New Product Development Flexibility in a Competitive Environment

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Managerial flexibility can have a significant impact on the value of new product development projects. We investigate how the market environment in which a firm operates influences the value and use of development flexibility. We characterize the market environment according to two dimensions, namely (i) its intensity, and (ii) its degree of innovation. We show that these two market characteristics can have a different effect on the value of flexibility. In particular, we show that more intense or innovative environments may increase or decrease the value of flexibility. For instance, we demonstrate that the option to defer a product launch is typically most valuable when there is little competition. We find, however, that under certain conditions defer options may be highly valuable in more competitive environments. We also consider the value associated with the flexibility to switch development strategies, from a focus on incremental innovations to more risky ground-breaking products. We find that such a switching option is most valuable when the market is characterized by incremental innovations and by relatively intense competition. Our insights can help firms understand how managerial flexibility should be explored, and how it might depend on the nature of the environment in which they operate.

Keywords: project management; OR in research and development; product development; dynamic programming

1. Introduction

Any new product development (NPD) project is susceptible to uncertainty regarding the success of its development. This uncertainty relates to the quality of the resulting product and to its commercial success, which is influenced by market conditions. An NPD firm should consider the evolution of both these uncertainties, i.e., its development success as well as the state of the market, when deciding how much to invest in the development, when to launch the product, or whether to abandon the development completely. Consider, for instance, Microsoft's announcement of postponing the launch of its Vista operating system for consumers in late 2005 (Lohr and Flynn 2006). It is likely that this decision, while being influenced by the success of its development effort, was also influenced by the fact that Microsoft did not face harsh competition in the operating system market. A delayed launch of Vista was less likely to have a negative impact on Microsoft's profitability. Similarly, consider Apple's decision to launch a compromised iPhone 4S rather than delaying the launch of the new iPhone until the iPhone 5 was fully functional, which was undoubtedly influenced by the highly intense smartphone market environment (Blodget 2011). In patent protected NPD environments such as pharmaceuticals, firms explicitly consider a set of future scenarios associated not only with their own technical success, but also with the commercial success and market conditions when evaluating their projects and related launch dates.

It is well known that managerial flexibility, also referred to as real options, can have a major impact on the value of NPD projects (Dixit and Pindyck 1994). Many have explored how this impact depends on the characteristics of the development process (Huchzermeier and Loch 2001, Wilhelm and Xu 2002, Santiago and Vakili 2005, Cui et al. 2011). What is not yet fully known, however, is how the value of flexibility in NPD is influenced by the competitive environment in which a firm operates. Some of the previous works (Canbolat et al. 2012, Chronopoulos et al. 2014) have employed game theoretical approaches to account for the competitive market environment when valuing NPD flexibilities. Whilst game theoretical approaches can be effective in dealing with duopoly markets with homogenous players, they may not be easily extendable for markets with several firms that are heterogeneous in their development capabilities, assets, and strategic development goals. In such markets, considering the competitive environment in aggregate, as a stochastically evolving process, can be useful. This is the approach that Clark (1985) proposes. There is limited research, however, that does so whilst focusing on investigating the valuation and optimal use of NPD flexibilities. Therefore, our main objectives for this study are to (i) develop modeling tools that allow accounting for, in aggregate, the stochastically evolving competitive market environment and (ii) derive insights about the value and optimal use of the development flexibilities under different competitive market environments. Thus, we aim to advance the practice and theory of successful NPD project management (Cooper and Kleinschmidt 1987).

To achieve the objectives of the study, we develop a stochastic dynamic programming framework for a single firm. We do this by expanding the model of Huchzermeier and Loch (2001) to incorporate the stochastic evolution of the competitive market environment. We are not aware of a similar approach being developed before or used in the investigation of the value of NPD flexibilities under competitive market environments. Our model accounts for (i) uncertainty in a firm's development success and in the competitive market environment via their stochastic processes, (ii) different market types, such as a winner-takes-all market where only the best performing product earns revenues and a shared market where also inferior products can earn some revenue, and (iii) several types of managerial flexibilities. Specifically, we consider the following types of flexibility: (i) abandon the development, (ii) enhance the development, (iii) defer the product launch, and (iv) switch the development strategy to pursue more radical innovation. In next few paragraphs, we review related studies that investigate the use and value of some of these options. For a broader review of the NPD literature, see Krishnan and Ulrich (2001).

In previous NPD literature, the use of abandonment option alone has been investigated by Hsu and Schwartz (2008). They examine the value created by an option to abandon a two-phased R&D project at the end of each development phase. Their model incorporates uncertainty in the duration of development, development cost, and quality of the R&D output. Brandão and Dyer (2011) expand this model by allowing the option to abandon to be exercised throughout the development phase. They show that opportunities to further expand the product once the development has been successful can significantly affect the project value and the optimal investment decisions. We add to this line of investigation by introducing an option to defer the launch of the product, which allows for additional product improvements during the delay. We explore how the viability of this option depends on the nature of the market in which the firm operates.

Miltersen and Schwartz (2004) show that competition in R&D shortens the development time and increases the probability of successful development. Their model highlights that for a monopolist, the value of the R&D investment is higher than the aggregate value of the R&D investment for both duopolists and that, on average, the time until the first project is completed is shorter. Souza et al. (2004) consider the impact of industry clockspeed, or the rate of declining prices of products, on the timing of the introduction of new products. Using an infinite-horizon Markov process, they show that it is optimal to introduce products more frequently under faster clockspeed conditions. Carillo (2005) defines the NPD clockspeed as the rate of introduction of new products, which is analogous to the competition's intensity we employ here. She analyzes optimal firm level NPD clockspeed and how it depends on whether the firm is the industry leader, operationally limited, or the industry optimizer. We add to the research on product introduction timing by showing how the timing depends also on the market's radicalness in innovation.

The performance and time-to-market tradeoff is also studied by several others. Cohen et al. (1996) use a two-stage optimization model and show that if competition is either very strong or very weak, delaying product launch is suboptimal. Armstrong and Lévesque (2002), Lévesque and Shephard (2002) employ dynamic programming to characterize the optimal market entry time. The former study considers uncertainties in funding availability, product development success, and the growth in the competition and the latter study considers uncertainties in the environmental volatility and market competition. They both show that optimal quality and time targets can be derived for product launch. Langerak and Hultink (2006) investigate empirically the impact of product innovativeness on the link between development speed and new product profitability. They show that the profitability is an inverted U-shape function of the development speed and that the optimal development time depends on the innovativeness of the product (or the ease by which it is adapted in a new market). Several others have also considered the relationship between development speed and NPD success, as an extensive review of Cankurtaran et al. (2013) shows. Our work advances knowledge in this area by providing thresholds on the firm's performance advantage for launching or abandoning developed products.

Previous studies have analyzed more subtle development flexibilities. For example, Cui et al. (2011) focus on the use and value of flexibility in adjusting the scope of product launch using a system dynamic model. They show that such flexibility is highly valuable when the product is new and faces high uncertainty regarding the prelaunch forecasts. Similarly, Pennings and Lint (2000) analyze the value of a phased roll-out of a new product to learn about the market before abandoning the product or launching it globally. They conclude that a phased roll-out is an effective strategy when the uncertainty of the product success is high. Carillo and Franza (2004) assess the linkage between investing in product development and production capabilities and characterize optimal policies for them. McCardle (1985) investigates, using a dynamic programming model, the value gained from acquiring more information about the profitability of a new technology and whether it is optimal to adopt or reject the technology. He shows that even if the NPD project manager behaves optimally occasionally unprofitable technologies are adopted and profitable ones rejected. Yassine et al. (2008) analyze using a dynamic programming model the development flexibility in deciding when to incorporate new information in product development. In our study, we investigate also a managerial flexibility that has gained little attention in previous research, namely the flexibility to switch a development strategy trading-off some probability of successful development for pursuing a more innovative product.

2. The Problem

2.1. The NPD Project

We view an NPD project as composed of three phases: (i) initial development, (ii) additional development, and (iii) market phases. The initial development phase corresponds to the time required to develop a complete product that can be launched. During this phase, the product *performance*, reflecting the expected desirability of the product, can improve or deteriorate, due to uncertainty in the development process (Lévárdy and Browning 2009). At each discrete time period, dictated by a phase-gate approach commonly used in NPD projects, the firm can decide whether to continue or abandon the development. A firm can also decide to enhance the development at a certain cost, to include new features or to integrate new innovative technologies, resulting in an increase in the expected product performance with the ultimate aim to maximize the expected net present value (eNPV) of the product. We assume that the duration of this phase is fixed, but that the resulting quality of the developed product is not.

Once the initial development is completed, the additional development phase begins. Within this phase, the firm can continue the development with or without enhancing the product, abandon the development, or launch the product. In this phase, however, the product's performance can no longer deteriorate, as it is always possible to disregard unsuccessful additional developments and launch the product as is. The duration of the additional development phase is not fixed, and terminates when a decision is made to launch the product, or to abandon the development altogether. Once the product is launched, the product's performance remains constant. We consider upgrades of products already in the market and new generations of existing products as new products, with comparable development processes.

