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Exploring the effectiveness of pursuing competing technologies in parallel projects during predevelopment

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Abstract: Prior research has studied the effectiveness of parallel projects in the research and development stages. However, it has ignored predevelopment, which R&D intensive firms generally distinguish as a separate stage lodged between research and development. Predevelopment focuses on activities and decisions to select, from a subset of related technologies, the best option for a product application. Parallel projects are often a means of speeding up this process by actively pursuing learning spillovers. This paper develops assumptions about learning potential and then uses a real option model to test the trade-off between the higher costs and benefits of this parallel project approach. We compare outcomes for predevelopment using the same approach under research and development conditions, respectively. The results reveal that, when moving from research to development, the effectiveness of pursuing competing technologies in parallel projects first increases and then decreases, with a maximum positive result in predevelopment. The results also show that learning spillovers can compensate for the higher investment costs. Data from an empirical case support our findings.

Keywords: competing technologies; interproject learning; predevelopment; parallel development; real options.

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1 Introduction

To sustain their competitive position, firms invest in developing new technologies and their applications. They aim to do this quickly, but at the same time make the right choices regarding which technologies to develop and use for a particular new product application. To resolve this dilemma, they rely on developing technologies in parallel (e.g., Sommer et al., 2009; Sommer and Loch, 2004; Pich et al., 2002; Loch et al., 2001b), even though they can ultimately only market or use one in the product application.

Prior research on the benefits of running projects in parallel (e.g., Shibata, 2012; Kauffman and Li, 2005; Krishnan and Bhattacharya, 2002; Lint and Pennings, 2002; Childs and Triantis, 1999; Sobek et al., 1999) found it best to keep the options open for projects at the *research stage,* and consequently explore several technologies simultaneously for as long as possible (see Ward et al., 1995). In contrast, an early choice of technology and design freeze is preferable for projects at the *development stage* (e.g., Liker et al., 1996). However, these conclusions may be an artefact of how we look at firm innovation and dichotomise R&D projects in research (R) versus development (D) projects. Santiago and Vakili (2005), for example, identify projects with a probability of <0.5 as research projects and >0.5 as development projects. While useful for some purposes, this ‘tipping point’ approach is clearly a simplification.

In many R&D intensive firms, the transition between research and development is referred to as *predevelopment*[1] and considered a *stage* rather than a simple point (Langerak et al., 2004; Murphy and Kumar, 1996; Cooper, 1988). Lodged between basic research and product development, predevelopment’s objective is to improve and validate the results of fundamental research, and transfer the created functions and architectures to the development of a particular product, i.e., application (Van Bommel et al., 2014). More specifically, predevelopment involves the activities and decisions of selecting, from a subset of related technologies, the best alternative based on product performance and manufacturability criteria (Loch et al., 2001a). Predevelopment benefits from flexibility and often involves actively exploring related technologies in parallel. The predevelopment stage enables choices regarding types of material, component, architectural and/or process technology and relies on interproject learning to speed up and improve the application's product performance and thus value to the firm. Philips, for instance, contemplated proximity and remote phosphor solutions for creating white light from light emitting diodes (LEDs) and simultaneously pursued both technology options in the predevelopment of competing projects for new down-lighting applications (Hoelen et al., 2008). Insights from one project stimulated and helped the other and vice versa. The same approach was followed for backlighting of liquid crystal displays. Fluorescent and LED technology options were pursued in parallel (Sluyterman and Gielen, 2006). Here, too, interproject learning occurred. Finally, the LED-based solution was chosen and the other option abandoned. While the literature has begun to explore the best conditions for pursuing competing technologies in parallel (e.g., Eggers, 2015, 2014, 2012; Klingebiel and Adner, 2015; Klingebiel and Rammer, 2014; Shibata, 2012), neither the effectiveness of this approach for predevelopment nor the interproject learning effects identified above have been considered.

2 The focus of our study

The aim of this study is to evaluate the effectiveness of pursuing competing technologies in parallel projects in predevelopment. Focused on selecting the best option of related technologies, pursuing competing technologies in parallel projects relies on interproject learning to speed up development and the additional investment is used to benefit the application's performance and market value. The challenge is, however, how to balance these important benefits against the additional costs involved. We address this issue systematically. Firstly, we draw on technology S-curve theory and relatedness to explain the learning opportunities in predevelopment. Secondly, we develop a real option model and then validate, using simulation, the usefulness of this strategy under predevelopment conditions, comparing it to research and development conditions, respectively[2]. Thirdly, we carry out sensitivity analyses to explore how long and under what conditions a firm can use this approach. Finally, the results are related to an empirical case. The emphasis is on the benefits of learning spillovers from pursuing competing technologies in parallel projects at the predevelopment stage. We define learning spillover as the knowledge transferred between R&D projects (Van Bommel et al., 2014; Bartezzaghi et al., 1997). Learning arises from sharing information between project teams via knowledge brokers, shared resources, reports, presentations, emails and meetings about the technology, application and market (e.g., Birkinshaw, 2001). It typically happens when technologies are related, e.g., are based on a similar physical principle. This explains why new knowledge obtained in project A, can benefit the knowledge development in project B.

We contribute to the literature in two important ways. First, we extend the R&D and technology management research on developing competing technologies in parallel projects (e.g., Eggers, 2015, 2014, 2012; Klingebiel and Rammer, 2014; Klingebiel and Adner, 2015; Shibata, 2012), by exploring the effectiveness of this approach in predevelopment. Moving beyond the 'tipping point' notion, we conceptualise predevelopment as a separate stage. We draw on the technology S-curve (e.g., Foster, 1986) and relatedness to propose that different learning opportunities exist in research, predevelopment and development. We show that the parallel project approach is indeed best suited to predevelopment because at this stage the focus is on related technologies and the opportunities for performance improvement are most beneficial.

