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Innovation speed under uncertainty and competition

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Innovation speed is widely considered to be a key factor for a firm's ability to maintain competitive advantage. Primarily, empirical evidence has found contradictory interdependencies regarding the role of innovation speed. The prevailing proposition of "the faster the better" has been challenged by results of empirical studies heavily depending on the methodological setup used. In contrast, we propose a model of the complete innovation process to study innovation speed under uncertainty and competition. We find that higher market uncertainty speeds up innovation and encourages firms to innovate incrementally. Strong competition tends to reduce innovation speed and encourages rather radical innovation.

1 | INTRODUCTION

Socioeconomic forces, such as digitalization and globalization, rapidly change the innovation landscape (European Commission, 2018, p. 7). In consequence, the pace of changes in business environments increases, and uncertainties about customers' needs, market-viable technologies and products as well as planning and timing of (financial) resources arise (Mullins & Sutherland, 1998), impeding firms' efforts to maintain their competitive advantages (Baum & Wally, 2003; Wu & Yen, 2007). Against this background, especially one key factor is of particular importance: the innovation speed, which is generally defined as time elapsed between initial development and commercialization (Kessler & Chakrabarti, 1996; Mansfield, 1988; Murmann, 1994). Correspondingly, it is also referred to as "new product development speed," "time-to-market," "cycle time," or "speed-to-market" (Chen, Damanpour, & Reilly, 2010). Although innovation speed has gained much attention in the strategic literature and particularly in empirical studies, there still has only been little theoretical advancement regarding the role of the speed of innovation in sustaining competitive advantage (Chen, Reilly, & Lynn, 2005; Kessler & Chakrabarti, 1996). One central and prevailing opinion among business scholars and practitioners refers to fast innovations being positive by strengthening the competitive edge (Cankurtaran, Langerak, & Griffin, 2013; Carbonell & Rodriguez, 2006; Chen, Reilly, & Lynn, 2012; Kessler & Chakrabarti, 1996; Lint & Pennings, 2001; Stanko, Molina-Castillo, & Munuera-Aleman, 2012). However, being the first or the fastest does not necessarily result in certain benefits but can also cause devastating results, for example, in case of a failure due to changing market demands or suboptimal timing (Adner & Kapoor, 2016; Golder & Tellis, 1993). In this context, it is not surprising that interdependencies regarding innovation speed identified by the strategic literature are ambiguous and lead to inconsistent managerial implications (Cankurtaran et al., 2013; Chen et al., 2005, 2012; Kessler & Chakrabarti, 1996).

Therefore, we aim to contribute to the literature by studying innovation speed based on a rather holistic model of the innovation process. From a bird's eye perspective, we divide the innovation process into two linked phases: the R&D phase and the market phase. The former is accompanied with the initial management decision whether at all and when to start as well as whether to continue incurring R&D efforts. Following, the latter phase involves decisions regarding marketing and therewith innovating and, if necessary, exiting the market. Since timing during the new product development is crucial (Adner & Kapoor, 2016; Kim, Kim, Miller, & Mahoney, 2016) and because of the apparent option features inherent in the innovation process (Lee & Paxson, 2001; van Bekkum, Pennings, & Smit, 2009), we apply a real option modeling framework.

Starting with Myers (1984), who is the first to explicitly notice the option characteristics of R&D, various option models for its valuation have emerged. Early works similar to Herath and Park (1999) or Lint and Pennings (1998) rely on a basic decision tree framework or a simple application of the Black and Scholes (1973) formula. For the price of ease and traceability, these approaches do not capture the pronounced sequential character inherent in almost all R&D projects. Models, however, that account for the sequential character, which can be referred to as time to build, lead time, or investment lag, provide remedy. Majd and Pindyck (1987) are the first who study investment timing linked with time to build (see also Dixit & Pindyck, 1994, pp. 319–356). They limit the speed of spending the investment budget and thereby introduce a minimum time for finishing the project. Bar-Ilan and Strange (1996) take a different approach. They study the effect of an exogenously fixed investment lag. Sarkar and Zhang (2015) allow the time to build to be fully uncertain by letting it depend on the stochastic evolution of the underlying.

Furthermore, many R&D models do not consider technical failure, although this source of uncertainty is omnipresent in R&D. Pindyck (1993) provides a way to account for this feature. In his model, investment costs encompass technological risk and are assumed to evolve stochastically over time. Other approaches, for instance, Pennings and Lint (1997), Martzoukos and Trigeorgis (2002), or Pennings and Sereno (2011), use jump processes to capture technical risks.

Models that comprehensively combine the sequential nature of R&D investment and multiple sources of uncertainty are rare (e.g., Schwartz and Moon, 1996). Nishihara (2018a) was among the first who developed a sequential real option model that considers three distinct forms of uncertainty impacting an R&D investment project. His findings reveal that—unlike market uncertainty—uncertainty associated with R&D duration and cost has a positive effect on the investment pattern of firms. In particular, higher uncertainty of the research duration accelerates investment. Moreover, competition has a U-shaped impact on investment timing. Hence, while higher risk of competition usually erodes the value of waiting, thereby accelerating investment, the findings furthermore reveal that severe competition might incentivize the firm to return to a wait-and-see strategy. Hence, high enough levels of competitor risk might increase a firm's propensity to delay R&D investment. In another recent paper, that is, Nishihara (2018b), the modeling framework of Nishihara (2018a) is extended in three different ways. First, the pace by which competition preempts the firm and the competitor's impact on firm profitability are also assumed uncertain. Second, the model extension also considers the possibility to additionally finance the R&D project by debt. Third, after completion of the R&D investment, the firm can further lever its sales by investing in a subsequent growth option. Hence, the additional findings are that debt financing accelerates investment and that the growth option amplifies the overall impact uncertainty of technological success exerts on investment policy.