2.2. The Market Environment

The product's success in the market depends not only on its performance, driven by the capability of the firm to develop a high-performing product, but also on the competitors' capability to develop competing products, which we view as the market conditions. We consider the market to comprise numerous competing firms. With numerous competing firms, it may not be possible to know the development capabilities of all firms, but instead firms can observe the rate at which new products are launched and the improvement in performance these products bring. Thus, in our setting, we consider competitors on aggregate. We introduce the concept of the *market's performance*, interpreted as the current state-of-the-art performance of the leading competing product

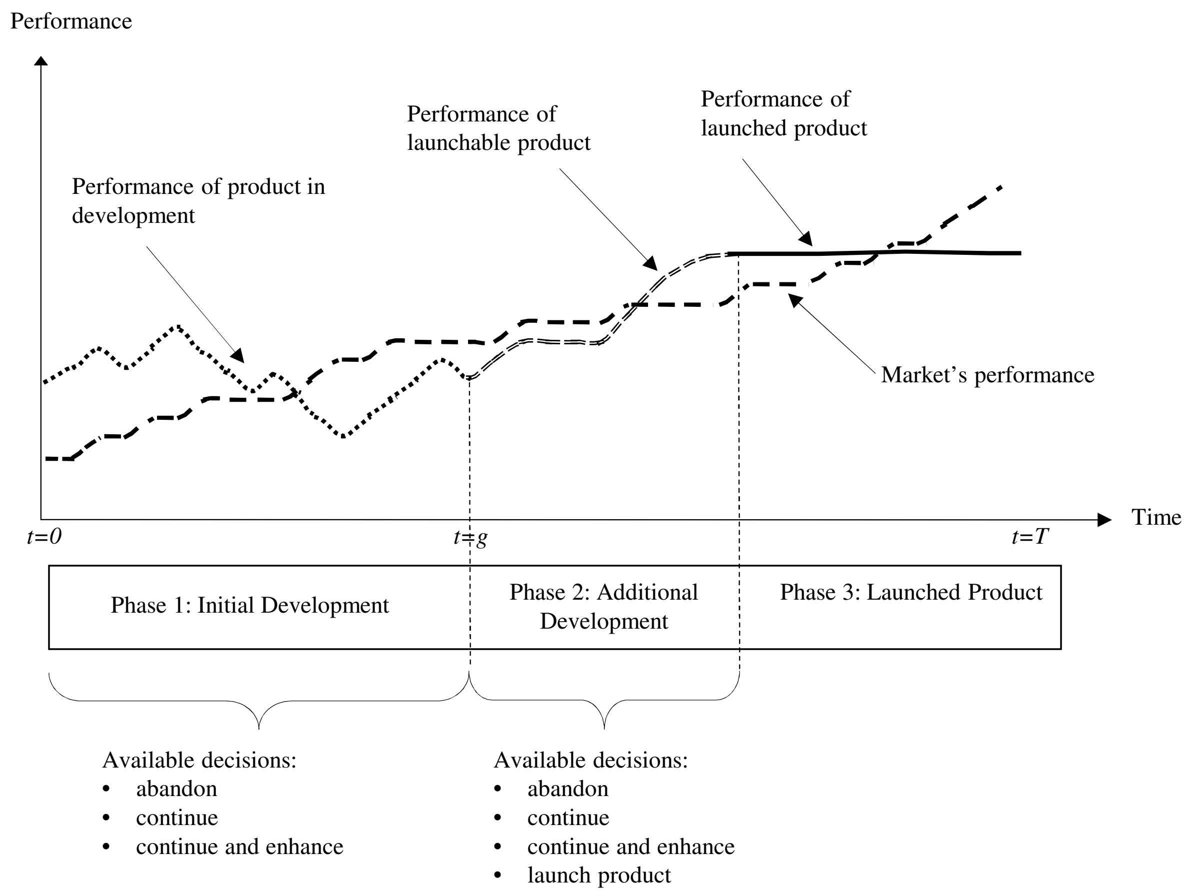


Figure 1 A multi-phase NPD project

on the market. The more a firm's new product's performance exceeds the market's performance, the higher the expected revenues will be. The expected revenues also depend on the market characteristics, represented by different revenue structures. For instance, in a winner-takes-all market, only the leading product on the market will enjoy positive revenues, while all others will receive zero revenues, whereas in a shared market inferior products can still capture some market share.

Over time, the market's performance evolves. However, it does not decrease, since it reflects the current leading competing product on the market. Figure 1 illustrates the timeline of an NPD project, the decisions available to the firm during each phase, and a possible evolution of the product's performance and the competition's performance over this timeframe.

The evolution of the competition that a firm encounters is driven by the intensity of the competitive environment and the degree to which new products in the market are innovative. *The* *intensity of the competitive market environment* that a firm experiences is the pace at which new improved products are introduced by the firm's competitors. This can be modeled as the probability of an improvement in the performance of competing products. When it is close to zero, this can be interpreted as a lack of innovation in this product market. When it is close to one, the competition's performance increases in almost every period due to the competitors continuously introducing improved products on market. *The market's degree of innovation* that a firm faces is the magnitude of a possible improvement that is expected in upcoming new product launches by competitors.

We will show that these two characteristics of the competitive market environment and the market type have a different impact on the value and use of flexibility in NPD. For instance, consider a firm developing a product that is currently outperforming any existing competing product on the market. The optimal strategy concerning whether or not to continue, enhance or abandon the development depends, among other things, on the firm's expectations concerning the competitors' development success. We will show that to be able to make this decision, the firm needs to know the magnitude of its current performance advantage relative to the competitors, how much the competitors are likely to improve the performance of their products, and how frequent those improvements are likely to be. Figure 2 represents a conceptual model of the investigated impacts.

Defining the market's competitive environment as a two-dimensional construct is consistent with the empirical findings of Lunn and Martin (1986), who found that two dimensions of competition are significant when predicting R&D expenditures. Boone (2008) also advocates the use of multi-dimensional competition factors, criticizing existing one-dimensional measures of competition as firms are likely to differ in more than one dimension and therefore it may no longer be possible to summarize their market position with a single scalar. Other definitions of competition intensity have been also proposed. De Figueiredo and Kyle (2006) define the intensity of competition as the number of competing products on the market. Boone (2001) defines the competition intensity based on the ease with which customers can switch between competing products. Our definition of the competition intensity differs from those in the literature, as (i) we view competition as a

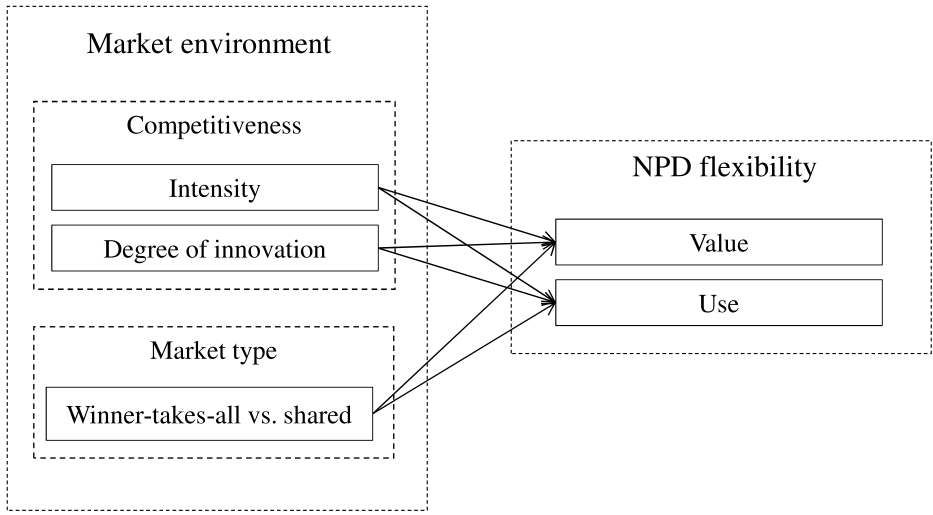


Figure 2 **A conceptual model for investigated impacts**

stochastic process, and (ii) we measure it from the perspective of a firm, which enables different firms to experience competitive pressures differently, e.g. depending on whether they are market leaders or not. Our definition for the market's degree of innovation, however, is consistent with the definitions in the literature. Manso (2011), for instance, defines an innovation activity to be radical when there is a high probability of failure, relative to the probability of failure of a more conventional innovation action. Naturally, the higher the desired performance improvement, the lower the likelihood of success. We will expand on this trade-off in Section 6, when we consider the flexibility of changing a firm's development strategy.

3. The Model

Let a_t denote the decision a firm makes regarding an NPD project at time, t, $t = 0, 1, ..., T$, where

$$a_t \in \begin{cases} \{0,1,2\} & 0 \leq t < g \\ \{0,1,2,3\} & g \leq t < T \\ \{2,3\} & t = T \end{cases}$$

in which $a_t = 0, 1$ or 2 denotes the decision to continue, enhance or abandon the development, respectively, $a_t = 3$ represents launching the product, available only during the additional development phase, which starts at time g, $0 < g \leq T$.

To capture the key properties of the NPD problem as discussed in previous section, we define the following parameters:

$\pi_t(a_{t-1})$	product performance at time t, $1 \le t \le T$,
	with π_0 the initial product performance at time $t=0$,
u	improvement in product performance during each period, $[t, t+1]$, $0 \le t < T$,
	with probability p,
d	deterioration in product performance during each period $[t, t+1]$, $0 \le t < g$,
	with probability $(1-p)$,
i	additional improvement in product performance during period $[t, t+1]$,
$n_t(a_t)$	development cost incurred at time t, $0 \le t < T$,
c_t	cost of continuing development at time t, $0 \le t < T$,
e_t	cost of enhancing development at time t, $0 \le t < T$, with $e_t > c_t$,
	$0 \le t < T$, if $a_t = 1$,
γ_t	market's performance, i.e., performance of the leading competing product on the
	market, at time t, $0 \le t \le T$,
v	increase in the market's performance during each period $[t, t+1]$,
	$0 \le t < T$, with probability q, and $(1-q)$ is the probability of market's
	performance remaining constant,
Δ_t	firm's performance advantage at time t, $\pi_t - \gamma_t$, $1 \le t < T$
	with $\Delta_0 = \pi_0 - \gamma_0$ being the firm's initial advantage, and
λ	discount rate.

Note that $\pi_0, \pi_t(a_{t-1}), \gamma_t \in \mathbb{R}$, $p, q \in (0,1)$ and all other parameters are defined in $\mathbb{R}^+$.