Second, we add to the work on modelling learning effects using the real options approach (e.g., Van Bommel et al., 2014; Erat and Kavadias, 2008). Prior research has focused on *intraproject* learning (e.g., Santiago and Vakili, 2005; Huchzermeier and Loch, 2001) and generally assumed that each project developed had some remaining market value, i.e., would ultimately be commercialised (see Santiago, 2008). Conversely, we focus on *interproject* learning in parallel projects where *only one* technological solution, i.e., one version is chosen and used in an application that is marketed. The ultimate value of the alternative technology will be zero. We outline the issue using the real options approach put forward by Huchzermeier and Loch (2001) and adopt their parameter settings where possible. This enables a comparison with earlier findings (Van Bommel et al., 2014; Santiago, 2008; Rese and Baier, 2007; Santiago and Vakili, 2005; Santiago and Bifano, 2005). By varying parameter settings (in particular for cost and interproject learning), we address some of the complexity of learning in new product development (Bartezzaghi et al., 1997) and explore the boundary conditions that are favourable and unfavourable for this parallel project approach.

The results provide a better understanding of the usefulness of parallel projects. The outcomes stress the benefits and high effectiveness of interproject learning in predevelopment through a comparison with similar projects run under research and development stage conditions.

We begin by elaborating on the predevelopment stage and conceptualising interproject learning between competing projects (Section 3). We argue for a relationship with the technology S-curve concept and different opportunities to learn in research, predevelopment and development. Then, in Section 4, we develop our model and methodology. We present our results including the outcomes of sensitivity analyses (Section 5), and an empirical case to illustrate our approach (Section 6). After drawing conclusions (Section 7), we discuss the limitations and implications of our work (Section 8).

3 Predevelopment, competing technologies, and learning opportunities

3.1 Defining predevelopment

Predevelopment is when new technology is transferred from the lab (research) to the business (development) by taking the first steps to transform it, either alone or in combination with other technologies, into a product application that can be manufactured (Van Bommel et al., 2014). It typically involves identifying the best suited option from a small set of technological options and aims to optimise the product's market value and thus profits for the firm (Loch et al., 2001a). The set of technologies typically involves versions or alternative interpretations of the same underlying technology (e.g., using proximity *or* remote phosphor technology), or are related through similarities in architecture or processes (e.g., using fluorescent *or* LED backlighting technology). Mostly a decision has to be made regarding a material or component for the desired product application.

Whereas research projects and development projects' probabilities of success are < 0.5 and >0.5 (Santiago and Vakili, 2005), respectively, for predevelopment projects, this is approximately 0.5. Referring to the transition from research to development, this can be 0.5 +/– 0.2 (see also Van Bommel et al., 2014). While *research* is uncertain and risky, *development* is characterised by certainty and lower risk. Research requires seed money to explore unrelated technologies using trial-and-error (Chandy and Tellis, 1998), whereas development requires focus on exploiting intraproject learning (Santiago and Vakili, 2005). In the intermediate stage of predevelopment, however, managers need to decide on alternative options for exploiting a new product application. It is beneficial to explore alternative paths or related technologies for the same application.

We can describe technology development and R&D progress using a technology S-curve perspective, which shows the evolution of a technology over time or as a function of the engineering effort, generally resembling an S or life cycle-like curve (Foster, 1986). The phenomenon suggests that a technology evolves from an initial phase of slow growth, through an intermediate phase of fast growth, to a final phase with a decline in growth (Sood and Tellis, 2005). However, Cebon et al. (2008) suggest that each product architecture can also have its own S-curve. Thus, performance improvement in a technology can be described with a composite of multiple S-curves, each showing progress in linkages or layouts and materials or parts within the same scientific principle (Sood et al., 2012; Sood and Tellis, 2011; 2005; Tellis, 2006; Bowden, 2004; Foster, 1986). Zif and McCarthy (1997) argue that the S-curve phenomenon exists in and can thus even be applied to *individual* R&D projects or an *aggregate* of several projects.

Based on the above, we assume an S-curve pattern within an R&D process. An R&D process consists roughly of a research, predevelopment and development stage. The notion of an S-curve for an R&D process suggests a relatively lower potential to increase the probability of success in the initial research and final development stages, and the highest potential to increase this probability in the intermediate, predevelopment stage (Van Bommel et al., 2014). This implies that the opportunities for learning *within* a project, but also *across* related projects performed in parallel, will be highest during predevelopment.

3.2 Prior research on competing technologies

There is a great amount of literature regarding (modelling) the effects of running R&D projects in parallel (e.g., Farrukh et al., 2009; Schneider et al., 2008; Fredberg, 2007; Kauffman and Li, 2005; Lint and Pennings, 2002). Two contrasting views have emerged: one suggests keeping the options open as long as possible (Sobek et al., 1999; Ward et al., 1995). They argue that R&D success is increased by delaying decisions because this prevents path dependency and rework. The opposing view promotes early abandonment of the alternative project to prevent escalation of costs and depletion of resources [e.g., Ford and Sobek, 2005; Pich et al., (2002), p.1009]. The aim is to minimise development costs and improve time-to-market or product performance by focusing on a single technology if there is one dominating technology (e.g., Childs and Triantis, 1999; Liker et al., 1996).