Against the background of recent literature, our model is mostly related to both, Nishihara (2018a) and Nishihara (2018b) as we alike develop a generic and tractable real option model that considers three distinct forms of uncertainty. Our model, however, deviates from Nishihara (2018a) and Nishihara (2018b) in several ways. First, we assume that after the R&D phase is completed, the firm can still benefit from new information and thus has an incentive to avoid having paid sunk cost for the marketing phase too early. Hence, we explicitly differentiate between the gestation lag and application lag, which are treated as one lag, that is, the research duration, in Nishihara (2018a) and Nishihara (2018b). There is ample evidence that successful R&D is not immediately translated in market success. Exemplary, neither Eastman Kodak's world-first digital camera developed in 1975 nor Google's new product GoogleGlass in 2014 went beyond the R&D stage. Second, unlike Nishihara (2018a) and Nishihara (2018b), we also assume that two of the three sorts of uncertainty are no longer independent. In particular, R&D projects that are less costly can be completed faster as they resemble incremental innovations. Due to the marginal level of "newness" these innovations have less chances to receive patent protection, and thus, enforcing property rights is too costly, which results in attracting competitors. Hence, less costly incremental R&D projects face higher competitor risks. Third, we allow the firm to also control for the length being active in the product market once committed to sell the new innovation. Hence, rather than staying infinitely active in the market, the firm in our model can decide on when to leave the market. Obviously, such a situation is advisable should competition erode too much project value, if demand falls to deep, or should suppliers have strong bargaining powers. To conclude, our model allows for a more fine-grained investment policy that allows the firm to choose not only its investment timing optimally, that is, x_I, but also its optimal capital spending rate by which it financially supports R&D activity over time, that is, k, as well as its optimal exit timing strategy, that is, x_D.

We find that higher market uncertainty speeds up innovation and encourages firms to innovate incrementally. Hence, the generally accepted opinion is supported that "the faster the innovation is realized the better". Strong competition, however, tends to reduce innovation speed and encourages rather radical innovation. This stands against the general opinion. The latter finding is also supported by the findings of Nishihara (2018a). He also finds that for a fixed level of research duration, a higher arrival rate of a competitor's technology development decreases the incentive to invest and, hence, decreases the innovation speed.

The remainder of this paper is organized as follows: Section 2 introduces the model setup and provides a numerical solution for the firm's optimal investment policy. Section 3 presents the results by means of a numerical analysis allowing for the derivation of research hypotheses. Finally, Section 4 briefly summarizes the findings.

2 | THE MODEL

Before we will elaborate on the mathematical assumptions, we will start with qualitatively describing the model structure. Consider a single firm that has to decide today whether to start investing in an R&D-intense investment that holds promise to generate a new product. For simplicity reasons, we assume that the firm is risk-neutral and has deep pockets. The overall investment project consists of two stages: The first stage is linked to R&D activity that only generates cost $K(t)$ but no direct positive cash flow. During the R&D stage, that is, the gestation lag, the firm has a certain R&D budget $K_{t=0}$ that can be constantly spent to finish R&D. Obviously, this stage is subject to several sources of risk. First, the R&D efforts might lead to no innovative results by which a new product may be justified. We refer to this risk as the risk of a technical failure and rely on a Poisson process leading to a sudden death of the project with mean arrival time $\lambda_{R\ \&\ D} > 0$. Second, the R&D phase is also impacted by market uncertainty, which is mainly comprised of the risk associated with the forecasted demand-driven cash flow $x(t)$. For traceability reasons, we will assume that the pure market uncertainty is driven by a geometric Brownian motion. After completion of the R&D stage, that is, the gestation lag, the firm has an option to decide when to time marketing and for how long it plans to sell the product. Entry and exit are associated with lump sum cost being sunk, that is, I and D for investment and desinvestment, respectively. Hence, optimal exercise is of crucial importance as this stage is also impacted by several risks. First, there is—again—general market uncertainty σ that affects the firm's cash flows $x(t)$. Second, a competitor might successfully market a similar idea sooner and capture market share. We will refer to this risk as a competitor risk during the application lag, i.e. the firm itself has not yet timed. For simplicity reasons, we will assume that this risk is governed by a Poisson process with mean arrival time $\lambda_0 > 0$ and intensity $\phi_0 \in [0,1)$. Third, as soon as the firm has been timed and chosen to be active in the market, further competition risk is present that summarizes the threats new market entrants and market incumbents exert on the firm. Because this will be of different magnitude compared with the application lag, we will refer to this risk as incumbent risk in the marketing phase. Again, we will assume this risk being governed by a Poisson process with mean arrival time $\lambda_1 > 0$ and intensity $\phi_1 \in [0,1)$. Figure 1 displays a sample path of the project cash flow and the firm's optimal investment policy.

Against the background of this sequential nature and the multiple sources of uncertainty, the firm has to decide on an optimal investment policy to determine whether to start the project in t_0, how much to spend on R&D, when to abandon R&D in the R&D stage, when to time the market entry, and how long to stay active in the market before exiting. Let us assume that $x(t)$ represents the state variable that captures the different sources of risk, then the firm has to decide on (a) the exit threshold that determines abandonment of R&D activity, that is, $x_{exit}(t)$, (b) the optimal capital spending rate k^* that indicates the pace by which R&D is financially supported given an initial perception of earnings x_0, (c) the optimal investment threshold that indicates when to enter the market phase, that is, x_I, and (d) the optimal exit threshold that indicates when to exit the market and abandon the project, that is, x_D.