The product performance at time t depends on the previous level of performance $\pi_{t-1}(a_{t-2})$ and the decision a_{t-1} as follows:

$$\pi_t(a_{t-1}) = \begin{cases} \pi_0 + u & \text{with probability } p, & \text{if } a_0 = 0, & t = 1 \\ \pi_{t-1}(a_{t-2}) + u & \text{with probability } p, & \text{if } a_{t-1} = 0, & 1 < t \le T \\ \pi_0 - d & \text{with probability } (1-p), & \text{if } a_0 = 0, & t = 1 \\ \pi_{t-1}(a_{t-2}) - d & \text{with probability } (1-p), & \text{if } a_{t-1} = 0, & 1 < t \le g \\ \pi_{t-1}(a_{t-2}) & \text{with probability } (1-p), & \text{if } a_{t-1} = 0, & g+1 \le t \le T \\[1ex] \pi_0 + u + i & \text{with probability } p, & \text{if } a_0 = 1, & t = 1 \\ \pi_{t-1}(a_{t-2}) + u + i & \text{with probability } p, & \text{if } a_{t-1} = 1, & 1 < t \le T \\ \pi_0 - d + i & \text{with probability } (1-p), & \text{if } a_0 = 1, & t = 1 \\ \pi_{t-1}(a_{t-2}) - d + i & \text{with probability } (1-p), & \text{if } a_{t-1} = 1, & 1 < t \le g \\ \pi_{t-1}(a_{t-2}) + i & \text{with probability } (1-q), & \text{if } a_{t-1} = 1, & g+1 \le t \le T \\[1ex] 0 & & \text{if } a_{t-1} = 2, & 1 \le t \le T \\[1ex] \pi_{t-1}(a_{t-2}) & & \text{if } a_{t-1} = 3, & g+1 \le t \le T \end{cases} \tag{1}$$

The development cost at time t, $t = 0, 1, ..., T-1$, is:

$$n_t(a_t) = \begin{cases} c_t & \text{if } a_t = 0 \\ e_t & \text{if } a_t = 1 \\ 0 & \text{if } a_t \in \{2,3\} \end{cases} \tag{2}$$

The market's performance evolves as follows, $t = 1, ..., T$:

$$\gamma_t = \begin{cases} \gamma_{t-1} + v & \text{with probability } q \\ \gamma_{t-1} & \text{with probability } 1 - q \end{cases} \tag{3}$$

As in the problem description in Section 2.2, the evolution of the market's performance is characterized by two dimensions, namely the intensity of the competitive market environment and the market's degree of innovation. The first dimension reflects the pace at which new improved products are introduced by the firm's competitors. In our model, this corresponds to the probability of an improvement in the market's performance during each period, represented by the parameter q. The second dimension of the evolution of the market's performance is the magnitude of the improvement. In our model, this is represented by the parameter v. Therefore, we provide the following formal definitions.

Definition 1. The competitive intensity of the market environment is captured by q.

Definition 2. The market 's degree of innovation is captured by v.

The combination of the market environment's competitive intensity and degree of innovation will determine the market's overall competitive strength.

Definition 3. The competitive strength of the market is $s = qv$.

The payoff, obtained once a product is launched, depends on the product's performance and the market's performance at the time of launch and thereafter. We calculate the discounted total net revenue as follows:

$$\sigma_t(\Delta_t, a_t) = \begin{cases} 0 & \text{if } a_t \in \{0,1,2\}, \quad 0 \le t < T \quad \text{or } a_T = 2 \\ \sum_{j=t}^{T} \mathbb{E}[(1+\lambda)^{t-j} f(\Delta_j)] & \text{if } a_t = 3, \qquad g \le t \le T \end{cases} \tag{4}$$

$f(\Delta_t) : \mathbb{R} \to \mathbb{R}$ is a non-decreasing revenue function in Δ_t, the difference in performance between the firm's product and the leading product on the market. In order to capture the effect of performance on revenues, we model the revenue function as an s-curve. As in Huchzermeier and Loch (2001), such a revenue function is used to reflect the fact that the performance improvements have little

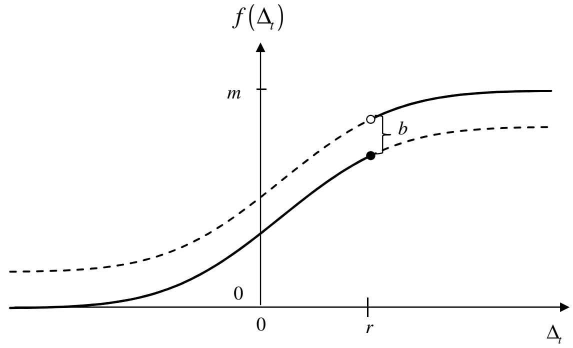


Figure 3 Revenue function (black solid line)

impact on revenues when the product's performance is either very low or very high compared to the market's performance, but small improvements to intermediate performance levels can have a major impact. Our model also allows capturing the effects of becoming a performance leader, which we present with a point of discontinuity at $\Delta_t = r$. At larger advantage levels, the product is perceived by the market as the dominant leader in product performance, resulting in further revenues due to either a premium price or an increase in demand. Figure 3 depicts such a revenue function by the black solid line, with:

$m \in \mathbb{R}^+$ is the maximum possible revenue level, i.e., when capturing the entire market,
$b \in \mathbb{R}^+$ the size of the jump in the revenue function, and
$r \in \mathbb{R}^+$ point of discontinuity.

The eNPV of an NPD project can be maximized using a stochastic dynamic program, solved with backward induction using the following recursive formula:

$$\begin{cases} P_t(\Delta_t) = max_{a_t \in \{0,1,2,3\}}\{-n_t(a_t) + \sigma_t(\Delta_t, a_t) + \\ \qquad (1+\lambda)^{-1}\mathbb{E}[P_{t+1}(\Delta_{t+1})|\Delta_t, a_t \in \{0,1\}]\} & t = 0, ..., T-1 \\ P_T(\Delta_T) = max_{a_T \in \{2,3\}}\{\sigma_T(\Delta_T, a_T)\}. \end{cases} \tag{5}$$

The following definitions will be used in Sections 5 and 6:

Definition 4. The eNPV of a project with all options Ω available is $P(\Omega)$, where $P(\Omega) = P_0(\Delta_0)$. The eNPV of a project without development options is $P(\emptyset)$, where $P(\emptyset) = P_0(\Delta_0)$ with $a_t = 0$, $0 \le t < g$ and $a_g = 3$. The eNPV of all options Ω is $V(\Omega) = P(\Omega) - P(\emptyset)$.

Definition 5. The launch and abandon thresholds are Δ_t^L, $t = g, ..., T$, and Δ_t^A, $t = 0, ..., T$, respectively such that $\Delta_t^L = L_t^{-1}(0)$ and $\Delta_t^A = A_t^{-1}(0)$, where

- $L_t(\Delta_t) = P_t(\Delta_t | a_t = 3) - P_t(\Delta_t | a_t \in \{0,1,2\})$ is the incremental value of launching at time $t = g, ..., T$, and
- $A_t(\Delta_t) = P_t(\Delta_t | a_t \in \{0,1,3\}) - P_t(\Delta_t | a_t = 2)$ is the incremental value of not abandoning at time $t = 0, ..., T$.

A launch threshold is defined as the firm's minimum performance advantage that will result in launching the product being the optimal strategy. Similarly, an abandon threshold is defined as the firm's minimum performance disadvantage that will result abandoning the product being the optimal strategy.

4. Market Environment and NPD Flexibility

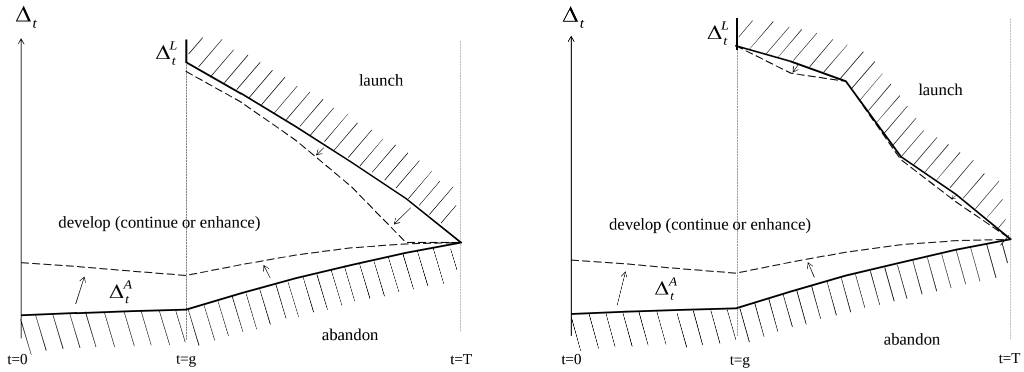
We can now explore how the market environment influences the use and value of a firm's NPD flexibility.

4.1. The Thresholds for Using Flexibility

To best allocate resources and prepare for project execution, NPD firms must consider the strategies they will adopt, which are also a function of the market conditions. Proposition 1 formalizes the monotonic increase and decrease in the abandon and launch thresholds, respectively, caused by an increase in the competition's intensity or the market's degree of innovation.

Proposition 1. *As the market's competitive intensity, q, or market's degree of innovation, v, increases then (i) the abandon threshold, Δ_t^A, $t = 0, ..., T$, increases monotonically and (ii) the launch threshold, Δ_t^L, $t = g, ..., T$, decreases monotonically.*

Proofs of all propositions can be found in Appendix. We illustrate Proposition 1 in Figure 4, which outlines the behavior of the launch and abandonment thresholds over time. The shift from the solid to the dashed line indicates the effect of a stronger competition, i.e., q or v is increased. Note that the abandonment threshold increases monotonically over time during the additional development period, under a non-decreasing cost structure. This means that abandonment becomes more and more likely, as the potential time on the market decreases (formally expressed in Proposition A.1, found in Appendix). This intuition, however, does not necessarily hold during the



4a 4b

Figure 4 The impact of an increase in competition's intensity on the abandon and launch threshold levels (a) $b = 0$ **and (b)** $b > 0$

initial development period. When faced by strong competitors that are expected to catch up or pull further ahead, the abandoning threshold might decrease as the time remaining until possible launch decreases. This makes sense as abandoning might be wise earlier on in the development, when it is clear that there is a high chance that the competition will have time to surpass the firm's performance, but not necessarily the optimal course of action later in the development (formally expressed in Proposition A.3 in Appendix). The launch threshold, on the other hand, decreases monotonically over time under a non-decreasing cost structure. This means that launching a product becomes more and more likely as additional development is carried out, as is expected (see Proposition A.2 in Appendix). When the competition is stronger, illustrated by the shift from the solid to the dashed lines, the region representing further development becomes smaller. For products that end up between the solid and dashed lines, it is then optimal to abandon or launch them. Consequently, due to competitive pressures, products might be launched even if they still have some minor shortcomings.

Figure 4a and 4b illustrate that when $b = 0$ (in Figure 4a), the launch threshold can be lower than when $b > 0$ (in Figure 4b). This is because when $b > 0$ there are benefits to invest in further development to produce a product that the market perceives as the performance leader. Also, these figures show that the launch threshold is less sensitive to the increase in the competition's strength when $b>0$, as illustrated by the smaller gap between the solid and dashed lines. The reason for this is that the additional revenue, obtained due to developing a product that is perceived as the performance leader, compensates for the additional development effort.