Recent research has begun to identify contingencies regarding the usefulness of parallelised execution of R&D projects. For example, Sommer et al. (2009), Sommer and Loch (2004), Pich et al. (2002), and Loch et al. (2001b) studied the moderating role of uncertainty and complexity of the project, whereas McGrath and Nerkar (2004) explored the contingency effect of a firm's competition level. Klingebiel and Rammer (2014) analysed empirically the conditions whereby pursuing parallel projects makes sense and showed that the parallel project approach is most beneficial for novel products and ambitious innovators. Klingebiel and Adner (2015) tested various resource allocation strategies, but found no performance difference between having one highly committed project and several low commitment projects in parallel. In addition, recent research focused on learning effects as a result of investments in competing technologies (Eggers, 2012, 2014, 2015; Lee et al., 2009). These studies show, based on data from the display industry, that firms can recover or even benefit from wrong technology choices or initial technology failure. They benefit by having the option of "switching to the winning technology" and "the ability to transfer useful learning from the losing technology" [Eggers, (2014), p.159 and 174].

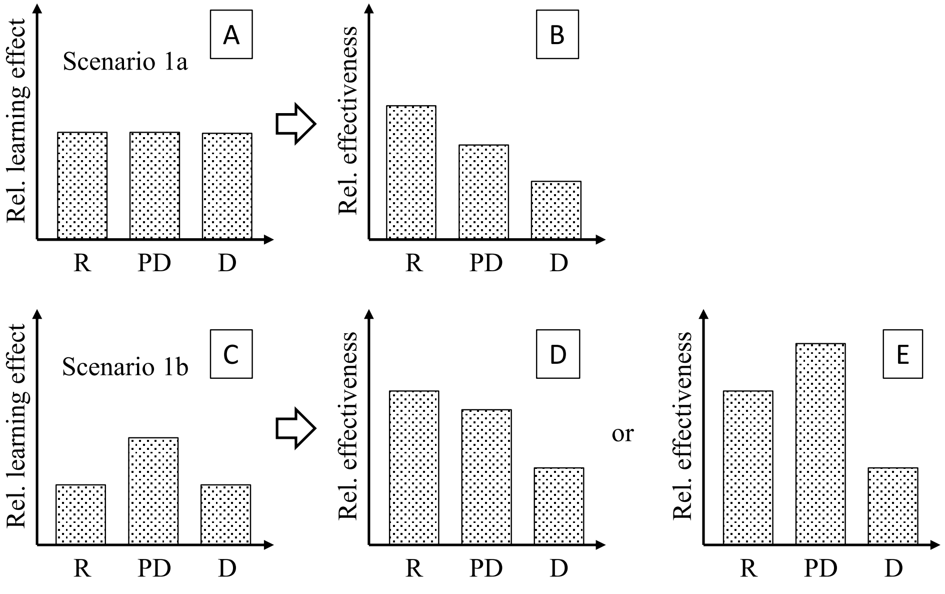
3.3 The role of intra- and interproject learning

Based on the above, it is clear that running projects in parallel at the predevelopment stage can be useful. The additional knowledge acquired may stimulate learning and enable decision makers to choose the best technology option. This helps to mitigate the risks involved in developing new technology and enhances the project's market value.

Two types of learning are involved: intra- and interproject learning. The first refers to learning in a project by furthering a particular technology for an application. This means ironing out kinks in a technology by experimenting with it to develop the application (Schneider et al., 2008). This learning is what researchers normally try to model using real options (Huchzermeier and Loch, 2001). The second type is learning by exploring simultaneously two (or more) different projects so that two competing technologies for the same application are developed in parallel. This involves knowledge spillovers. If the relatedness of the technologies is high, it is more likely that the knowledge created in one project can be used in the other and vice versa. In predevelopment, parallel projects typically involve related technologies. The crucial factor, however, is how long to pursue both projects together, because only one alternative will be used in the firm's product application, while the other will become obsolete. This factor involves learning spillover, cost, and possibly certainty about one option's superiority over its alternative.

We focus on interproject learning and account for it by modelling an increase in the probabilities of success (or a decline in market requirement variabilities) between parallel projects pursuing competing technologies. Modelling the consequences of learning by uncertainty reduction through probability updating is consistent with Loch et al. (2001b) and Van Bommel et al. (2014). They modelled the value of different sequences of technological interdependent R&D projects and concluded that by accounting for interproject learning, different sequences have varying trajectory values. Prior research assumes no or equal learning spillovers in the different stages of R&D [see Figure 1(a)], suggesting that the effectiveness of parallel strategies declines [Figure 1(b)]. Explicitly factoring in interproject learning can achieve a more nuanced perspective. Based on technology S-curve and relatedness, we can assume higher learning spillovers between parallel projects pursuing competing technologies under predevelopment (i.e., $p = 0.5 +/- 0.2$) than research (< 0.5) and development (> 0.5) conditions [see Figure 1(c)]. This assumption raises several questions, namely: what is the impact on the effectiveness of parallel strategies; how are costs and benefits played out? Does it just lead to more positive project returns [Figure 1(d)]? Or can it even achieve more positive results in predevelopment than in research and development [Figure 1(e)]?

Figure 1 Relative interproject learning effects and the effectiveness of pursuing competing technologies in parallel projects in research, predevelopment and development



Note: R – research; PD – predevelopment; D – development.