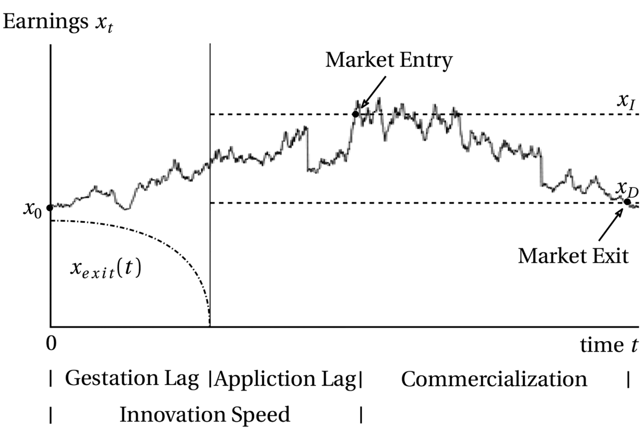

FIGURE 1 Sample path and the firm's optimal investment policy

In the following, we explain how to solve the firm's decision problem and what determines the firm's optimal investment policy. Because the problem is a two-stage optimal stopping problem, we solve the model backward, i. e. we first solve for the firm's exit threshold in the market phase and subsequently solve for the firm's optimal investment and capital spending rate in the R&D stage.[1]

2.1 | The market phase

During the market stage, the firm is exposed to market uncertainty and competitor risk. We use the earnings x_t as the uncertain state variable and assume that x_t follows a jump diffusion of the form[2]

$$dx_t = \alpha x_t dt + \sigma x_t dz_t - x_t dq_i, \tag{1}$$

$$dq_i = \begin{cases} \phi_i > 0 & \text{with Prob. } \lambda_i \mathrm{d}t \\ 0 & \text{with Prob. } 1 - \lambda_i \mathrm{d}t. \end{cases} \tag{2}$$

The first term describes the deterministic change in x_t, where α denotes the drift rate. The second term represents the continuous stochastic change in x_t with σ as volatility and dz_t as the Wiener increment. The last term describes the discontinuous stochastic change in x_t, where dq_i takes values of size $0 \le \phi_i < 1$[3] with probability $\lambda_i dt$ and 0 with converse probability $1 - \lambda_i dt$. The index $i \in \{0,1\}$ denotes whether the firm is out of the market or already in the market respectively. Independent of whether the firm is inactive or active, we assume that the firm is exposed to forces as described by Porter (1979, 2008). In particular, we assume that the threat of potential entrants, the rivalry among existing competitors, and the threat of potential substitutes are affecting the earnings dynamics via the jump part of the stochastic differential equation. In this context, λ_0 and ϕ_0 can be interpreted as anticipated competitive entry and loss, respectively, whereas λ_1 and ϕ_1 describe the impact of competitors, potential competitors, and substitutes being active in the market. The bargaining power of buyers is included into the drift and volatility parameter of the process representing the demand side. The last force, the bargaining power of the suppliers, occurs in the valuation functions as an essential determinant of operating cost w. Furthermore, the market entry requires some sunk entry cost I, and when the conditions for being active in the market are getting too bad, the firm exits the market that is associated with sunk cost D.

Suppose the firm has finished its R&D successfully and waits the introduction of its invention to the market until the earnings rise to an entry level x_I. As soon as the entry level is reached, the firm pays the sunk entry cost I. Further, after entering the market, the firm is active until the earnings reach an exit level x_D, i.e. until the market conditions for being active get sufficiently worse. At this point, the firm decides to leave the market once and for all by incurring the irreversible exit cost D.[4] As shown in more details in Appendix A, the valuation functions in the active and inactive state are as follows:

$$V_0(x) = A_1 x^{\beta_{01}} \tag{3}$$

$$V_1(x) = A_2 x^{\beta_{12}} + \frac{x}{\delta + \lambda_1 \phi_1} - \frac{w}{r} \tag{4}$$

$$V_2(x) = B_1 x^{\beta_{21}} + B_2 x^{\beta_{22}} + \frac{x}{\delta + \lambda_1} - \frac{w + D}{r + \lambda_1} + \frac{-\lambda_1 A_1 ((1-\phi_1)x)^{\beta_{01}}}{-\lambda_1 + \lambda_0 - \lambda_0 (1-\phi_0)^{\beta_{01}}}. \tag{5}$$

Here, $V_0(x)$ defines the valuation function describing the market entry option in the inactive state. $V_1(x)$ and $V_2(x)$ are the valuation functions in the active state for the two cases $(1 - \phi_1)x > x_D$ and $x_D \geq (1 - \phi_1)x$, respectively. In $V_1(x)$, the first term represents the value of the exit option, whereas in $V_2(x)$, a complex interplay between the exit and the re-entry option is given (latter is ruled out via boundaries). Further, r denotes the riskless interest rate, $\delta = r - \alpha$ can be interpreted as convenience yield or dividend rate, and β_{mn} is the positive or negative root of the fundamental quadratics

$$\frac{1}{2}\sigma^2 \beta_0 (\beta_0 - 1) + (r - \delta)\beta_0 - (r + \lambda_0) + \lambda_0 (1 - \phi_0)^{\beta_0} = 0 \tag{6}$$

$$\frac{1}{2}\sigma^2 \beta_1 (\beta_1 - 1) + (r - \delta)\beta_1 - (r + \lambda_1) + \lambda_1 (1 - \phi_1)^{\beta_1} = 0 \tag{7}$$

$$\frac{1}{2}\sigma^2 \beta_2 (\beta_2 - 1) + (r - \delta)\beta_2 - (r + \lambda_1) = 0, \tag{8}$$

with $m \in \{0,1,2\}$ corresponding to the valuation functions and $n \in \{1,2\}$ indicating a root >1 or <0, respectively. A_1, A_2, B_1, and B_2 are the constants, which need to be determined simultaneously together with x_I and x_D by the boundaries given in Appendix A. Because no analytical solution can be found, we solve the complex 6×6 system of equations numerically to determine the four constants and two optimal thresholds for entry and exit.

