infty} e^{-(r+\lambda)T} \left(\frac{(\lambda T)^n}{n!}\right) \Big[& \kappa N(d_1) - \epsilon V_1 m^n e^{(r-\delta-(m-1)\lambda)T} N(d_2) \\
& + e^{\Omega_2 T} B (V_1 m^n)^{\beta_2} (N(d_3) - N(d_4)) + e^{\Omega_1 T} A (V_1 m^n)^{\beta_1} (N(d_5) - N(d_6)) \\
& + (\bar{\epsilon} - \epsilon) V_1 m^n e^{(r-\delta-(m-1)\lambda)T} N(d_7) - I N(d_8) \,\Big],
\end{aligned}
\tag{31}
$$

with V_1 as the value of the overall IJV at time t_1, $N(\dots)$ as the cumulative normal distribution and

$$
\begin{aligned}
d_1 &= \frac{\ln\left(\frac{V_\infty}{(V_1 m^n)}\right) - (r-\delta-(m-1)\lambda - \frac{1}{2}\tilde{\sigma}^2)T}{\tilde{\sigma}\sqrt{T}}, \quad d_2 = d_1 - \tilde{\sigma}\sqrt{T}, \\
d_3 &= \frac{\beta_2 \ln\left(\frac{\zeta}{(V_1 m^n)}\right) - (\Omega_2 + \frac{1}{2}\tilde{\sigma}^2\beta_2^2)T}{\tilde{\sigma}\beta_2\sqrt{T}}, \qquad d_4 = d_3 + \frac{\ln\left(\frac{V_\infty}{\zeta}\right)}{\tilde{\sigma}\sqrt{T}}, \\
d_5 &= \frac{\beta_1 \ln\left(\frac{V^\infty}{(V_1 m^n)}\right) - (\Omega_1 + \frac{1}{2}\tilde{\sigma}^2\beta_1^2)T}{\tilde{\sigma}\beta_1\sqrt{T}}, \qquad d_6 = d_5 + \frac{\ln\left(\frac{\zeta}{V^\infty}\right)}{\tilde{\sigma}\sqrt{T}}, \\
d_7 &= \frac{\ln\left(\frac{(V_1 m^n)}{V^\infty}\right) + (r-\delta-(m-1)\lambda + \frac{1}{2}\tilde{\sigma}^2)T}{\tilde{\sigma}\sqrt{T}}, \quad d_8 = d_7 - \tilde{\sigma}\sqrt{T},
\end{aligned}
$$

and

$$
\begin{aligned}
\tilde{\sigma} &= \sqrt{\sigma^2 + \frac{\nu^2 n}{T}}, \\
\Omega_i &= (r - \delta - (m-1)\lambda)\beta_i - \frac{1}{2}\beta_i\tilde{\sigma}^2 + \frac{1}{2}\beta_i^2\tilde{\sigma}^2 \quad \forall i = 1, 2.
\end{aligned}
$$

7.3 Optimal Timing of R&D Collaboration

So far, the present results value the overall flexibility of an active RJV. The question remains when to initiate the RJV and what is the assigned value if the RJV is impending. First, the MNE will invest in the RJV if the expanded

NPV is greater then zero, i.e.:

$$\epsilon V(t) + F(V(t), \lambda, m, \nu) - I_1 \geq 0. \tag{32}$$

Moreover, if the MNE has the option to wait for new information before initiating the RJV, we have to discount the expectations assigned to the above market entry criteria. Putting this formally, the goal is to solve:

$$G = \sum_{n=0}^{\infty} \left(\mathbb{P}(n) \mathbb{E}^Q \left[\frac{[\epsilon V(t) + F(V(t), \lambda, m, \nu) - I_1]^+}{e^{rt_1}} | \mathcal{F}, \text{n jumps} \right] \right), \tag{33}$$

which is equivalent to solving the following integral:

$$G = e^{-rt_1} \sum_{n=0}^{\infty} \left(\mathbb{P}(n) \int_{V_1^*}^{\infty} (\epsilon V(t) + F(V(t), \lambda, m, \nu) - I_1) dP \right). \tag{34}$$

where V_1^* designates the optimal threshold for exercising the option which is determined numerically by solving equation (32), i.e. $\epsilon V_1^*(t) + F(V_1^*(t), n, m, \nu) - I_1 = 0$. The solution results in:

$$\begin{aligned} G = {} & \epsilon V_0 e^{-\delta t_1} N(d_9) - I_1 e^{-rt_1} N(d_9 - \sigma\sqrt{t_1}) + \sum_{n=0}^{\infty} e^{-\lambda T} \left(\frac{(\lambda T)^n}{n!} \right) \\ & \Big[\kappa I_0 e^{-rt_2} M(h_1, k_1; -\tilde{\rho}) - \epsilon V_0 m^n e^{-\delta t_2} e^{-(m-1)\lambda T} M(h_1 + \sigma\sqrt{t_1}, k_4; -\tilde{\rho}) \\ & + B V_0^{\beta_2} m^{n\beta_2} e^{(\Omega_2 - r)T} \left(M(h_2, k_7; -\tilde{\rho}) - M(h_2, k_8; -\tilde{\rho}) \right) \\ & + A V_0^{\beta_1} m^{n\beta_1} e^{(\Omega_1 - r)T} \left(M(h_3, k_5; -\tilde{\rho}) - M(h_3, k_6; -\tilde{\rho}) \right) \\ & + (\bar{\epsilon} - \epsilon) V_0 m^n e^{-\delta t_2} e^{-(m-1)\lambda T} M(h_1 + \sigma\sqrt{t_1}, k_3; \tilde{\rho}) - I_2 e^{-rt_2} M(h_1, k_2; \tilde{\rho}) \Big], \end{aligned}$$

where V_0 states the value of the project at time $t = 0$, $\tilde{\rho} = \Gamma\sqrt{t_1/t_2}$, and

$$\begin{aligned} \Lambda_i &= (m-1)\lambda\beta_i - \frac{1}{2}\frac{\nu^2 n}{T}\beta_i(2\beta_i - 1), \quad \forall i = 1, 2 \\ \Delta_1 &= (m-1)\lambda + \frac{1}{2}\frac{\nu^2 n}{T}, \end{aligned}$$

$$\Delta_2 = \Delta_1 - \frac{\nu^2 n}{T},$$
$$\Gamma = \frac{\sigma}{\tilde{\sigma}\sqrt{1 + ((\frac{\sigma}{\tilde{\sigma}})^2 - 1)(t_1/t_2)}}.$$

$M(\ldots)$ designates the bivariate cumulative standard normal distribution:

$$M(x, y; \rho) = \frac{1}{2\pi\sqrt{1-\rho^2}} \int_{-\infty}^{y} \int_{-\infty}^{x} e^{-\frac{1}{2}\frac{(x^2 - 2\rho y x - y^2)}{1-\rho^2}} dx dy, \tag{35}$$

and parameters defined as follows:

$$k_1 = \Gamma\left(\frac{\ln\left(\frac{V_\infty}{V_0 m^n}\right) - (r - \delta - \frac{1}{2}\sigma^2)t_2 + \Delta_1 T}{\sigma\sqrt{t_2}}\right), \quad k_7 = \Gamma\left(\frac{\beta_2 \ln\left(\frac{\zeta}{V_0 m^n}\right) - (r + \frac{1}{2}\sigma^2\beta_2^2)t_2 + \Lambda_2 T}{\sigma\beta_2\sqrt{t_2}}\right),$$
$$k_2 = \Gamma\left(\frac{\ln\left(\frac{V_0 m^n}{V^\infty}\right) + (r - \delta - \frac{1}{2}\sigma^2)t_2 - \Delta_1 T}{\sigma\sqrt{t_2}}\right), \quad k_8 = \Gamma\left(\frac{\beta_2 \ln\left(\frac{V_\infty}{V_0 m^n}\right) - (r + \frac{1}{2}\sigma^2\beta_2^2)t_2 + \Lambda_2 T}{\sigma\beta_2\sqrt{t_2}}\right),$$
$$k_3 = \Gamma\left(\frac{\ln\left(\frac{V_0 m^n}{V^\infty}\right) + (r - \delta + \frac{1}{2}\sigma^2)t_2 - \Delta_2 T}{\sigma\sqrt{t_2}}\right), \quad h_1 = \frac{\ln\left(\frac{V_0}{V_1^*}\right) + (r - \delta - \frac{1}{2}\sigma^2)t_1}{\sigma\sqrt{t_1}},$$
$$k_4 = \Gamma\left(\frac{\ln\left(\frac{V_\infty}{V_0 m^n}\right) - (r - \delta + \frac{1}{2}\sigma^2)t_2 - \Delta_2 T}{\sigma\sqrt{t_2}}\right), \quad h_2 = \frac{\beta_2 \ln\left(\frac{V_0}{V_1^*}\right) + (r + \frac{1}{2}\sigma^2\beta_2^2)t_1}{\sigma\beta_2\sqrt{t_1}},$$
$$k_5 = \Gamma\left(\frac{\beta_1 \ln\left(\frac{V^\infty}{V_0 m^n}\right) - (r + \frac{1}{2}\sigma^2\beta_1^2)t_2 + \Lambda_1 T}{\sigma\beta_1\sqrt{t_2}}\right), \; h_3 = \frac{\beta_1 \ln\left(\frac{V_0}{V_1^*}\right) + (r + \frac{1}{2}\sigma^2\beta_1^2)t_1}{\sigma\beta_1\sqrt{t_1}},$$
$$k_6 = \Gamma\left(\frac{\beta_1 \ln\left(\frac{\zeta}{V_0 m^n}\right) - (r + \frac{1}{2}\sigma^2\beta_1^2)t_2 + \Lambda_1 T}{\sigma\beta_1\sqrt{t_2}}\right), \; d_9 = \frac{\ln\left(\frac{V_0}{V_1^*}\right) + (r - \delta + \frac{1}{2}\sigma^2)t_1}{\sigma\sqrt{t_1}}.$$