4.2. The Value of Development Flexibility

Consider for instance, a two-period example with the parameters as detailed in Table 1. The parameters are selected, such that the example is as simple as possible to still illustrate the key results discussed in this section. In this setting, a firm has the option to abandon the development, defer the launch by one period, or enhance the development. Also, we simplify the launch phase by assuming a fixed lump sum revenue is received upon launch. We model this with the following piecewise-linear market revenue function (seen in Figure 5):

$$f(\Delta_t) = \begin{cases} min\left\{\left[\frac{(\Delta_t - \underline{\Delta})}{\overline{\Delta}-\underline{\Delta}}\right]^+, 1\right\}(m-b) & \text{if } \Delta_t \leq r \\ min\left\{\left[\frac{(\Delta_t - \underline{\Delta})}{\overline{\Delta}-\underline{\Delta}}\right]^+, 1\right\}(m-b)+b & \text{if } \Delta_t > r \end{cases} \tag{6}$$

where $\underline{\Delta} \leq \overline{\Delta}$. Here, $\underline{\Delta}$ is the minimum difference in performance levels, below which no one purchases the firm's product and $\overline{\Delta}$ is the maximum difference in performance levels, above which maximum revenues are limited to m, due to the decreasing willingness to pay (Adner and Levinthal 2001). When a firm's performance advantage is between $\underline{\Delta}$ and r, the market rewards better performing products with linearly increasing revenues until the firm's performance advantage reaches a point r above which the product is perceived by the market as the dominant leader, resulting in a stepwise increment in revenues due to either a premium price or an increase in demand. A performance advantage beyond point r results in a linear increase in revenues until the maximum difference in performance levels that rewards further revenues $\overline{\Delta}$ is reached. When $b \to m$, $r=0$, and $\underline{\Delta} = \overline{\Delta} = 0$, the setting resembles an extreme case of a winner-takes-all market.

Figure 6 depicts the project value without options $P(\emptyset)$, the project value with options $P(\Omega)$, and the options value $V(\Omega)$ as a function of either q (competition intensity) when $v=0.7$ or v (market's degree of innovation) when $q=0.6$. The optimal decisions at time $t=0,1$ are shown at the bottom of the figure. For example, at $t=0$, we observe that if the competition's intensity is

Table 1 Parameters in the two-period example

Parameter	Value	Parameter	Value
g, p, $\overline{\Delta}$	1	u	0.5
$\underline{\Delta}$, π_0, γ_0	0	i	0.4
c_t, t=0,1	4	m	20
e_t, t=0,1	7	λ	0
r	0.3	b	8

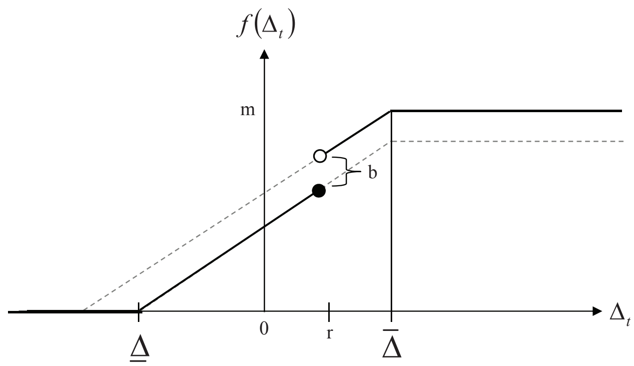


Figure 5 Piecewise-linear revenue function

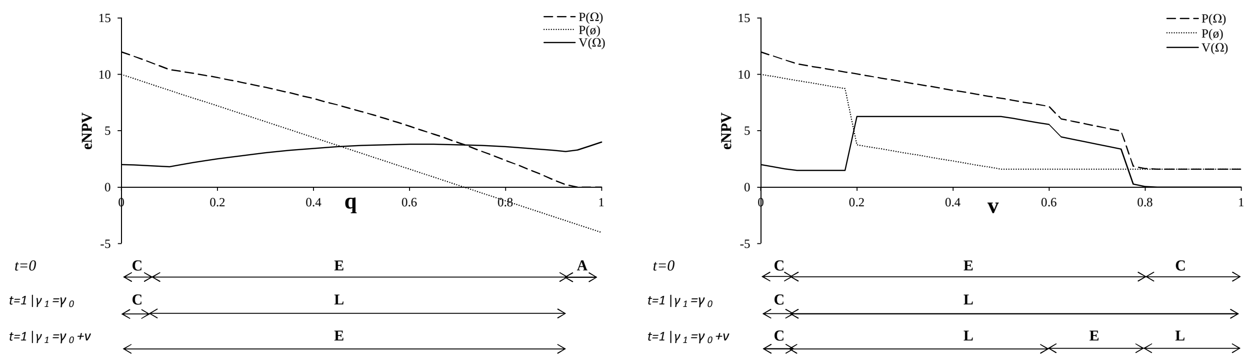


Figure 6 Project and option value as a function of the competition's intensity (left) keeping the market's degree of innovation constant (v=0.7) and the competition's degree of innovation (right) keeping intensity constant (q=0.6) and optimal decisions (C = continue, E = enhance, L = launch, and A = abandon)

low the optimal course of action is to continue (C) the project as is. As the competition becomes more intense, then enhancing (E) the development prevents the competition from catching up, or getting further ahead. Under highly intense competition, abandoning (A) the development is optimal. Similarly, we can observe the optimal development decisions at $t = 1$ when the market's performance did not improve, i.e., $\gamma_1 = \gamma_0$, or improved, i.e., $\gamma_1 = \gamma_0 + v$, during the previous period.

Whereas $P(\emptyset)$ and $P(\Omega)$ always decrease monotonically as a function of q and v (see Lemma A.2 in Appendix), this is not necessarily the case for the value of the options themselves, as shown in Proposition 2. This result formalizes the impact of market conditions on the value of flexibility, i.e., on the eNPV of the set of development options.

Proposition 2. *The eNPV of development options, $V(\Omega)$, is not a monotonic function of either market's competitive intensity, q, or the market's degree of innovation, v.*

Figure 6 illustrates Proposition 2. Clearly, $V(\Omega)$ is not necessarily a monotonic function of q and v. This indicates that the impact of the market environment on the value of managerial flexibility can be complex and needs to be taken into account when managerial flexibilities are valued.

We also find that the non-monotonicity of $V(\Omega)$ w.r.t. q and v does not always behave as one might expect. For instance, as seen in Figure 6, even when the project without options is firmly in or out of the money (corresponding to low and high values of q and v, respectively), flexibility still plays a role and has at times even higher value than when the project without options is at the money ($P(\emptyset)=0$).

4.3. The Use of Development Flexibility

In Section 4.2 we showed that the characteristics of the market a firm faces impact the value it can gain from flexibility in its NPD projects and that this change in value is accompanied by a change in the optimal development policy. To gain further insight, we conducted a full numerical exploration and examined the firm's optimal strategies over a wide set of parameters. Table 2 provides details of the explored settings. In these examples, the development horizon consists of three periods, and we allow launched products to earn revenues for up to twenty periods, during which γ_t evolves according to (3). Figure 7 represents the likelihood of the development options being exercised in the optimal NPD strategy as a function of v and q. The darker areas represent a higher probability of the option being exercised. Bold values in Table 2 specify the values of the case for which Figure 7 was generated. We have chosen the setting and parameters employed in

Table 2 Parameters in three-period factorial experiment

Parameter	Value	Parameter	Value
$\pi_0 - \gamma_0$	$\{0,\mathbf{1}\}$	λ	$\{0.05,\mathbf{0.1}\}$
u, d	$\{\mathbf{0.5},4,8\}$	g	**2**
i	$\{\mathbf{0.5},2,4\}$	c_t, t=0,1,2	**13**, **50**, **5**
m	$\{25,\mathbf{100}\}$	e_t, t=0,1,2	**39**, **150**, **30**
p	$\{0.5,\mathbf{0.8}\}$		

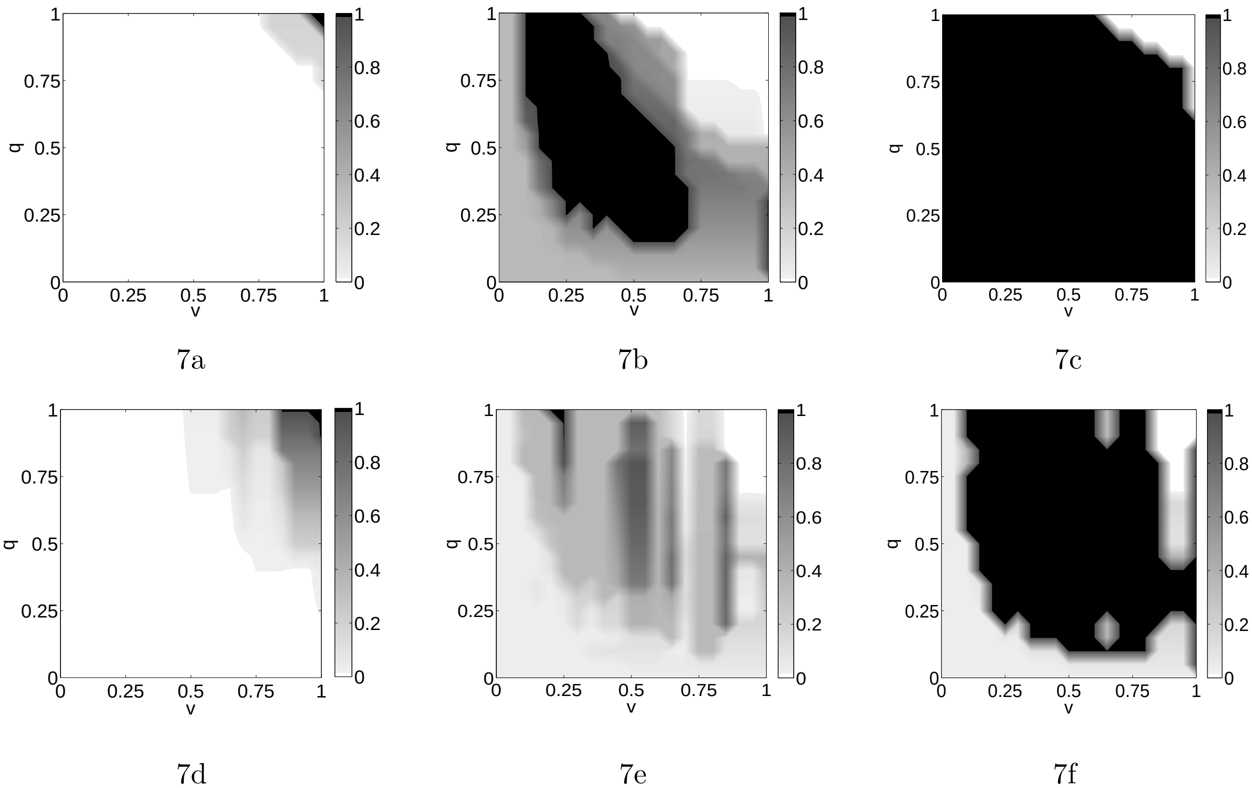


Figure 7 Probability of abandoning the product (a,d), delaying the launch (b,e), enhancing the development (c,f) at least once according to the optimal policy in a shared market (a,b,c: $\overline{\Delta}=3$, $\underline{\Delta}=-3$, r=1.5, b=25) and a winner-takes-all market (d,e,f: $\overline{\Delta}=\underline{\Delta}=0$, r=0, b=m)

Figure 7 such that they still allow us to demonstrate all the key results from one set of figures. Similar six-period experiments confirmed the qualitative results discussed here.