4 Model and methodology

Next, we develop a conceptual model to evaluate the effectiveness of pursuing competing technologies in parallel projects. We focus on a situation with two (related) projects aimed at developing the same product application. The individual project values are determined using the real option model developed by Huchzermeier and Loch (2001). For more information on real options, see Amram and Kulatilaka (1999), Trigeorgis (1997, 1996) and Dixit and Pindyck (1994). This model is extended by accounting for the higher development costs and benefits of interproject learning when projects are conducted in parallel. We compare the outcomes of this strategy for predevelopment with research and development stage settings as well as with a single project strategy. We first develop assumptions regarding the individual projects and then regarding relatedness and learning.

Similar to Van Bommel et al. (2014), Santiago (2008), Santiago and Vakili (2005), and Santiago and Bifano (2005), we cast each *individual project* in the framework described by Huchzermeier and Loch (2001). Each single project has a fixed lead time, with decision moments at regular intervals when management can decide whether and how to proceed by choosing one of three options: abandon, continue or improve. Abandonment represents termination of the project, incurring no further costs and revenues. The option to continue involves continuation costs. The model allows for intraproject learning through improvement steps within a project. It shifts the transition probabilities upwards and includes improvement costs as well as continuation costs [see Huchzermeier and Loch, (2001), p.90, specifically Figure 2].

Each project has its own specific project and market characteristics. These include product performance, project budgets and project schedules, as well as market payoffs and market requirements. We assume the value of a single project to be a function of its underlying technology state X_t and time t (Van Bommel et al., 2014). The technology state X_t then evolves over time t in our multistage decision model as follows:

$$X_{t+1} = \begin{cases} X_t + \omega_t, & \text{if } \; u_t = 1 \text{ (continue)}, \\ X_t + 1 + \omega_t, & \text{if } \; u_t = 2 \text{ (improve)}, \\ -\infty, & \text{if } \; u_t = 3 \text{ (abandon)}. \end{cases}$$

The random variable ω_t is based on a binomial distribution with probability of success $p_k(t)$ and depends on the model setting k and time, indicated by $t = 1,\ldots, T$. The control variable u_t reflects the decisions a manager can make when developing a single project.

Further settings are adopted entirely from Huchzermeier and Loch (2001) and Van Bommel et al. (2014). We assume that the technology X_t of a single project relates to performance and needs to reach a minimum required level of technical performance D_k before the new product can be commercialised. If the technology reaches the minimum required level of technical performance D_k, it yields a premium profit margin M_k. If X_t does not reach the minimum required level of technical performance D_k, the profit margin will be lower, thus $m_k < M_k$. The performance requirement variable D_k is assumed to be random, with a normal distribution of mean $\mu(D_k)$ and variance $\sigma^2(D_k)$. Each project incurs a start-up investment cost I_k^0. In summary, the parameters of each project k are denoted by:

1 the individual project time T_k

2 the distribution of the required level of technical performance D_k, its mean $\mu(D_k)$ and variance $\sigma^2(D_k)$

3 the minimum profit margin m_k and the maximum profit margin M_k

4 the initial investment cost I_k^0.

The parameter N_k, which represents the number of branches in the tree for X_t, is set at $N_k = 1$ for all model settings k. The continuation and improvement costs are denoted by C_{tk} and α_{tk}, respectively. The time value of money is taken into account by the discount rate r. The structural parameters described above are captured in a set θ_k and reflect cost, market requirements and market payoff.

The value function for a particular model setting k, denoted by $V_k(X_t, t, \theta_k)$, shows the dependence of model setting k on the technology state, time, and the set of structural parameters θ_k. The value function[3] can be denoted as:

$$V_k(X_t,t) = \begin{cases} u_t = 1\text{: } -C_{tk} + \dfrac{1}{1+r}\left(p_k(s_k)V_k\left(X_t + \dfrac{1}{2}, t-1\right) + (1 - p_k(s_k))V_k\left(X_t - \dfrac{1}{2}, t-1\right)\right), \\ u_t = 2\text{: } -C_{tk} - \alpha_{tk} + \dfrac{1}{1+r}\left(p_k(s_k)V_k\left(X_t + 1\dfrac{1}{2}, t-1\right) + (1 - p_k(s_k))V_k\left(X_t + \dfrac{1}{2}, t-1\right)\right), \\ u_t = 3\text{: } 0. \end{cases} \quad (1)$$

and for $t = T_k$.

$$V_k\left(X_T, T_k\right) = \begin{cases} u_{T_k} = 1: & -C_{T_k k} + \frac{1}{1+r}\left(\Pi_k\left(X_{T_k}\right)\right), \\ u_{T_k} = 2: & -C_{T_k k} - \alpha_{T_k k} + \frac{1}{1+r}\left(\Pi_k\left(X_{T_k}\right)\right), \\ u_{T_k} = 3: & 0. \end{cases} \tag{2}$$

In the final period ($t = T_k$) the project value is determined by the anticipated profit, which can be calculated using the Huchzermeier and Loch (2001) model. The expected payoff of model setting k, the function Π_k, is denoted as:

$$\Pi_k\left(X_{T_k}\right) = m_k + \Phi\left(X_{T_k}\right)\left(M_k - m_k\right), \tag{3}$$

$\Phi(X_{T_k})$ is the cumulative normal distribution function which has a mean $\mu(D_k)$ and a variance $\sigma^2(D_k)$, evaluated at the end of the model setting k ($t = T_k$). The value functions have a recursive structure and require backward evaluation.