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	Incremental Innovation	Radical Innovation
λ Jump-Frequency (yearly)	1	0.2
m Mean Jump-Size	1.05	1.3
ν Standard Deviation of Jump Size	0.2	0.4

Table 1

Parameter for incremental and radical innovation trajectories. Moreover, the following values have been used: joint research collaboration time T=3 years, equity share ϵ=0.5, risk-free interest rate r=0.05.

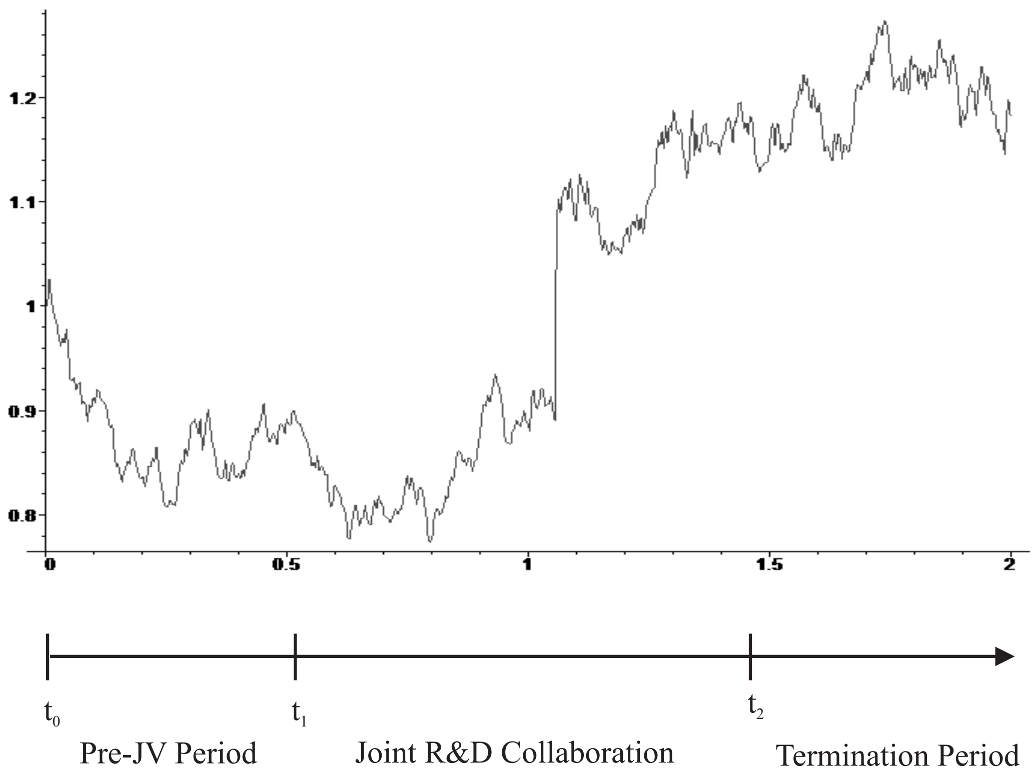

Figure 1. Dynamics of overall project value V(t) assuming the probability of a radical innovation during the joint research period.