2.2 | The R&D phase

In the R&D phase, we slightly modify the jump-diffusion process for the earnings[5]

$$dx_t = \alpha x_t dt + \sigma x_t dz_t - x_t dq_{R\&D}, \tag{9}$$

$$dq_{R\&D} = \begin{cases} 1 & \text{with Prob. } \lambda_{R\&D} dt \\ 0 & \text{with Prob. } 1 - \lambda_{R\&D} dt. \end{cases} \tag{10}$$

Compared with Equation 2, a jump immediately leads to abandonment of the project and can be interpreted as technical failure of the R&D.[6] In addition to this first state variable, the R&D budget K serves as a second state variable. Originating from an initial R&D budget $K_{t=0}$, the dynamics of K are captured by

$$dK_t = -k dt, \tag{11}$$

where $k > 0$ describes the capital spending rate. Since R&D requires time and typically permanent efforts such as wages or maintenance cost, we assume k to be positive and constant and therewith rule out the possibilities of (costlessly) suspending the R&D project temporarily or speeding it up by choosing a higher k during the R&D. Hence, the R&D phase takes a total time of $\frac{K_{t=0}}{k}$ to complete, provided that no technical failure has occurred by that time. As shown in Appendix A, the valuation function for the R&D project $F(x,K)$ has to satisfy the partial differential equation.

$$\frac{1}{2}\sigma^2 x^2 F_{xx} + (r - \delta) x F_x - (r + \lambda_{R\&D}) F - \max_k [k(F_K + 1)] = 0. \tag{12}$$

Because no analytical solution exists to this equation, we apply a Crank–Nicholson finite differences method with regard to the boundaries provided in Appendix A.

2.3 | Incremental versus radical innovation

It is common to differentiate between radical and incremental innovations (see, e.g., Ettlie, Bridges, & O'Keefe, 1984, or Dewar & Dutton, 1986). While radical innovation is often complex, requires great (financial) efforts, and is based on rather high R&D lead times, incremental innovation requires less of those critical factors.[7] However, associated therewith, the competition for being inactive in the market should be higher for an incremental innovation in contrast to a radical innovation. Hence, a further link between the initial cost, the length of the R&D phase, and the competition in the market phase is needed. First, to establish this relationship, we assume that the initial R&D budget $K_{t=0}$ is linked to the capital spending rate via

$$K_{t=0} = \tilde{K} + \nu \frac{1}{k}, \tag{13}$$

where $\nu \geq 0$ is a scaling factor and $\tilde{K} > 0$ is a basic R&D budget ruling out costless innovation by choosing k infinitely high. This equation ensures that choosing a high capital spending rate and pursuing a rather incremental innovation requires less initial R&D budget than pursuing a radical innovation by choosing a small capital spending rate. In other words, a radical innovation is more expensive than an incremental innovation (see, e.g., Ettlie et al., 1984). Second, we assume that the intensity of competition in the inactive state λ_0 depends on k as well.

$$\lambda_0 = \frac{1}{\sqrt{\eta \frac{K_{t=0}}{k}}}. \tag{14}$$

Here, $\eta > 0$ is a scaling parameter. The equation ensures that incremental innovation leads to a higher anticipated competition, because choosing a high capital spending rate decreases the gestation period $\frac{K_{t=0}}{k}$ for the R&D phase. On the contrary, since radical innovation is associated with a higher capital budget and, hence, with a lower capital spending rate k (see Equation 13), choosing a low k results in a longer gestation period $\frac{K_{t=0}}{k}$ and, hence, less anticipated competition. By choosing λ_1, as well as ϕ_0 and ϕ_1, exogenously,[8] different competitive environments can be set up (see also Trigeorgis, 1991). In general, we require functional forms for $K_{t=0}$ and λ_0 that fulfill $\frac{\partial K_{t=0}}{\partial k} < 0$ and $\frac{\partial \lambda_0}{\partial k} > 0$, respectively.

3 | NUMERICAL ANALYSIS

For the numerical analysis, we set the base case values to $r = 0.07$, $\delta = 0.03$, $\sigma = 0.1$, $\phi_0 = 0.1$, $\phi_1 = 0.1$, $\lambda_1 = 0.1$, $\lambda_{R\,\&\,D} = 0.1$, $w = 1$, $I = 1$, $D = 1$, $\tilde{K} = 1$, $\nu = 1$, and $\eta = 1$. The parameters r, δ, and σ are set going along with Sarkar and Zhang (2015) and corresponding real options literature.

The whole innovation process should be carried out in value maximizing fashion. Hence, a firm's management needs to choose an optimal initial capital spending rate k^* that, given a current state of earnings, an anticipated technical probability of failure and the expected market circumstances, maximizes the value of the complete innovation process. By choosing a certain k^*, the firm simultaneously chooses a value maximizing initial R&D budget $K^*_{t=0}$ and, hence, the direction towards incremental or rather radical innovation.

Figure 2 shows the value of the complete innovation process $F(x, K_{t=0})$ for an initially chosen k and a given current state of earnings x.[9] First, we observe for small levels of initial earnings x, i.e. weak future prospects, that $F(x, K_{t=0})$ is neglectably small. Hence, the R&D phase should not be initiated at all. As future prospects start to change for the better, we observe that the innovation process gains value and a maximum in $F(x, K_{t=0})$ emerges, which can be determined numerically as k^*. For lower x, this maximum is located around small k. Here, because small x corresponds to a small market that is further expected to be divided among competitors in the inactive and active state, the firm tends to accept a longer gestation period with a higher likeliness to fail in return for an expectation of lower competition after successfully finishing the R&D phase. Further, as the anticipated competition is lower with a longer gestation period, also the conditions for entering the market get less strict, i.e. x_l decreases. Hence, a small level of current earnings motivates rather radical innovation by increasing the gestation period and, given no technical failure has occurred, decreasing the anticipated application lag. Figure 2 further shows that k^* increases as the current state of earnings increases. This indicates that the firm accepts a higher expected competition in return for reducing the time for being "stuck" in the R&D phase and getting a faster access to its option to market. For high x, the anticipated volume of the market is sufficient for the firm to tolerate competitors. Hence, currently high anticipated earnings motivate for rather incremental innovation than radical innovation. Further, as $F(x, K_{t=0})$ strictly increases with k for sufficiently high x, it is optimal to initially choose k^* as high as possible.