Before we can model the trade-offs between costs and benefits arising from competing projects, we first must further specify the settings for the relatedness in technology and thus for potential learning between the two projects. Supposing we have two individual projects, denoted with the letters A and B, that have stand-alone values V_A (X_0, 0, θ_A) and V_B (X_0, 0, θ_B), respectively. The individual project values can be calculated using Huchzermeier and Loch's (2001) method. As both projects A and B are targeting the same product application, with a different but related technology, we model the parallel development of projects A and B as outlined by Huchzermeier and Loch (2001). However, in order to represent the learning effect of two simultaneous projects, we incorporate a time-varying probability of success. We assume that the probability of success that both projects aim to develop, benefits from the continuation of both projects; that is to say there is an increase in the probability of success. This stops when the competing project is discontinued; in other words, the probability of success drops when one of the two projects is stopped[4]. Likewise, the parameter settings regarding costs are adapted so that the continuation costs double when two projects are conducted. For project A, we explore different periods of abandonment ($T_k = 6$) and no project payoff is anticipated as only project B is assumed to be completed and brought to market, resulting in a payoff for project B. The cost of developing project A will be charged to project B. Consequently, there is a trade-off between higher costs and increasing the probability of success.

If we extend the notation of a project's values with the time of stopping either project A or B denoted by τ, and with the probabilities of success before and after stopping times p^- and p^+ and continuation costs C^- and C^+, the total project value for which one project (A or B) stops at time τ, can be written as V_{AB} (X_0, 0, τ, C^-, C^+, p^-, p^+).

The problem we face is optimisation: determining the optimal period to run both projects simultaneously in the research, predevelopment and development stages. The probability of success $p_k(j)$ is set at 0.5 for predevelopment projects. In contrast, the probabilities of success for R and D projects are set at 0.3 and 0.7, respectively (see Santiago and Vakili, 2005). Taking into account these probabilities, the corresponding market values are calibrated in such a way that all projects have identical values. The learning spillover is factored in by increasing the probability of success e.g., +0.2. We apply dynamic programming and use MATLAB for the calculations. The optimisation is done using total project value for the final application and accounting for higher costs versus the benefits of interproject learning. Abandoning the second project early implies minimum additional development costs, but also a minimum additional value due to learning. Stopping the second project at the end of the lead time, implies almost doubling the development costs, but also maximising the overall value through learning. The total project value for the application is derived from the contribution and costs of pursuing the two projects in parallel and comparing the total project value (at the different time) to the total value of the application developed using a single project/technology strategy. If the total project value of the parallel development option is higher than the single technology development option i.e., the baseline, it is financially beneficial to pursue two projects.

5 Results

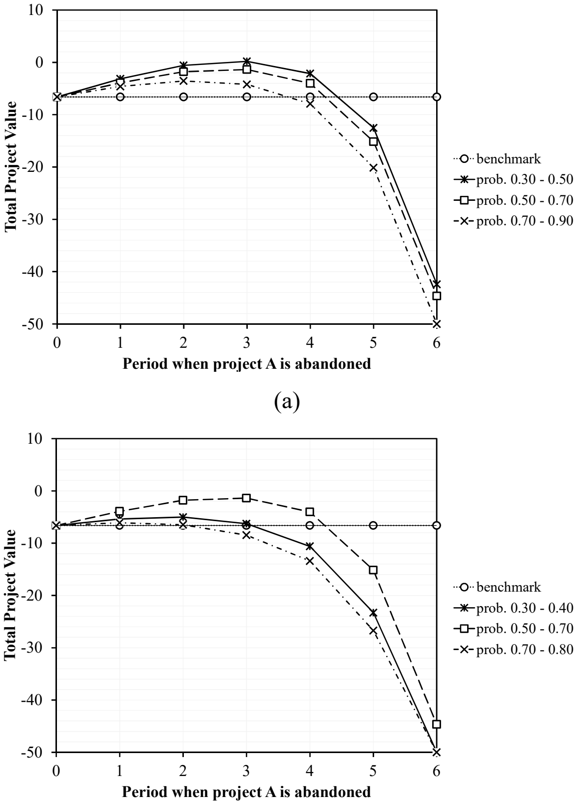
Using the model and methodology introduced above, we explore four scenarios. Scenario 1 compares the effectiveness of pursuing competing technologies in two parallel projects in the predevelopment stage to the research stage and the development stage.

We report the results for Scenarios 1.1 and 1.2, where Scenario 1.1 refers to a parameter setting assuming equal learning spillovers in all three stages, while Scenario 1.2 refers to our manipulation involving higher learning spillovers under predevelopment conditions. Scenario 1.1 reflects what the literature has argued thus far and acts as benchmark for Scenario 1.2, which indicates the results under the assumptions that an S-curve exists within an R&D process and a high level of relatedness with predevelopment projects. To test the robustness of the Scenario 1 findings, we perform sensitivity analyses. In Scenarios 2 and 3, we study the effect of interproject learning on the total project value by manipulating the probabilities of success and market requirement variabilities. In these two scenarios, we explore the sensitivity by manipulating the extent of the learning effects. Scenario 4 extends the sensitivity analysis by modelling the parallel development of three competing projects. We discuss the scenarios and their parameter settings in detail below and Appendix A shows a systematic overview of these scenarios and their manipulations. Finally, the results are related to an empirical case.