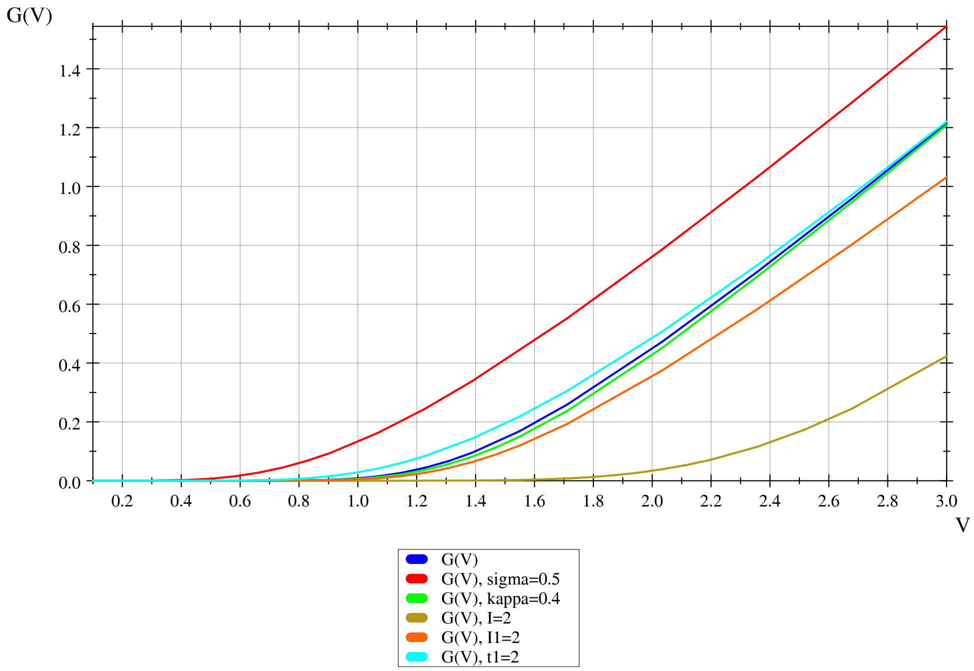

Figure 2. Value of pending cross-border RJV $G(V)$. The parameters used are: $r = 0.05$, $\delta = 0.03$, $\sigma = 0.25$, $I = 1$, $I_1 = 1$, $\kappa = 0.7$, $T = 3$, $\nu = 0.01$, $m = 1$, $\lambda = 0.01$, $\epsilon = 0.5$.

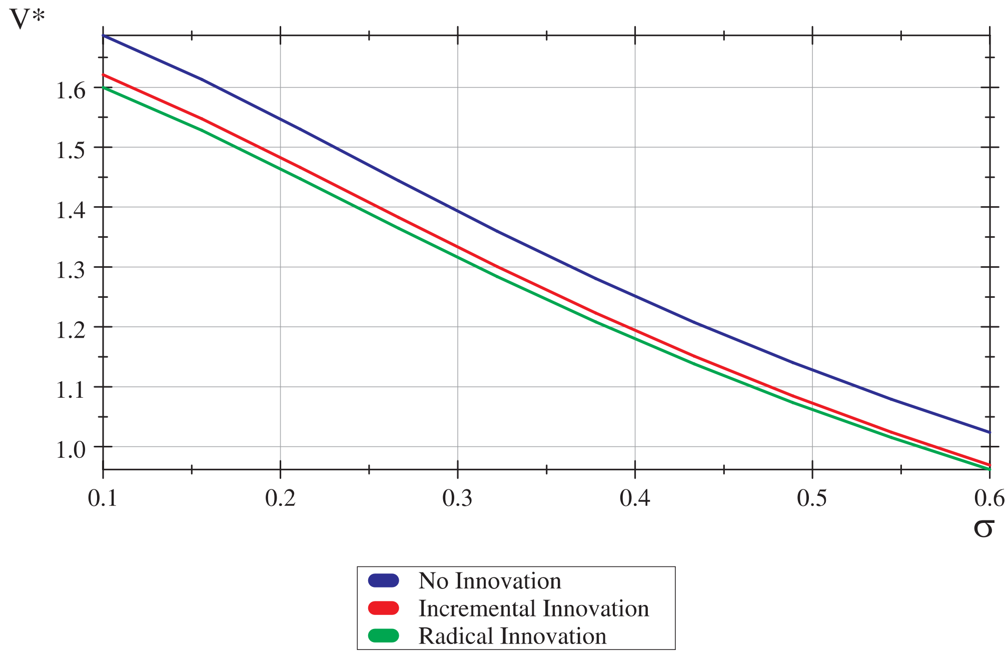

Figure 3. Optimal threshold V^* for initiating an RJV under environmental and technological uncertainty. The parameters used are: $r = 0.05$, $\delta = 0.03$, $I = 1$, $I_1 = 1$, $\kappa = 0.7$, $T = 3$, and $\epsilon = 0.5$.