3.1 | The impact of uncertainty

To study the impact of uncertainty expressed by parameter σ on the innovation speed, we start with investigating the impact of σ on the optimal initial capital spending rate k^* as introduced in Figure 2. To do so, we choose an initially observed level of earnings of $x_0 = 0.60653$[10] arbitrarily and find a corresponding value maximizing k^* with increasing σ. As Figure 3 indicates, the higher the uncertainty, the higher the firm is supposed to choose k^* to align its innovation process in a value maximizing fashion. This can be explained as follows: As higher

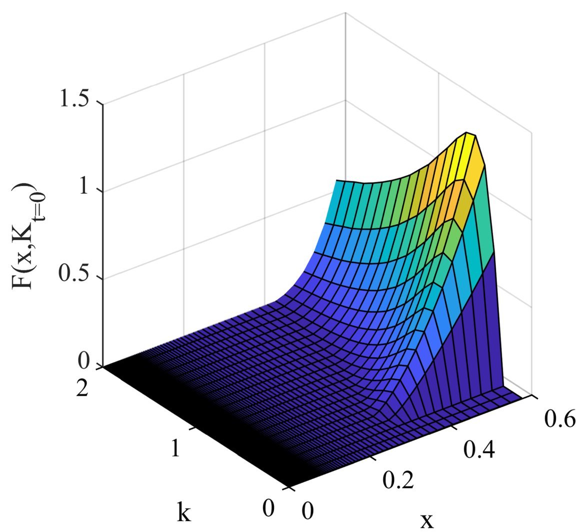

FIGURE 2 Value of the complete innovation process as a function of the earnings x and the capital installment rate k in $t = 0$ [Colour figure can be viewed at wileyonlinelibrary.com]

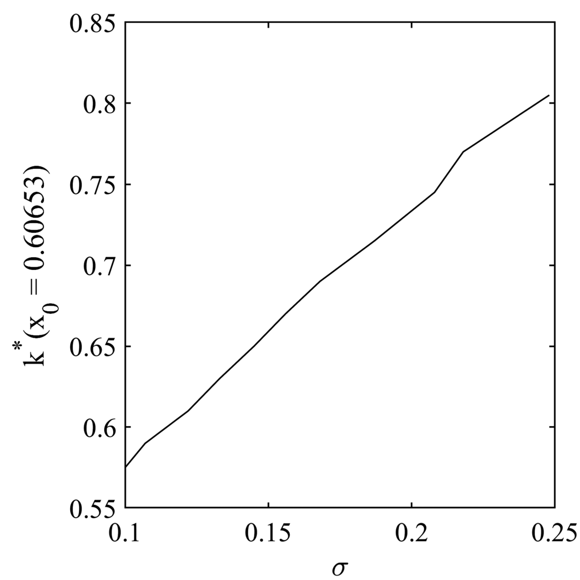

FIGURE 3 Optimal initial capital spending rate k^* for initially observed earnings $x_0 = 0.60653$ and increasing σ

uncertainty increases the potential for success, i.e. the upside potential, the downside potential is truncated by the options the firm holds, both the abandonment option during the gestation lag and the option to market during the application lag gain value. However, because there is no cash flow during the gestation period, the firm is incentivized to shorten the R&D stage in order to sooner enjoy the higher earnings potential as induced by σ. Consequently, the firm chooses a higher k^* to reduce the R&D duration and thereby stipulates to pursue incremental rather than radical innovations. This holds despite an accompanying increase in the anticipated competitive intensity λ_0 (see Equation 14). However, this raises the question whether the firm will more successfully finish R&D. To answer this, we have to take a closer look at the optimal exit threshold $x_{exit}(K)$. As Figure 4 reveals for a fixed level of σ, the threshold $x_{exit}(K)$ monotonically decreases with K. This indicates that the further the R&D progresses, i.e. the more from the original budget has already been spent, the stronger the willingness of the firm gets to keep the R&D alive and finish it. As uncertainty increases, the exit threshold will be further affected in the following way: Because increased uncertainty raises k^*, the firm opts for incremental innovation, which is associated with a lower overall budget further driving down $x_{exit}(K)$.[11] As a direct consequence, we can conclude that higher uncertainty not only shortens the gestation lag but also increases the chances of successful R&D.

In how far is the innovation speed affected by this? To answer this question, we have to take a closer look on how uncertainty drives the application lag as indicated by the sensitivity of the investment threshold on σ. Figure 5 shows that x_I monotonically increases as σ increases. This is a common result in the real options literature (see, e.g., Dixit & Pindyck, 1994, p. 155), i.e. higher uncertainty increases the value of waiting. Hence, higher earnings are required to pay for the entry cost I and for giving up the marketing option to get an active project in return. Hence, the application lag will increase as uncertainty increases. As we have defined innovation speed as the sum of both lags, the overall effect deserves special attention. To study the impact of uncertainty on innovation speed, Figure 6 maps the innovation speed for increasing σ. We calculated the mean innovation time as a proxy for the expected innovation speed by only considering the successful simulation paths within a Monte Carlo simulation, i.e. the paths that reached the market entry for a given level of uncertainty. Figure 6 indicates that a higher uncertainty reduces the expected innovation time and thereby increases innovation speed. Hence, the overall effect of uncertainty stands in contrast to the traditional real