Scenario 1.1

To compare pursuing competing technologies in two parallel projects in research, predevelopment and development, we vary the probability of success. Specifically, we set the probability of success of project B1 at $p^{\min}{}_{B1} = 0.3$ (Scenario 1.1a), project B2 at $p^{\min}{}_{B2} = 0.5$ (Scenario 1.1b), and project B3 at $p^{\min}{}_{B3} = 0.7$ (Scenario 1.1c), to represent a research, predevelopment and development project, respectively. The learning spillover is factored in by increasing the probability of success. In Scenario 1.1, we evaluate the effectiveness of parallel technology development projects, setting the learning spillover for all three stages equal, i.e., +0.2. This means that we set the maximum probability of success of project B1 at $p^{\max}{}_{B1} = 0.5$ (Scenario 1.1a), project B2 at $p^{\max}{}_{B2} = 0.7$ (Scenario 1.1b), and project B3 at $p^{\max}{}_{B3} = 0.9$ (Scenario 1.1c). Note that the initial values of project B2 are set to completely mimic those used by Huchzermeier and Loch (2001, p.96, Figure 8). That is why project B2's setting is ($M_B = 280$, m = 0)($p_B = 0.5$, $N = 1$). Taking into account these probabilities of success, we calibrate the corresponding market values M_{B1} and M_{B3} using 'reverse engineering', so that all the projects have identical project values. Thus, projects B1 and B3 settings are (M_{B1} = 334.72, m = 0)(p_A = 0.3, N = 1) and (M_{B3} = 233.02, m = 0) (p_C = 0.7, N = 1), respectively. The other parameters are the same for all projects, similar to those presented by Huchzermeier and Loch (2001): (μ = 0, σ = 3); (C_{5k} = 50, α_{5k} = 45); (C_{4k} = 20, α_{4k} = 35); (C_{3k} = 8, α_{3k} = 30); (C_{2k} = 4, α_{2k} = 25); (C_{1k} = 2, α_{1k} = 20); (C_{0k} = 1, α_{0k} = 6). For both projects we use a discount rate r = 0.08. As project infrastructure (e.g., testing facilities) can be shared between projects (Childs and Triantis, 1999), the investment costs of I = 50 are deducted only once (as in Huchzermeier and Loch, 2001) i.e., (I_K^0 = 50, r = 0.08). Because of the aforementioned calibration of market values, research project B1 has a higher anticipated market value M_{B1} while development project B3 has a lower expected market value M_{B3}.

Figure 2 (a) Results for Scenarios 1.1a to 1.1c showing the total project value for different periods of abandoning competing project A, using a 0.3 probability of success (Scenario 1.1a), a 0.5 probability (Scenario 1.1b) and a 0.7 probability (Scenario 1.1c) with an equal increase in 0.2 probability of success during parallel development (b) Results for Scenarios 1.2a to 1.2c showing the total project value for different periods of abandoning competing project A, using an increase from 0.3 to 0.4 probability of success (Scenario 1.2a), an increase from 0.5 to 0.7 (Scenario 1.2b) and an increase from 0.7 to 0.8 (Scenario 1.2c)



(a)

Note: The benchmark value represents the project value of single project development.

Figure 2(a) shows the findings for Scenarios 1.1a to 1.1c. They confirm substantial total project value differences in the various scenarios but also that a firm can gain considerable benefits from interproject learning. All the Scenarios 1.1a to 1.1c show an increase in total project value as long as project A is abandoned before breaking through the benchmark line (the line representing the development of only one single project). The curves show that running project A in parallel for half of the anticipated project duration results in maximum total project value. The research project (Scenario 1.1a) benefits more from interproject learning than the predevelopment project (Scenario 1.1b), and the predevelopment project (Scenario 1.1b) benefits more from interproject learning than the development project (Scenario 1.1c). The results confirm findings from prior literature, suggesting that the effectiveness of parallel strategies decreases if the interproject learning effects are equal in research, predevelopment and development.

Scenario 1.2

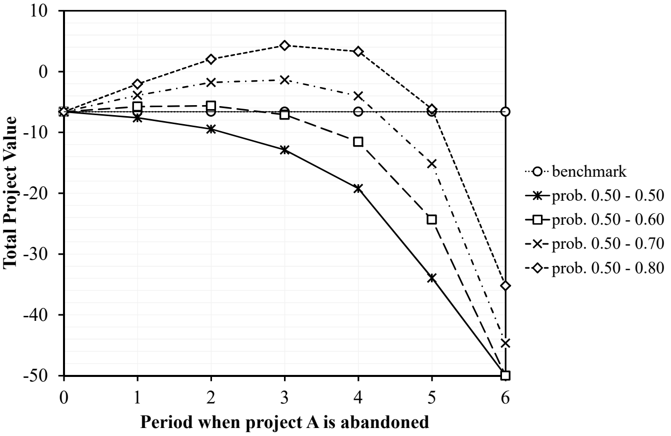
Based on our discussion of technology S-curves, we assume a higher potential for predevelopment projects to increase their probability of success compared to research and development projects. We also assume a higher level of relatedness of predevelopment projects (technology and application wise), compared to research and development projects. This positively influences the potential for interproject learning and thus spillover. Therefore, we assume a higher learning potential, and thus increase in probability of success, for predevelopment rather than research or development projects. Thus, we set the maximum probability of success of simultaneously developed competing project B1 at $p^{\max}{}_{B1} = 0.4$ (Scenario 1.2a), project B2 at $p^{\max}{}_{B\,2} = 0.7$ (Scenario 1.2b), and project B3 at $p^{\max}{}_{B\,3} = 0.8$ (Scenario 1.2c) (due to learning, an increase in probability of +0.1, +0.2 and +0.1, respectively). All the other parameters are similar to those presented in Scenarios 1.1a to1.1c.