Figure 7 illustrates that (i) the decision whether or not to exercise each of the options depends on the market's competitive intensity and the market's degree of innovation and (ii) the use of the options is not symmetric in v and q. For example in Figure 7b, if $q=0.5$ and $v=0.1$ any increase in q will not have an impact on the probability of using the option to defer a product launch whilst a minor increase in v will result in a 100% probability of delaying the product launch.

From the patterns observed in Figure 7, it seems the options interact in specific ways. The darker area in Figures 7a and 7d (top right corner) corresponds to the lighter areas in Figures 7b and 7c and 7e and 7f respectively, indicating that abandonment serves as a substitute to the enhance and delay options, which in turn complement each other. Delaying a product launch provides an opportunity to improve an inferior product, which is useful when the competition's strength is not very high, allowing for the firm to catch up. Figures 7b and 7e illustrate this.

Figure 7b shows that even if the firm's development strategy is incremental compared to the market environment, i.e., $0.5 = u < v$, and competition is weak, i.e., competition's strength is less than that of the firm ($vq < up = 0.4$), it may still be optimal to delay the product launch to try to improve the product's performance. This is the case in Figure 7b and 7e when $v = 0.6$ and $q = 0.5$, for example. Intuitively, a firm with an incremental development strategy facing weak competition can benefit from delaying the launch and pursuing a greater advantage in performance and thus an increase in revenues. However, delaying is seldom useful when the strength of competition is very low, e.g. when $s = 0$ and if the product's performance is initially significantly higher than the market's performance, $\Delta_0 > \overline{\Delta}$. This is the case in Figure 7e when $q = 0$ or $v = 0$ because $\Delta_0 = 1 > 0 = \overline{\Delta}$. If the competition strength is increased from low to medium, delaying becomes more beneficial. Interestingly, this indicates that an increase in competition can in some circumstances actually result in a delayed product launch, adding to the results of Miltersen and Schwartz (2004).

5. Switching Development Strategies

In previous sections, we assumed that the firm's success probability p and the performance increment u remained constant throughout the development. In this section, we extend our analysis to consider the case in which a firm can switch its development strategy during the development to pursue a more or less radical development strategy, depending on the development progress of the firm and the state of the market.

To model this, we redefine the firm's success probability and the performance increments as decision variables in each time period, i.e., $p_t \in (0,1)$ $u_t \geq 0$, at time $t = 0, ..., T$. To capture the inherent trade-off that exists between the improvement in performance created by a radical development strategy and its associated success probability, we define a firm's development capability, $\kappa = p_t u_t$. We assume that a firm's development capability remains the same throughout the development, which can be due to financial resource constraints (Gibbert et al. 2014), for example. Therefore, a decision to pursue a more radical development strategy comes at a price in terms of a reduced probability of success (Manso 2011). In other words, the firm can choose to trade-off some of its success probability p_t in order to increase its performance increment size u_t and vice-versa. We refer to exercising such a trade-off and changing the development strategy as exercising a *switch option*.

To analyze the value of being able to switch the development strategy, we consider a two-period setting consisting of an initial development phase. We focus here purely on the value of the switch option and thus consider it without the other managerial flexibilities. We maintain the relative strength of the competition that the firm faces the same by keeping firm's capabilities equal to the strength of the competition, i.e., $\kappa = s$, and setting the firm's initial development level on par with the leading competing product on the market, i.e., $\Delta_0 = 0$. For simplification, we set the deterioration in performance during the development if the firm fails to be zero, i.e., $d = 0$ and the discount rate and development costs to zero. Including a non-zero deterioration, discount rate, and development costs, does not change the overall pattern we derive for the optimal development strategies and value of flexibility. We focus on a winner-takes-all market, i.e., $b = m/2$, $r \to 0^+$, and $\underline{\Delta} = \overline{\Delta} = 0$ and analyze the effects of the competitive environment on the optimal use and value of the option to switch development strategies. The former is formalized in Proposition 3 and the latter in Proposition 4.

Proposition 3. *At $t = 0$, the optimal performance increment u_0^*, which defines the development strategy, decreases as the intensity of competition increases from 0 to 0.5, then increases as q*

increases from 0.5 to q_1, remains constant for $q_1 < q \leq q_2$, and decreases for $q_2 < q < 1$. At $t = 1$, u_1^* is non-increasing in Δ_1, except for $\Delta_1 = 0$ and $\sqrt{2} - 1 < q \leq 0.5$, when it increases in a singularity.

The optimal development strategies, u_0^*, u_1^*, are reported in Table 3 and q_1 and q_2 are given in the proof of Proposition 3 in Appendix.

Proposition 3 says that when the market's competitive intensity is relatively low (few new products are launched), it is optimal for a firm to become less radical as the market's competitive intensity increases. However, as q reaches 0.5, i.e., when new product launches become more frequent (in each period, a new launch is more likely than not), it is optimal for a firm to become more radical with an increase in competition's intensity. When the intensity increases further and reaches a specific threshold (q_1), it is optimal for the firm to maintain and then (beyond q_2) reduce its radicalness. In the second period, the strategy depends on the relative position of the firm vis-à-vis the market (Δ_1). As Δ_1 is higher, it is optimal for a firm to choose more and more incremental development strategy, with a sudden increase in optimal radicalness when a firm's product and its competition are exactly aligned in terms of performance ($\Delta_1 = 0$) and competition's intensity is low.

Table 3 Optimal development strategies u_0^* and u_1^* depending on q and Δ_1 (the darker the background the more radical the optimal development strategy

Intensity of competitive environment	$q \leq \sqrt{2} - 1$	Far behind $\Delta_1 \leq -vq$ $\Delta_1 < v - v/q$	Behind $\Delta_1 \leq -vq$ $\Delta_1 \geq v - v/q$	Little behind $\Delta_1 < 0$ $\Delta_1 > -vq$	Matched $\Delta_1 = 0$	Little ahead $\Delta_1 > 0$ $\Delta_1 < v - vq$	Ahead $0 < \Delta_1 < v$ $\Delta_1 \geq v - vq$	Uncatchable $\Delta_1 \geq v$
Extremely low $q \to 0^+$	0^+				0^+			
Very low $q \leq \sqrt{2} - 1$	$(v - vq)^+$		v^+	$(vq)^+$	$(vq)^+$		$(vq)^+$	
Low $\sqrt{2} - 1 < q \leq 0.5$	$(v - vq)^+$		v^+	$(vq)^+$	v^+		$(vq)^+$	
Medium $0.5 < q \leq q_1$	$(vq)^+$			$(vq)^+$			$(vq)^+$	
High $q_1 < q \leq q_2$	v^+	$(2v)^+$			v^+	v^+		$(vq)^+$
Very High $q > q_2$	$(2v - vq)^+$	$(2v)^+$			v^+		$(vq)^+$	$(vq)^+$
Extremely High $q \to 1^-$	v^+				v^+			
	$u_0^* =$	$u_1^* =$						

Proposition 3 and Table 3 show that the initial development strategy should be adjusted at $t = 1$

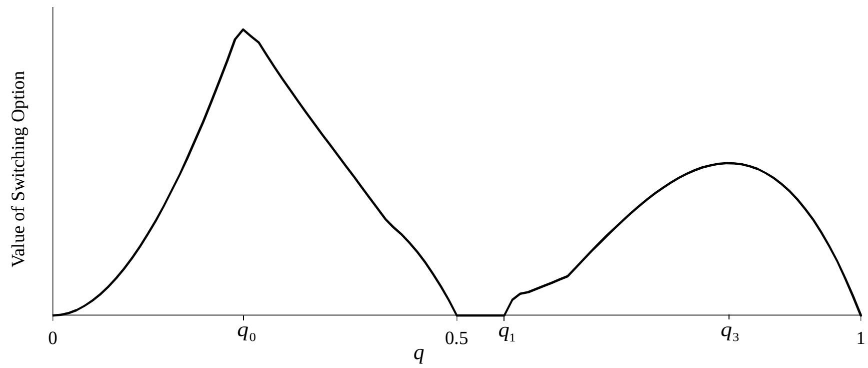


Figure 8 **The impact of intensity of competitive environment on the value of flexibility in switching development strategy,** $\kappa = s$

depending on Δ_1, v, and q. Sticking to the initial development strategy at $t = 1$ is optimal only when there is no uncertainty in the competitors' development outcomes, i.e., when $q \to 0$ or $q \to 1$, or when $0.5 < q \leq q_1$, i.e., when uncertainty regarding the success of the competition is highest. The former is intuitive (if there is no uncertainty, switching strategies is not required), but the latter is not, as one would think that if uncertainty regarding possible competing products is high, switching strategies would be very valuable. It turns out, however, that the optimal development strategy $u_0^* \to (vq)^+$ in this setting is robust with respect to the development outcomes of the competition. When uncertainty regarding the competition is high, a strategy chosen in period 0 needs to be robust, and therefore switching is not valuable. But when uncertainty decreases, a firm can take a risk on the expected outcome, making switching a valuable option in case the firm ends up lagging behind or leading its competitors. Therefore, we find that switching strategies becomes valuable when uncertainty is medium.

The behavior of the value of switching development strategies from incremental to radical and vice-versa is formalized in Proposition 4, with thresholds q_0, q_1, and q_3 defined in Appendix.