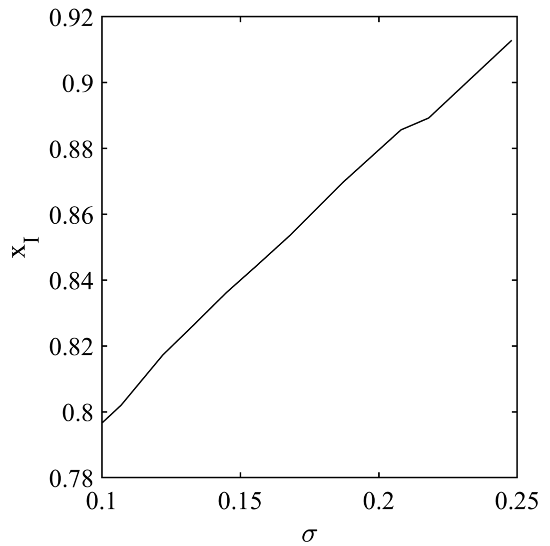

FIGURE 5 Optimal market entry threshold x_I for initially observed earnings x_0 = 0.60653 and increasing σ

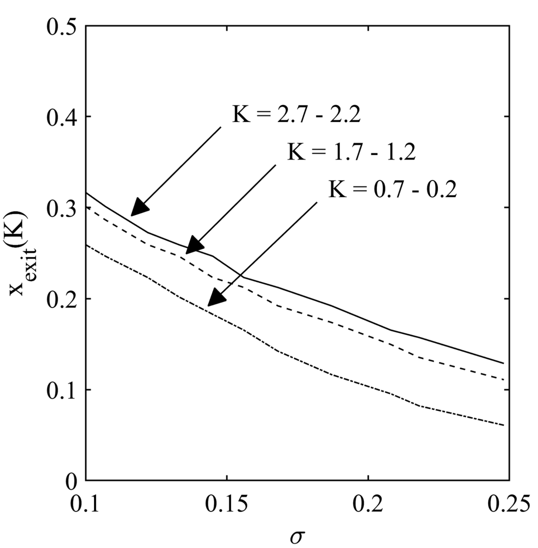

FIGURE 4 Optimal R&D exit threshold $x_{exit}(K)$ for initially observed earnings x_0 = 0.60653 and increasing σ for different remaining R&D budgets K starting from the solid line with $K_{t=0}(k^*) = 2.7$ at $\sigma = 0.1$ and $K_{t=0}(k^*) = 2.2$ at $\sigma = 0.25$ (see also Figure 3). Progress in the R&D phase decreases the remaining budget for a fix level of σ (dashed and dot-dashed lines)

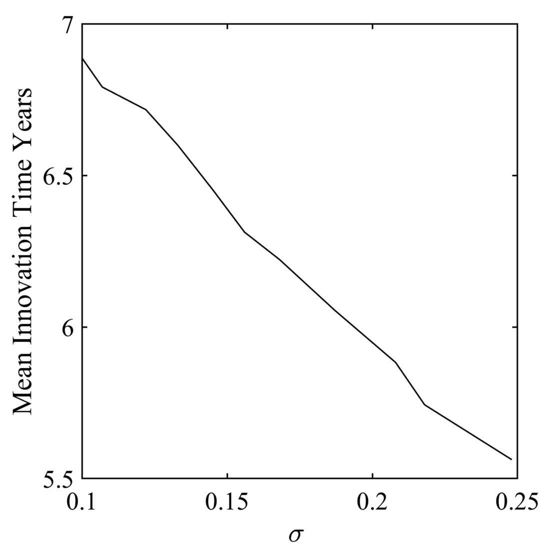

FIGURE 6 Mean innovation time (time elapsed between initiating the R&D phase and market entry) for initially observed earnings x_0 = 0.60653 and increasing σ

options logic, i.e. higher σ increases the propensity to delay investment.

To explain this effect, we consider Table 1 that shows the percentage share of the paths for the possible cases of R&D exit and failure as well as the cases that, after surviving the R&D phase, entered the market or failed to do so. Since x_0 is arbitrarily chosen sufficiently high, no R&D exit occurs during the R&D phase. Further, the percentage of failed innovations due to technical impossibility decreases as σ increases, because the firm aligns towards incremental innovation, chooses a high k^*, and spends less time in the R&D phase. However, spending less time on innovating increases the anticipated competitive intensity before marketing λ_0. This directly translates into a stronger competitive environment and less over all entries, which is further amplified given the monotonic increase of the investment threshold with uncertainty. Hence, uncertainty decreases the number of successful innovation commercialization but at the same time speeds them up. To conclude, we can hypothesize from our results that highly uncertain industries will see much more incremental driven R&D suffering from increased competition and less commercialization rates. On the contrary, less uncertain industries will see much more radical driven innovations with less competition that suffer from higher R&D abandonment rates.

3.2 | The impact of competition

To study the effect of the competitive environment on innovation speed, we now focus on the two anticipated loss parameters ϕ_0 and ϕ_1. As Figure 7 shows, an increasing competitive loss ϕ_0 during the application lag increases innovation speed. At a first glance, this seems counterintuitive as a higher ϕ_0 constitutes an even more competitive environment raising the question why the firm would speed up its innovation. Again, in order to be able to explain the overall effect, we first describe the impact of ϕ_0 on the gestation lag as well as on the application lag separately.

We start with the gestation lag. As k^* is decreasing and $x_{exit}(K)$ is increasing in ϕ_0, the gestation lag and the chance of abandonment during the gestation lag increase.[12] By choosing a lower k^*, the firm aligns towards radical innovation reducing λ_0. Hence, the firm reduces the probability of an anticipated loss, i.e. $\lambda_0 dt$, during the application lag especially for high ϕ_0. Further, because $x_{exit}(K)$ increases, the firm tightens the earnings requirements of its R&D projects, i.e. only the

TABLE 1 Monte Carlo results in percent for R&D exit, R&D failure, successful entry, and rest, for initially observed earnings x_0 = 0.60653 and different levels of σ

σ	0.1	0.15	0.2	0.25
Simulations	500,000			
Exit R&D	0	0	0	0
Tech. Fail.	23.84	22.45	20.72	19.99
Entry	49.57	46.68	44.69	43.75
Rest	26.59	30.87	34.59	36.26