Figure 2(b) shows the results of the manipulations in Scenarios 1.2a to 1.2c. We see a more positive effect on the total project value for the predevelopment project (Scenario 1.2b) than the research (Scenario 1.2a) and development project (Scenario 1.2c). The threshold value, where the cost of learning surpasses the benefits (i.e., compared to developing a single technology, see Figure 2(b), the straight line), shifts to the right for predevelopment projects, to reach a maximum at halfway to two-thirds of the project duration. For the research project, this point is at one-third of the project duration, whereas in development there is almost no benefit from pursuing competing technologies in parallel projects. The results of Scenario 1.2 show that, compared to Scenario 1.1, the relative effectiveness does change if we consider predevelopment as a separate stage with a higher learning potential than the research and development stages. When moving from research to development, the effectiveness of pursuing competing technologies in parallel projects first increases and then decreases. Thus, we find that a subtly higher learning spillover effect in predevelopment does change the optimum, suggesting it is more beneficial to pursue competing technologies in parallel projects in predevelopment than in research and development conditions.

Scenario 2

In order to test the robustness of our findings, we make additional manipulations. For example, in the second scenario, we explore the effects of the interproject learning level on the total project value by increasing the probabilities of success for the period the competing projects run in parallel. Consistent with our focus on predevelopment, we use around a 0.5 probability of success for the completed project B[5]. Based on the above, projects A and B can be described as follows: project A ($M_A = 280$, $m = 0$); ($\mu = 0$, $\sigma = 3$); ($p^{\min}_A = 0.5$, $N = 1$); and project B ($M_B = 280$, $m = 0$); ($\mu = 0$, $\sigma = 3$); ($p^{\min}_B = 0.5$, $N = 1$) with ($c_5 = 50$, $\alpha_5 = 45$); ($c_4 = 20$, $\alpha_4 = 35$); ($c_3 = 8$, $\alpha_3 = 30$); ($c_2 = 4$, $\alpha_2 = 25$); ($c_1 = 2$, $\alpha_1 = 20$); ($c_0 = 1$, $\alpha_0 = 6$); ($I^0_K = 50$, $r = 0.08$). The learning spillover is factored in by increasing the probability of success. We set the maximum probabilities of success $p^{\max}_B$ for Scenarios 2a, 2b, 2c and 2d at 0.5, 0.6, 0.7 and 0.8, respectively.

Figure 3 Results of Scenarios 2a to2d showing the evolution of the total project value for different periods of abandoning competing project A, using a minimum probability of success of 0.5 (Scenario 2a), and varying the probability of success from 0.5 to 0.6 (Scenario 2b), from 0.5 to 0.7 (Scenario 2c) and from 0.5 to 0.8 (Scenario 2d)



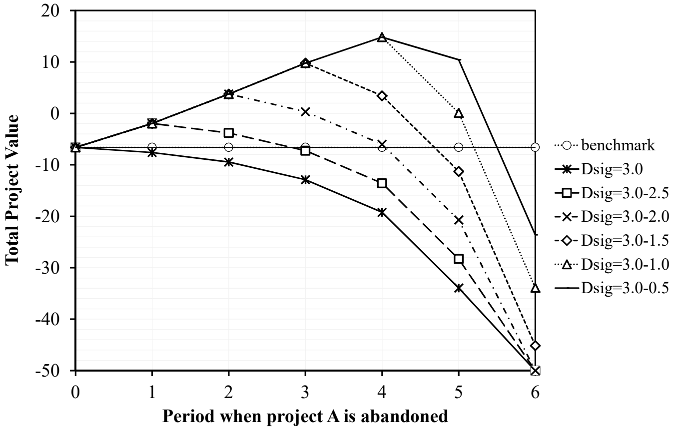
Note: The benchmark value represents the project value of single project development.

Figure 3 depicts the results for Scenarios 2a to 2d. The curve shows the level of total project value for different periods of abandoning project A (thus running parallel project A for just one or multiple periods). The benchmark of developing only one single project is also shown (see Figure 3, the straight line; calculated according to Huchzermeier and Loch, 2001). The total project value slowly decreases in cases where there is no interproject learning (Scenario 2a) *or*, first increases and then decreases in cases of interproject learning (Scenarios 2b to 2d). This implies that despite higher investment in pursuing competing technologies in parallel projects, learning spillovers can compensate for the additional costs involved and increase total project value. The results show that even for projects with limited interproject learning (e.g., probability of success increases +0.1 or +0.2 as shown in Figure 3 Scenarios 2b and 2c, respectively), it is worthwhile to pursue competing technologies in parallel projects. An increase in total project value (compared to the benchmark of developing only one single project) indicates where the level of interproject learning compares favourably to the cost incurred. The parallel option is best abandoned at the maximum of the curve and thus halfway through the project's duration, approximately after three periods (in Scenarios 2c and 2d). The benefits of interproject learning on the total project value are higher if technologies are related and projects have a high potential to increase their probability of success.