Proposition 4. *The value of flexibility in switching development strategies increases with the market's competitive intensity for* $0 < q \leq q_0$*, decreases for* $q_0 < q \leq 0.5$*, is constant for* $0.5 < q \leq q_1$*, increases for* $q_1 < q \leq q_3$*, and decreases for* $q_3 < q < 1$*.*

Proposition 4, which is illustrated in Figure 8, confirms that there is no value to have the

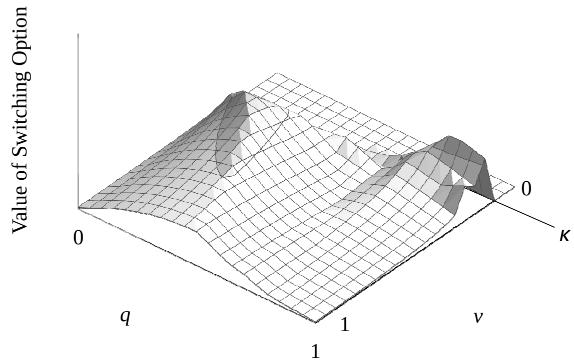


Figure 9 The impact of competitive environment on the value of flexibility in switching development strategy, $\kappa = 0.1$

flexibility to switch in the region $0.5 < q \leq q_1$ and when $q \to 0^+, 1^-$. Also, it shows that the flexibility to switch is most valuable at q_0 (exact value is computed in the Proof of Proposition 4).

Figure 9 shows that when the firm's capability is no longer equal with the competition, but instead is a constant $\kappa = 0.1$, both dimensions of the market have an influence on the value of switching option. On the one hand, a switch option is the most valuable when the market's competitive intensity is relatively low or high. On the other hand, the value of switching option is (i) zero if $\kappa > v$ because then the firm can beat competitors by playing safe and choosing $u_0^* = u_1^* \to \kappa^+$, $p_0^* = p_1^* \to 1^-$ and (ii) approaches zero when $v \to \infty$ as the firm has to trade off its performance increment to deterioration in success probability. Switching option is most valuable in relatively low or high levels of market's competitive intensity q given that the market's degree of innovation v is low, such that the firm can effectively react to the initial period development outcomes.

6. Conclusions

In this work, we have developed modeling tools to characterize the market environment a firm faces. We have used these tools to provide insights on how the value and use of development flexibility is impacted by different market environments. We have characterized the market environments using two dimensions, namely the market's competitive intensity and the market's degree of innovation. We have showed that the value of development flexibility is non-monotonic and non-symmetric in the defined market environment dimensions. This implies for NPD managers that modeling both of these dimensions is of importance as otherwise the development strategies may be suboptimal. Therefore, the developed NPD valuation framework can help in planning the types of flexibility that the market conditions require. This alleviates the need to make unplanned allocation of resources, which typically results in lower performance (Repenning 2001).

Our contributions beyond the existing literature are threefold. First, we have derived boundaries when managerial flexibility to delay or abandon product development are optimal to be executed and how they depend on the competitive market environment. This expands the results of Armstrong and Lévesque (2002) by (i) relating the launch threshold to the performance advantage instead of an absolute performance level accounting hence for the stochastic evolution in the competitors' performance and (ii) providing the performance advantage threshold for the abandonment option. Furthermore, we have showed that an increase in the market's competitiveness results in that the optimal course of an action becomes launching or abandoning the product earlier. This explains why in more competitive markets products may be optimal to launch even if they still have some shortcomings. Also, this implies for an NPD project manager that the development decisions should be assessed more frequently in more competitive markets as it is more likely that one of these threshold boundaries is reached. More generally, highly competitive markets require active project management whilst in less competitive markets a passive project management can suffice.

Second, we have provided managerial insights when to use development flexibilities depending on market environments. Our results confirm that the abandonment option is highly beneficial when the competition on the market is intense and even more so in a winner-takes-all market. Also, we have demonstrated that the option to defer a product launch and enhance development are typically valuable when the competition is weak, as the potential for increased profits due to producing a better-performing product makes up for the lost revenues due to the additional cost of delaying or enhancing. Under certain conditions, however, we showed that defer options can actually be valuable in more competitive environments. This is a surprising result, as a highly competitive environment typically incentivizes firms to try and accelerate their product launches

(Miltersen and Schwartz 2004). We have showed this in a setting that relates revenues to time-on-market and to the relative performance of the launched product. These results advance the investigation of the potential uses and misuses of flexibility in firms (Reuer and Tong 2007).

Third, our study provides understanding for NPD managers about the value gained by having the flexibility to switch development strategies, between more certain and incremental innovations to more risky and ground-breaking ones, and vice-versa. We found that such a switch option is not very valuable when there is either no uncertainty or a high degree of uncertainty as to whether many new competing products will be launched. Instead, we showed that switching offers the most value in a competitive environment with some uncertainty regarding upcoming competing product launches, corresponding to relatively low or high levels of competition intensity and when the competitive environment is characterized by incremental innovation. In such an environment, an NPD manager can effectively react to changes in the state of the market and benefit from the flexibility of changing the development strategy. These results are useful for academic community and practice by providing initial understanding of the optimal use of such flexibility.

Our two-dimensional market characterization and the project valuation framework is useful as it is flexible enough to be extended, for instance, to include multiple product generations, where cannibalization effects can be investigated. Further research could also investigate different cost structures, correlation and mean reversion in product performance and performance of competitors' products, technology jumps, and complicated development option structures and their effects on the value of flexibility.

Acknowledgments

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Appendix

The first section contains proofs for all propositions that appear in the body of the paper. The second section includes auxiliary definitions, lemmas, propositions, and their proofs. Particularly, Definition A.1, Lemmas A.1-A.4 are used in the proof of Proposition 1, Propositions A.1-A.3 are referred to when describing the shapes of abandon and launch thresholds in Section 4.1.

Proofs for Main Results

Proof of Proposition 1. As there exist unique abandon and launch thresholds (Lemma A.3), an increase in q or v results in a monotonic decrease in project value $P_t'(\Delta_t) \leq P_t(\Delta_t)$, $t = 0, ..., T$ (Lemma A.2). Furthermore from Lemma A.4, a monotonic decrease in project value results in a monotonic increase in the abandon threshold level, i.e., $\Delta_t^{A'} \geq \Delta_t^A$, $t = 0, ..., T$, and in a monotonic decrease in the launch threshold levels, i.e., $\Delta_t^{L'} \leq \Delta_t^L$, $t = 0, ..., g$.

Proof of Proposition 2 Assume $V(\Omega)$ is a monotonic function in q and v. In Figure 6a $V(\Omega)$ is decreasing over the interval $q = [0,\ 0.1]$ and increasing over the interval $q = [0.1,\ 0.6]$, and in Figure 6b $V(\Omega)$ is monotonically decreasing over the interval $v = [0,\ 0.18]$ and increasing over the interval $v = [0.18,\ 0.2]$. Therefore, by counter example, $V(\Omega)$ is not necessarily a monotonic function of q and v.

Proof of Proposition 3. To solve the optimal development strategies at $t = 0$ and $t = 1$, we solve a dynamic stochastic programming problem as described in Section 4, except the recursive function is as follows:

$$\begin{cases} P_t(\Delta_t) = max_{u_t}\{(1+\lambda)^{-1}\mathbb{E}[P_{t+1}(\Delta_{t+1})|u_t, \Delta_t, a_t = 1]\} & t = 0, 1 \\ P_2(\Delta_2) = \{\sigma_2(\Delta_2, a_2 = 3)\}. & \end{cases} \tag{7}$$

Therefore, u and p are replaced by their time dependent versions, which are now decision variables u_t, p_t. As the firm's development capability is assumed to be constant and equal to the strength of the competition, i.e., $\kappa = p_t u_t = s = qv$, it is sufficient to find optimal u_t^* because p_t^* is a function of it, i.e., $p_t^* = \frac{\kappa}{u_t^*} = \frac{vq}{u_t^*}$. Also, because the probability of success $p_t \in (0, 1)$, we have $u_t > \kappa$. Here we analyze the setting (i) $\Delta_0 = d_t = c_t = \lambda = 0$, $t = 0, 1$ and (ii) a winner-takes-all market, i.e., $f(\Delta_t) = m$ if $\Delta_t > 0$, $f(\Delta_t) = 0.5m$ if $\Delta_t = 0$, and zero otherwise.

We solve (7) using backward induction starting from $t=1$. At $t=1$, there are three possible cases that the firm might find it self in, either the performance of the firm's product is (i) ahead of the leading competing product, i.e., $\Delta_1>0$, (ii) on par with the leading competing product, i.e., $\Delta_1=0$, or (iii) behind the leading competing product, i.e., $\Delta_1<0$. In case (i), if $\Delta_1\geq v$, the competitors can not catch the firm's performance advantage and the firm can play safe, i.e., choose an incremental development strategy $u_1^*\to\kappa^+$ and $p_1^*\to 1^-$, and obtain full revenue m, case 1 in Table 6. In case (i), when $0<\Delta_1<v$, then the firm can obtain revenues that are illustrated in Table 4 depending on the chosen u_1 and how the firm's and competitors' development progresses. Based on this, we need to analyze regions $0<u_1<v-\Delta_1$, $u_1=v-\Delta_1$, and $u_1>v-\Delta_1$, because the function of the expected revenue is different in these cases, and find the optimal u_1^* that maximizes the expected revenue.