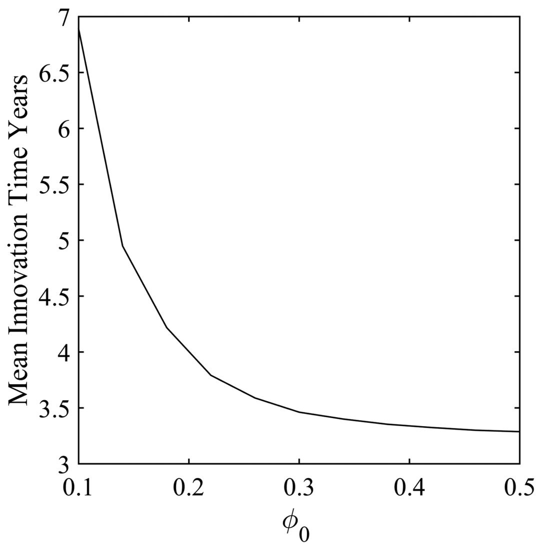

FIGURE 7 Mean innovation time for initially observed earnings x_0 = 0.60653 and increasing ϕ_0

most promising projects will be conducted. By doing so, the firm expects to protect itself from losing too much market share due to high ϕ_0 during the application lag. Hence, propagating through the gestation lag, ϕ_0 exerts a hampering effect on innovation speed.

Next, we focus on the application lag. Contrary to the gestation lag, the application lag shortens with increasing ϕ_0 because of decreasing x_I. This effect can be plausibly explained by a first mover advantage the firm expects to exploit. If ϕ_0 increases as compared with the fixed base case parameter ϕ_1, the firm can preempt the anticipated competition in the inactive state by simply being active. Hence, once the firm has managed to pass the gestation lag, it has a strong incentive to reduce the application lag in order to curtail bearing the strong competitive pressure as provoked by high ϕ_0.

We conclude: Large ϕ_0 has only a little effect when it is high compared with ϕ_1. The speed-hampering effect of the firm's hedging strategy during the gestation lag is offset by the first mover advantage opening up during the application lag. In consequence, the firm's innovation is sped up. However, when ϕ_0 is smaller than ϕ_1, the first mover advantage vanishes. For those cases, the mean innovation time increases as ϕ_0 or ϕ_1 increases. Therefore, the innovation speed is reduced by highly competitive environments.

4 | CONCLUSION

This paper develops a generic and tractable real option model that considers both the sequential nature of R&D-intense investment projects and multiple forms of uncertainty and impact factors related to Porter's five (market) forces. The generic model allows to analyze a firm's optimal investment policy that is comprised of optimal capital spending on R&D, optimal market entry, and exit timing.

The paper shows that innovation speed strongly depends on uncertainty. The higher the uncertainty, the higher the speed with which firms pursue the innovation process. However, high uncertainty also significantly reduces the number of innovations that end up being introduced to the market successfully. Hence, high uncertainty underlines the general opinion among business scholars and practitioners that "the faster the innovation is realized the better." However, the competitive environment in its different designs strongly impacts the innovation speed as well and should not be disregarded. We find that the commonly referred opinion about the advantageousness of fast innovations only holds if the firm possesses a sufficient (at least expected) first mover advantage. On the contrary, firms that do not posses or are not expected to gain such an advantage reduce their innovation speed and, hence, are better off pursuing a rather radical innovation.

Combining the results regarding uncertainty and competition, we can derive several managerial implications. If uncertainty is high (or even low) and the firm posses a more or less pronounced first mover advantage, the management should align their innovation management towards incremental innovations and therewith speed up innovation. However, if uncertainty is low and a firm does not posses a first mover advantage or is even expected to face strong competition in the active market, the management should reduce the innovation speed by aligning towards radical innovation. If uncertainty and competition are both high, we cannot recommend a clear direction towards advising the management how to align its innovation management. In such a situation, the effects of both uncertainty and competition can vanish, speed up innovation because of relatively strong uncertainty, or reduce innovation speed because of comparatively strong competition.

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DATA SHARING AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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ENDNOTES

[1] Please consider Appendix A for more technical details.

[2] We imply that the firm can observe the earnings at any point in time. Even if the firm is inactive, we require the firm to have at least an idea about the magnitude of earnings. Further, one can also think of including a product life cycle to the earnings such as Lukas, Spengler, Kupfer, and Kieckhäfer (2017).

[3] We only consider deterministic jumps with a negative impact on the earnings. However, also positive jumps are conceivable, for example, due to the existence of complementary innovation or the occurrence of positive externalities (see also Brandenburger & Nalebuff, 1995). In this paper, we neglect the possible positive effects to focus on the negative effective direction of the five forces as provided by Porter (1979).

[4] A possible re-entry to the market could easily be allowed as well. Respectively, consider the change in Boundaries A14 and A15 in Appendix A to $V_2(x_D) = V_0(x_D)\text{-}D$ and $V_2'(x_D) = V_0'(x_D)$. In this case, the firm would obtain an entry option in return for leaving the market.

[5] We assume the same α and σ as in the market phase but a different jump component. It is plausible that the anticipated competitive entry and loss from the market phase influence the earnings process in the R&D phase as well. Hence, multiple jumps could be included.

[6] Further, the technical failure can also be reinterpreted towards rival preemption as well. We thank an anonymous referee for pointing this out.

[7] A good example here is the smart phone market. Incrementally updating smart phones, for example, by updating cameras, capacity, and many other features year by year, should cost less and take less time than, for example, developing a (completely new) foldable smart phone.

[8] We acknowledge that other parameters of our model, for example, σ, α, or λ_1, can as well be seen dependent on the type of innovation, i.e. incremental or radical innovation. Exemplary, one could expect that incremental innovation further increases the anticipated competitive intensity in the active state λ_1, too.

[9] Because we derive a value maximizing k^* given a currently observed level of earnings $x = x_{t=0}$, we do not optimize the investment timing of the R&D phase but rather how to conduct the R&D optimally. Hence, the results are dependent on $x_{t=0}$.