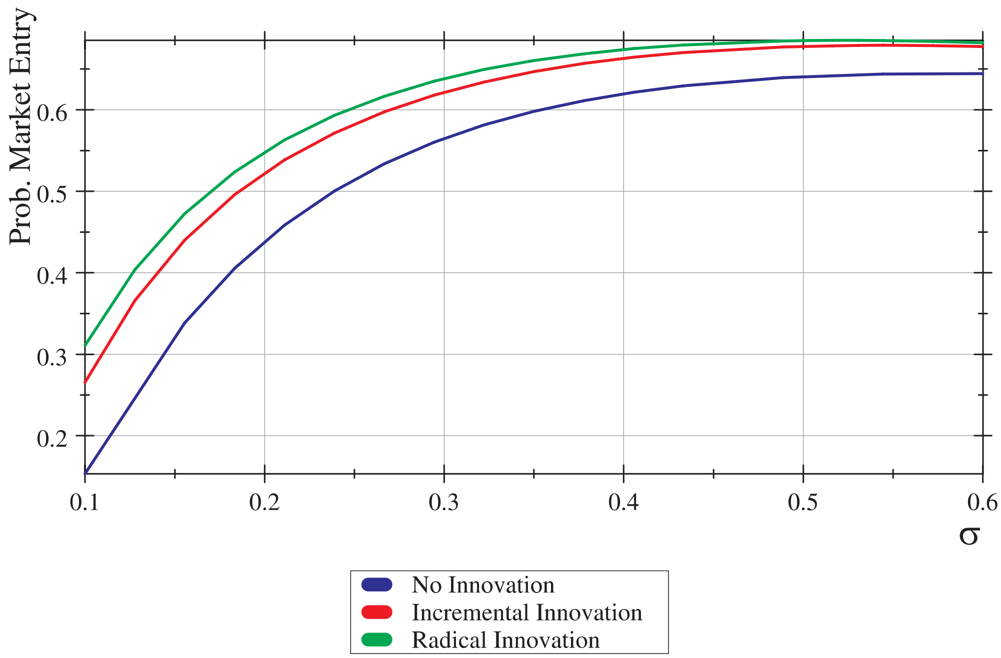

Figure 4. Probability of the formation of an RJV under environmental and technological uncertainty. The parameters used are: $r = 0.05$, $\delta = 0.03$, $I = 1$, $I_1 = 1$, $\kappa = 0.7$, $T = 3$, and $\epsilon = 0.5$.

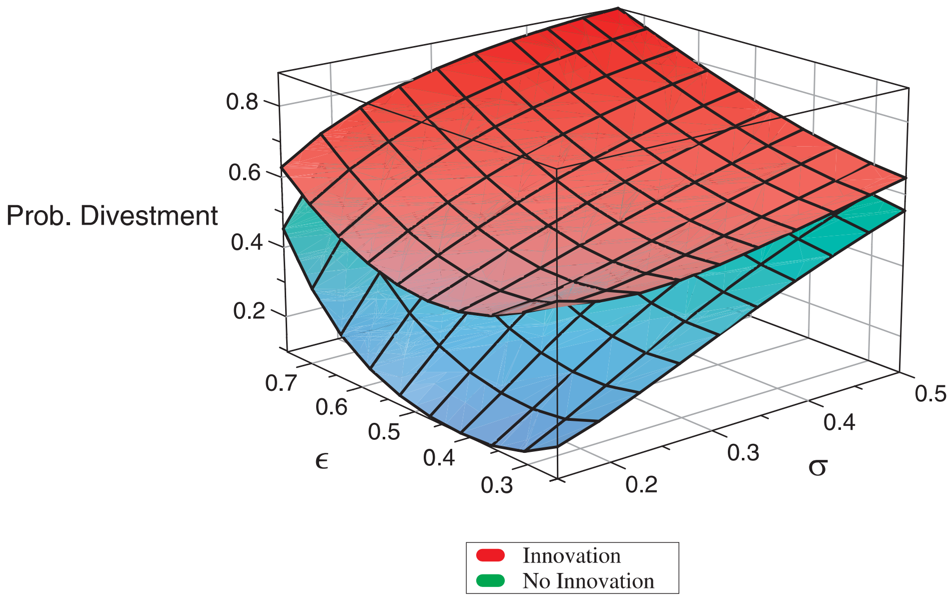

Figure 5. Probability of termination of a RJV via divestment with respect to initial equity share ϵ and both types of uncertainty. The parameters used are: $r = 0.05$, $\delta = 0.03$, $I = 1$, $I_1 = 1$, $\kappa = 0.7$, $T = 3$, $\nu = 0.4$, $m = 1.1$, and $\lambda = 0.5$.