Table 4 Development outcomes and obtained revenues if $0<\Delta_1<v$

Development outcome: Firm	Development outcome: Competitors	Probability	u_1	Revenue
Succeed	Succeed	$p_1 q$	$>v-\Delta_1$	m
			$=v-\Delta_1$	$m/2$
			$<v-\Delta_1$	0
Succeed	Fail	$p_1(1-q)$	any	m
Fail	Succeed	$(1-p_1)q$	any	0
Fail	Fail	$(1-p_1)(1-q)$	any	m

Table 5 Expected revenues and optimal u_1^*s if $0<\Delta_1<v$

	Region for u_1^*: $0<u_1<v-\Delta_1$	$u_1=v-\Delta_1$	$u_1>v-\Delta_1$
Expected revenue	$p_1(1-q)m+(1-p_1)(1-q)m=$ $m(1-q)$	$p_1qm/2+p_1(1-q)m+(1-p_1)(1-q)m=$ $mp_1q/2+m(1-q)=m\frac{\kappa}{2u_1}q+m(1-q)$	$p_1qm+p_1(1-q)m+(1-p_1)(1-q)m=$ $mp_1q+m(1-q)=m\frac{\kappa}{u_1}q+m(1-q)$
Optimal development strategy	$u_1^*\in(vq,v-\Delta_1)$	$u_1^*=v-\Delta_1$	if $\Delta_1<v-vq$, $u_1^*\to v-\Delta_1$ if $\Delta_1\geq v-vq$, $u_1^*\to(vq)^+$

As showed in Table 5, the optimal development strategy within region $0<u_1<v-\Delta_1$ is $u_1^*\in(vq,v-\Delta_1)$ including all feasible values of u_1 due to the expected revenue being independent of u_1. At the region $u_1=v-\Delta_1$, the optimal strategy is trivial, i.e., $u_1^*=v-\Delta_1$. Within the region $u_1>v-\Delta_1$, the optimal strategy is to select u_1 at the lower bound, i.e., $u_1^*\to(v-\Delta_1)^+$, if feasible, because expected revenues are decreasing in u_1. The feasibility is bounded by constraint $u_1 = \frac{\kappa}{p_1}$ where $p_1 \in (0,1)$. Thus, the lower bound, $u_1 \to (v-\Delta_1)^+$, is infeasible if $p_1 = \kappa/u_1 = vq/(v-\Delta_1) \geq 1$ $\Leftrightarrow \Delta_1 \geq v - vq$. Therefore, if $\Delta_1 \geq v - vq$ then the optimal lower bound value is $u_1 \to (\kappa)^+ = (vq)^+$ and if $\Delta_1 < v - vq$ then $u_1^* \to (v-\Delta_1)^+$. Finally, we can show that the optimal development strategy within the whole region $0 < \Delta_1 < v$ is $u_1^* \to (\kappa)^+ = (vq)^+$ if $\Delta_1 \geq v - vq$ and $u_1^* \to (v-\Delta_1)^+$ if $\Delta_1 < v - vq$ because the expected revenue obtained from the region $u_1 > v - \Delta_1$ is $m\frac{\kappa}{u_1}q$ greater to what received from the region $0 < u_1 < v - \Delta_1$ and $0.5m\kappa q/u_1$ greater to what received from the region $u_1 = v - \Delta_1$. These optimal development strategies correspond to cases 2 and 3 in Table 6. Similarly, we derive optimal decisions at $t = 1$ for cases (ii) $\Delta_1 = 0$ and (iii) $\Delta_1 < 0$. Summary of the optimal decisions at $t = 1$ is presented in Table 6.

Table 6 Optimal decisions at $t = 1$

Case #	Conditions	u_1^*	p_1^*	Expected revenue
1	$\Delta_1 \geq v$	$\to (vq)^+$	$\to 1^-$	m
2	$0 < \Delta_1 < v,\ \Delta_1 \geq v - vq$	$\to (vq)^+$	$\to 1^-$	m
3	$0 < \Delta_1,\ \Delta_1 < v - vq$	$\to (v-\Delta_1)^+$	$\to \frac{vq}{(v-\Delta_1)^+}$	$p_1^* qm + (1-q)m$
4	$\Delta_1 = 0,\ q \leq \sqrt{2}-1$	$\to (vq)^+$	$\to 1^-$	$(1-q)m$
5	$\Delta_1 = 0,\ q > \sqrt{2}-1$	$\to v^+$	$\to q$	$m/2(p_1^*(1+q)+1-q)$
6	$\Delta_1 < 0,\ \Delta_1 > -vq,\ \Delta_1 < v - \frac{vq}{1-q}$	$\to (vq)^+$	$\to 1^-$	$(1-q)m$
7	$\Delta_1 < 0,\ \Delta_1 > -vq,\ \Delta_1 \geq v - \frac{vq}{1-q}$	$\to (v-\Delta_1)^+$	$\to \frac{vq}{(v-\Delta_1)^+}$	$p_1^* m$
8	$\Delta_1 \leq -vq,\ \Delta_1 > v - \frac{v}{q}$	$\to (-\Delta_1)^+$	$\to \frac{vq}{(-\Delta_1)^+}$	$p_1^*(1-q)m$
9	$\Delta_1 \leq -vq,\ \Delta_1 \leq v - \frac{v}{q}$	$\to (v-\Delta_1)^+$	$\to \frac{vq}{(v-\Delta_1)^+}$	$p_1^* m$

Table 7 Optimal decisions at $t = 0$

Conditions	u_0^*	p_0^*	Expected revenue
$q \leq \sqrt{2}-1$	$\to (v-vq)^+$	$\to \left(\frac{q}{1-q}\right)^-$	$m(-2q^3+4q^2-2q+1)$
$\sqrt{2}-1 < q \leq 0.5$	$\to (v-vq)^+$	$\to \left(\frac{q}{1-q}\right)^-$	$m\left(-2.5q^3+2.5q^2+0.5q+0.5+1/(2-2q)(q^4-q^3+q^2-q)\right)$
$0.5 < q \leq q_1$	$\to (vq)^+$	$\to 1^-$	$m(1-q^2)$
$q_1 < q \leq q_2$	$\to (v)^+$	$\to q^-$	$m(1.5q^4-2.5q^3+1.5q^2+0.5)$
$q > q_2$	$\to (2v-vq)^+$	$\to \left(\frac{q}{2-q}\right)^-$	$m\left(1/(2-q)(0.5q^4-q^3+0.5q^2+0.5q)-0.5q^3+q^2-0.5q+0.5\right)$

The optimal decisions at $t = 0$ are derived analogously using the expected revenues at $t = 1$, as shown in Table 6, and having no performance advantage at $t = 0$, i.e., $\Delta_0 = 0$, which is one of the assumptions. Table 7 summarizes optimal u_0^* and expected revenues. The threshold level q_1 is obtained by finding when the expected revenues from following the corresponding development strategies $u_0^* \to (vq)^+$ and $u_0^* \to (v)^+$ are equal, i.e., $m(1.5q_1^4 - 2.5q_1^3 + 1.5q_1^2 + 0.5) = m(1 - {q_1}^2)$. This leads into the following quartic equation $1.5q_1^4 - 2.5q_1^3 + 2.5q_1^2 - 0.5 = 0$, which feasible solution, $q_1 \in (0,1)$, is $q_1 \approx 0.56$. Similarly, we can find the threshold level for q_2 from the following cubic equation $1/(2-q_2)(0.5q_2^3 - q_2^2 + 0.5q_2 + 0.5) - 1.5q_2^3 + 2q_1^2 - 0.5q_2 - 0.5 = 0$, which feasible solution is $q_2 \approx 0.63$. Based on Table 7, the optimal strategy u_1^* is decreasing in q on intervals $q \in (0, 0.5]$ and $q \in (q_2, 1)$, increasing in q on interval $q \in (0.5, q_1]$, and otherwise constant.

Given optimal decision at $t = 0$, which depends on q as shown in Table 7, the outcomes at $t = 1$ fall into cases 1-6 and 8-9 in Table 6. Consequently, the optimal strategy u_1^* is nonincreasing in Δ_1 except if $\sqrt{2} - 1 < q \leq 0.5$ (where the constraint $q \leq 0.5$ comes from $t = 0$ period) then u_1^* has a singularity $\Delta_1 = 0$ when it temporarily increases from $(vq)^+$ to v^+.

Proof of Proposition 4. The value of flexibility is the difference between the expected revenues of project value with and without switching option. The revenues of a project without switching flexibility is derived applying the same approach as used to prove Proposition 3 except we fix $u^* = u_0^* = u_1^*$ and $p^* = p_0^* = p_1^*$. The resulting expected revenues and optimal u^* are as follows:

(i) $(1-q^2)m$, $u^* = [vq]^+$ if $q \leq q_0$,

(ii) $m(1-q)(10q^3 - 4q^2 + 1.5q + 0.5)$, $u^* = [0.5v]^+$ if $q_0 < q \leq 0.5$,

(iii) $(1-q)(1+q)m$, $u^* = [vq]^+$ if $0.5 < q \leq q_{1b}$, and

(iv) $m(2.5q^4 - 4q^3 + 2q^2 + 0.5)$, $u^* = v^+$ if $q > q_{1b}$,

where q_0 and q_{1b} are feasible solutions, $q \in (0,1)$, to the following cubic and quartic equations $10q_0^3 - 4q_0^2 + 2.5q_0 - 0.5 = 0$ and $2.5q_{1b}^4 - 4q_{1b}^3 + 3q_{1b}^2 - 0.5 = 0$. This results $q_0 \approx 0.24$ and $q_{1b} \approx 0.57$. The exact solution for the cubic function is $q_0 = \frac{8}{60} + \sqrt[3]{-\frac{a}{2} + \sqrt{\frac{a^2}{4} + \frac{b^3}{27}}} + \sqrt[3]{-\frac{a}{2} - \sqrt{\frac{a^2}{4} + \frac{b^3}{27}}}$, when $a = -\frac{289}{13500}$ and $b = \frac{59}{300}$.

The difference between the expected revenues of project value with and without switching option (using Table 7 and above computed (i)-(iv) expected revenues) results in the option value of

(i) $mq^2(3-2q)$ if $q \leq q_0$,

(ii) $m(10q^4 - 16q^3 + 9.5q^2 - 3q + 0.5)$ if $q_0 < q \leq \sqrt{2} - 1$,

(iii) $m(10q^4 - 16.5q^3 + 8q^2 - 0.5q + 0.5/(1-q)(q^4 - q^3 + q^2 - q))$ if $\sqrt{2} - 1 < q \leq 0.5$,

(iv) 0 if $0.5 < q \leq q_1$,

(v) $m(1.5q^4 - 2.5q^3 + 2.5q^2 - 0.5)$ if $q_1 < q \leq q_{1b}$,

(vi) $mq^2(-q^2 + 1.5q - 0.5)$ if $q_{1b} < q \leq q_2$, and

(vii) $mq(1/(2-q)(0.5q^3 - q^2 + 0.5q + 0.5) - 2.5q^3 + 3.5q^2 - q - 0.5)$ if $q > q_2$.

Therefore, the option value is increasing in q on intervals $(0, q_0]$ and $(q_1, q_3]$, is constant on interval $(0.5, q_1]$, and is decreasing on intervals $(q_0, 0.5]$ and $(q_3, 1)$, where $q_3 \approx 0.83$ is the solution of the following equation $\frac{\partial}{\partial q_3}(mq_3[(1/(2-q_3)(0.5q_3^3 - q_3^2 + 0.5q_3 + 0.5) - 2.5q_3^3 + 3.5q_3^2 - q_3 - 0.5)]) = 0$.