[10] We use the transformation $P = log(x)$ to apply the Crank–Nicolson finite differences scheme. Hence, x_0 corresponds to $e^{P_0} = e^{-0.5} = 0.60653$.

[11] In addition, uncertainty also increases the option value of the abandonment option during the gestation lag. Hence, even if the earnings get worse compared with lower uncertainty, the firm would still continue incurring its R&D efforts.

[12] For the chosen set of parameters, higher ϕ_0 lead to a percentage increase of R&D exits. However, this only occurs with a very small magnitude. This is due to a slight increase in $x_{exit}(K)$ and a longer R&D phase due to decreasing k^*.

[13] We further assume a full profit distribution. For retained profits, an adjustment of the dividend rate $\delta = r - \alpha$ in the active state is needed.

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APPENDIX A: VALUATION FUNCTIONS FOR THE MARKET PHASE

A.1 | Inactive firm

If the firm is inactive, the valuation function is the solution to the basic Bellman equation in the region $0 \le x < x_I$

$$rV_0(x)dt = \mathbb{E}[dV_0], \tag{A1}$$

where

$$dV_0 = (V_0(x+dx-\phi_0 x) - V_0(x))\lambda_0 dt + (V_0(x+dx) - V_0(x))(1-\lambda_0 dt). \tag{A2}$$

Applying Itô's lemma leads to

$$\frac{1}{2}\sigma^2 x^2 V_0''(x) + (r-\delta)xV_0'(x) - rV_0(x) - \lambda_0(V_0(x) - V_0((1-\phi_0)x)) = 0. \tag{A3}$$

A.2 | Active firm

When the firm is active, the valuation function for the region $(1-\phi_1)x > x_D$ is the solution to the Bellman equation

$$rV_1(x)dt = (x-w)dt + \mathbb{E}[dV_1] \tag{A4}$$

with

$$dV_1 = (V_1(x+dx-\phi_1 x) - V_1(x))\lambda_1 dt + (V_1(x+dx) - V_1(x))(1-\lambda_1 dt). \tag{A5}$$

Applying Itô's lemma leads to an inhomogeneous ordinary differential equation[13]

$$\frac{1}{2}\sigma^2 x^2 V_1''(x) + (r-\delta)xV_1'(x) - rV_1(x) - \lambda_1(V_1(x) - V_1((1-\phi_1)x)) = -(x-w). \tag{A6}$$

When the firm is active, the valuation function for the region $x_D \ge (1-\phi_1)x$ is the solution to the Bellman equation

$$rV_2(x)dt = (x-w)dt + \mathbb{E}[dV_2] \tag{A7}$$

where

$$dV_2 = (V_0(x+dx-\phi_1 x) - D - V_2(x))\lambda_1 dt + (V_2(x+dx) - V_2(x))(1-\lambda_1 dt). \tag{A8}$$

Once again, applying Itô's lemma leads to

$$\begin{aligned}\frac{1}{2}\sigma^2 x^2 V_2''(x) + (r-\delta)xV_2'(x) - rV_2(x) - \lambda_1 V_2(x) = \\ -(x-w) + \lambda_1 D - \lambda_1 V_0((1-\phi_1)x).\end{aligned} \tag{A9}$$

A.3 | Boundaries

Counting together the unknowns in the inactive and active state leads to a total number of 6. To find those simultaneously, 3 value matching and 3 smooth pasting conditions are needed:

$$V_0(x_I) = V_j(x_I) - I \tag{A10}$$

$$V_0'(x_I) = V_j'(x_I) \tag{A11}$$

$$V_1\left(x = \frac{x_D}{1-\phi_1}\right) = V_2\left(x = \frac{x_D}{1-\phi_1}\right) \tag{A12}$$

$$V_1'\left(x = \frac{x_D}{1-\phi_1}\right) = V_2'\left(x = \frac{x_D}{1-\phi_1}\right) \tag{A13}$$

$$V_2(x_D) = 0 - D \tag{A14}$$

$$V_2'(x_D) = 0. \tag{A15}$$

Here, the index $j \in \{1,2\}$ denotes respectively whether the firm is still in the market or again out of the market when a jump occurs.

A.4 | Valuation function for R&D phase

The valuation function during the R&D phase is the solution to the Bellman equation and valid for $x_{exit}(K) < x$

$$rF(x,K)dt = \max_k[-kdt + \mathbb{E}[dF(x,K)]]. \tag{A16}$$

The dynamics of the R&D budget K are described as

$$dK = -kdt. \tag{A17}$$

Applying Itô's lemma leads to a partial differential equation

$$\frac{1}{2}\sigma^2 x^2 F_{xx} + (r-\delta)xF_x - (r+\lambda_{R\&D})F - \max_k[k(F_K+1)] = 0. \tag{A18}$$

To solve this partial differential equation the following boundaries are needed:

$$\lim_{x\to\infty} F(x,K) = F_{NPV} \tag{A19}$$

$$F(x_{exit},K) = 0 \tag{A20}$$

$$F_x(x_{exit}, K) = 0 \tag{A21}$$

$$\lim_{K \to \infty} F(x, K) = 0 \tag{A22}$$

$$x < x_I: \; F(x, 0) = V_0(x) \tag{A23}$$

$$x_I \leq x: \; F(x, 0) = V_j(x) - I. \tag{A24}$$

Here F_{NPV} is

$$F_{NPV} = E\left[e^{-rT(K)}\left(\frac{x_{T(K)}}{\delta + \lambda_1 \phi_1} - \frac{w}{r} - I\right) - \int_0^{T(K) \wedge T_{Jump}} e^{-rs} k ds\right], \tag{A25}$$

where $T(K) = \frac{K}{k}$ is the remaining time in the R&D phase and $x_{exit}(K)$ denotes the optimal state-dependent threshold for abandoning the R&D project.