Proofs for Auxiliary Results

Definition A.1 A development strategy A is the set of all development decisions made in all outcomes and time periods, $A = \{a_t \colon \forall \pi_t(a_{t-1}), \gamma_t,\ t = 0, ..., T\}$. The project value under the development strategy A is denoted $P_t(\Delta_t)\mid_A$, $t = 0, ...T$, i.e., the recursion in (5) is solved having only one choice of action available for all possible a_t defined by the development strategy A.

Lemma A.1 The project value under a development strategy A, $P_t(\Delta_t)\mid_A$, $t = 0, ..., T$, decreases monotonically in q and v.

Proof. Under development strategy A, an increase in q or v, results in a monotonic decrease in the expected relative performance $\mathbb{E}[\Delta_t]$, $t > 0$. As the revenue function $f(\Delta_t)$ decreases monotonically in Δ_t, a monotonic decrease in $\mathbb{E}[\Delta_t]$ results in a monotonic decrease in the total net revenue $\sigma_t(\Delta_t, a_t)$. Thus, the project value with increase in q or v under the development strategy A is $P_t^{'}(\Delta_t)\mid_A \leq P_t(\Delta_t)\mid_A$, $t = 0, ..., T$, confirming that $P_t(\Delta_t)\mid_A$, $t = 0, .., T$ decreases monotonically in q and v.

Lemma A.2 The project value $P_t(\Delta_t)$ decreases monotonically in q and v.

Proof. Consider two development strategies A and B, $A \neq B$ and assume that the development strategy A is optimal at the current level of the competition, i.e., $P_t(\Delta_t)\mid_A \geq P_t(\Delta_t)\mid_B$, $t = 0, ..., T$. Assume an increase in q or v, such that strategy B becomes optimal, i.e., $P_t^{'}(\Delta_t)\mid_B \geq P_t^{'}(\Delta_t)\mid_A$, $t = 0, ..., T$, and according to Lemma A.1 we have $P_t^{'}(\Delta_t)\mid_B \leq P_t(\Delta_t)\mid_B$, $t = 0, ..., T$. Hence, the project value with an increase in q or v is $P_t^{'}(\Delta_t)\mid_B \leq P_t(\Delta_t)\mid_B \leq P_t(\Delta_t)\mid_A$ and hence $P_t(\Delta_t)$, $t=0,...,T$, decreases monotonically in q and v.

Lemma A.3 There exist unique abandon and launch thresholds Δ_t^A, $t=0,...,T$, and Δ_t^L, $t=g,...,T$.

Proof. Based on Dixit and Pindyck (1994), sufficient conditions for the existence of unique abandon thresholds are that (i) $A_t(\Delta_t)$ is non-decreasing in Δ_t and (ii) positive persistence of uncertainty holds, i.e., cumulative probability distribution $\Phi(\Delta_{t+1}|\Delta_t)$ of future values Δ_{t+1} shifts uniformly to the right when the current value Δ_t increases. Sufficient conditions for the existence of a unique launch threshold can be developed similarly.

For the abandon threshold, the first condition is satisfied as an increase in Δ_t monotonically increases the net revenue and hence also $P_t(\Delta_t|a_t \in \{0,1,3\})$ and $A_t(\Delta_t)$. The second condition follows from the stochastic processes of product performance and the performance of competitors' products. Without loss of generality, consider that product development is continued and $\Delta_t^{'} = \Delta_t + \epsilon$, $\epsilon > 0$. Now if the firm and competitors succeed it results that $\Delta_{t+1}^{'} = \Delta_t + \epsilon + u - v$ and $\Delta_{t+1} = \Delta_t + u - v$ given $\Delta_t^{'}$ and Δ_t, respectively. Also, if the firm succeeds and competitors fail it results that $\Delta_{t+1}^{'} = \Delta_t + \epsilon + u$ and $\Delta_{t+1} = \Delta_t + u$ given $\Delta_t^{'}$ and Δ_t, respectively. Similarly, when the firm fails and competitors either succeed or fail the difference in $\Delta_{t+1}^{'} - \Delta_{t+1} = \epsilon$. This together with that success probabilities remain unchanged p and q proves that cumulative probability distribution $\Phi(\Delta_{t+1}|\Delta_t)$ of future values Δ_{t+1} shifts uniformly to the right when the current value Δ_t increases.

For the launch threshold, we need to prove that $L_t(\Delta_t^{'}) - L_t(\Delta_t) \geq 0$ $\forall \Delta_t^{'} > \Delta_t$, i.e., it is non-decreasing in Δ_t. Because $\Delta_t^{'} > \Delta_t$, we have (i) $P_t(\Delta_t^{'}|a_t \in \{0,1,2\}) \geq P_t(\Delta_t|a_t \in \{0,1,2\})$ and (ii) $P_t(\Delta_t^{'}|a_t = 3) \geq P_t(\Delta_t|a_t = 3)$ due to monotonic increase in the net revenue caused by the non-decreasing revenue function in (4). Consequently, $L_t(\Delta_t^{'}) - L_t(\Delta_t) = P_t(\Delta_t^{'}|a_t = 3) - P_t(\Delta_t^{'}|a_t \in \{0,1,2\}) - P_t(\Delta_t|a_t = 3) + P_t(\Delta_t|a_t \in \{0,1,2\}) \geq P_t(\Delta_t^{'}|a_t = 3) - P_t(\Delta_t|a_t = 3) \geq 0$ due to (i) and (ii). Hence, the first condition is satisfied. The second condition holds as it is same as for the abandon threshold.

Lemma A.4 A decrease in the project value, i.e., $P_t^{'}(\Delta_t) < P_t(\Delta_t)$, $t = 0, ..., T$, increases the abandon threshold levels, i.e., $\Delta_t^{A'} > \Delta_t^A$, $t = 0, ..., T$, and decreases the launch threshold levels, i.e., $\Delta_t^{L'} < \Delta_t^L$, $t = g, ..., T$.

Proof. A decrease in the project value, i.e., $P_t^{'}(\Delta_t) < P_t(\Delta_t)$, $t = 0, ..., T$, means that also $P_{t+1}^{'}(\Delta_{t+1}|\Delta_t, a_t \in \{0,1\}) < P_{t+1}(\Delta_{t+1}|\Delta_t, a_t \in \{0,1\})$, $t = 0, ..., T-1$. Hence, the incremental value of not abandoning decreases, i.e., $A_t'(\Delta_t) < A_t(\Delta_t)$, $t = 0, ..., T$, resulting in an increase in the abandon thresholds, i.e., $\Delta_t^{A'} > \Delta_t^A$, $t = 0, ..., T$. Similarly, the incremental value of launching increases, i.e., $L_t'(\Delta_t) \geq L_t(\Delta_t)$, $t = g, ..., T$, resulting in a decrease in the launch thresholds, i.e., $\Delta_t^{L'} < \Delta_t^L$, $t = 0, ..., g$.

Proposition A.1 During the additional development, $t \geq g$, if the cost structure is non-decreasing, $c_t \leq c_{t+1}$ and $e_t \leq e_{t+1}$, $t = g, ..., T-1$, then the abandon threshold Δ_t^A increases monotonically.

Proposition A.2 Under a non-decreasing cost structure, $c_t \leq c_{t+1}$ and $e_t \leq e_{t+1}$, $t = g, ..., T-1$, the launch threshold Δ_t^L decreases monotonically over time, $t = g, ..., T$.

Proof of Propositions A.1 and A.2. The value of the NPD project decreases monotonically in time, $P_{t+1}(\Delta) - P_t(\Delta) \leq 0$, $t = g, ..., T-1$, under non-decreasing cost structure, $c_t \leq c_{t+1}$ and $e_t \leq e_{t+1}$, $t = g, ..., T-1$. This holds because $P_t(\Delta)$ and $P_{t+1}(\Delta)$, $t = g, ..., T-1$, depend on (i) the total net revenue, in (4), and that decreases monotonically in time, $\sum_{j=t}^{T} \mathbb{E}[(1+\lambda)^{t-j} f(\Delta_t)] \geq \sum_{j=t+1}^{T} \mathbb{E}[(1+\lambda)^{t+1-j} f(\Delta_{t+1})]$ when $\Delta_{t+1} = \Delta_t$, $t = g, ..., T-1$, and (ii) the cost structure, which is non-decreasing $c_t \leq c_{t+1}$ and $e_t \leq e_{t+1}$, $t = g, ..., T-1$. Thus, according to Lemma A.4 the monotonic decrease in the NPD project value $P_{t+1}(\Delta) - P_t(\Delta) \leq 0$, $t = g, ..., T-1$, leads to the abandon threshold level increasing monotonically in time, $\Delta_t^A \leq \Delta_{t+1}^A$ and launch threshold level decreasing monotonically in time, $\Delta_t^L \leq \Delta_{t+1}^L$.

Proposition A.3 During the initial development, $t < g$, if $P_{t+1}(\Delta_{t+1}) - P_t(\Delta_t) > 0$, when $\Delta_{t+1} = \Delta_t$, $t = 0, ..., g-1$ then the abandon threshold Δ_t^A decreases monotonically, otherwise the abandon threshold Δ_t^A increases monotonically.

Proof. When $t=0,...,g-1$, there exists the following two cases (i) $P_{t+1}(\Delta_{t+1})-P_t(\Delta_t)>0$ when $\Delta_{t+1}=\Delta_t$, which occurs when $c=e=\lambda=0$ and $pu+(1-p)d+i<qv$, for example and (ii) $P_{t+1}(\Delta_{t+1})-P_t(\Delta_t)\leq 0$ when $\Delta_{t+1}=\Delta_t$, which occurs when $c_t=e_t=\lambda=0$ and $pu+(1-p)d+i\geq qv$, for example. According to Lemma A.4, the monotonic decrease in the NPD project value $P_{t+1}(\Delta_{t+1})-P_t(\Delta_t)\leq 0$, when $\Delta_{t+1}=\Delta_t$, $t=0,...,g-1$ results that the abandon threshold level increases monotonically in time, $\Delta_t^A\leq\Delta_{t+1}^A$. This proves (ii) and similarly to Lemma A.4, it can be shown that an increase in the project value $P_{t+1}(\Delta_{t+1})-P_t(\Delta_t)>0$ when $\Delta_{t+1}=\Delta_t$, $t=0,...,g-1$ decreases the abandon threshold level in time, $\Delta_t^{A'}\geq\Delta_t^A$, $t=0,...,T$, proving (i).

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