Scenario 3

In the third scenario, we assume that developing one or more competing projects in parallel will reduce market uncertainty through learning spillovers. The extra technological investments mitigate risk and increase market success by reducing the market requirement variability representing learning spillover. We model this by making the market requirement variability of the product application dependent on the number of projects developed in parallel for the same product application. While the basic settings are similar to Scenario 2: project A ($M_A = 280$, $m = 0$); ($\mu = 0$, $\sigma^{\max}{}_{\mathrm{A}} = 3$); ($p_A = 0.5$, $N = 1$); and project B ($M_B = 280$, $m = 0$); ($\mu = 0$, $\sigma^{\max}{}_{\mathrm{B}} = 3$); ($p_B = 0.5$, $N = 1$) with ($c_5 = 50$, $\alpha_5 = 45$); ($c_4 = 20$, $\alpha_4 = 35$); ($c_3 = 8$, $\alpha_3 = 30$); ($c_2 = 4$, $\alpha_2 = 25$); ($c_1 = 2$, $\alpha_1 = 20$); ($c_0 = 1$, $\alpha_0 = 6$); discount rates $r = 0.08$ and an initial investment cost of $I = 50$, the market requirement variability $\sigma^{\max}{}_{\mathrm{B}}$ lowers gradually from standard deviation 3 (no interproject learning, see Scenario 3a) to $\sigma^{\min}{}_{\mathrm{B}} = 0.5$ using steps of 0.5 as reflected in Scenarios 3b to 3f.

Figure 4 Results of Scenarios 3a to 3f showing the evolution of the total project value for different periods of abandoning competing project A, using a maximum market requirement variability of 3 (Scenario 3a), and varying the market requirement variability (Dsig) from 3 to 0.5 in steps of 0.5 as shown in Scenarios 3b to 3f



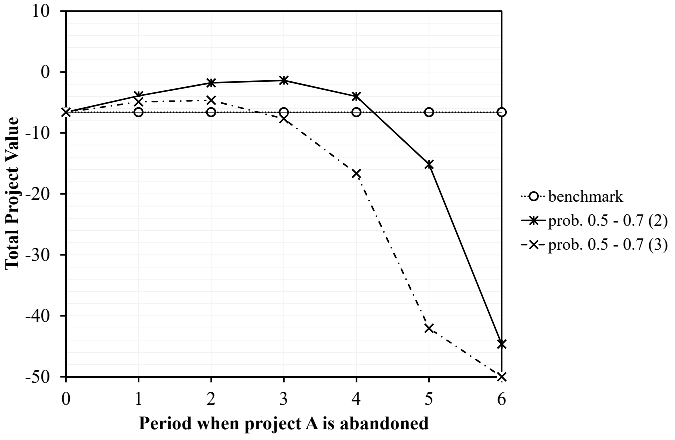
Note: The benchmark value represents the project value of single project development.

Figure 4 depicts the results for Scenarios 3a to 3f. The figure shows the total project value as a function of the period when project A is abandoned and the horizontal benchmark of total value outcomes for developing a single project (see Figure 4, the straight line). Again we find interproject learning is of considerable benefit to the total project value. A limited reduction in market uncertainty (i.e., Scenario 3b) enhances total project value up to one-third of the project duration. Higher levels of learning spillover (e.g., Scenarios 3c and 3d) result in a further increase followed by a decrease in total project value, shifting the threshold value (where the cost of learning surpasses the benefits) to the right, to approximately halfway through the project. The most positive effect occurs for projects where the spillover is highest. Then the second project may almost be continued until the end of the project duration (see Scenarios 3e and 3f). However, such a high reduction in market uncertainty may be rare in predevelopment.

Scenario 4

In order to further test the robustness of our findings, we make the following manipulations[6]. In Scenario 4, we explore the effects of interproject learning level on the total project value by modelling the parallel development of three competing technologies and comparing this with pursuing a single technology and two competing technologies in parallel. While the basic settings are similar to Scenario 2, we include alongside pursuing a single project and two competing technologies in parallel (Scenario 4a), also the parallel development of three technologies (Scenario 4b). Thus: project A ($M_A = 280$, $m = 0$); ($\mu = 0$, $\sigma^{\max}{}_{\mathrm{A}} = 3$); ($p_A = 0.5$, $N = 1$); and project B ($M_B = 280$, $m = 0$); ($\mu = 0$, $\sigma^{\max}{}_{\mathrm{B}} = 3$); ($p_B = 0.5$, $N = 1$); and project C ($M_B = 280$, $m = 0$); ($\mu = 0$, $\sigma^{\max}{}_{\mathrm{B}} = 3$); ($p_B = 0.5$, $N = 1$) with ($c_5 = 50$, $\alpha_5 = 45$); ($c_4 = 20$, $\alpha_4 = 35$); ($c_3 = 8$, $\alpha_3 = 30$); ($c_2 = 4$, $\alpha_2 = 25$); ($c_1 = 2$, $\alpha_1 = 20$); ($c_0 = 1$, $\alpha_0 = 6$); discount rates $r = 0.08$ and an initial investment cost of $I = 50$. Consistent with our focus on predevelopment, we use a 0.5 probability of success of the completed project B. For projects A and C, we explore different periods of abandonment ($T_k = 6$) and no project payoff is anticipated as only project B is assumed to be complete and brought to market, resulting in payoff for project B. The development costs of project s A and C will be charged to project B. The learning spillover is factored in by increasing the probability of success. We set the maximum probabilities of success $p^{\max}{}_B$ for both Scenarios 4a and 4b at 0.7.

Figure 5 Results of Scenarios 4a to 4b showing the evolution of the total project value for different periods of abandoning competing project A, varying the probability of success from 0.5 to 0.7 (Scenarios 4a and 4b). Scenarios 4a and 4b show the parallel development of two and three technologies, respectively



Note: The benchmark value represents the project value of single project development.

Figure 5 shows the results of Scenarios 4a to 4b. The curve shows the level of total project value for different periods of abandoning projects A and C. The benchmark of developing only one single project is also shown (see benchmark Figure 5, the straight line). The total project value first increases and then decreases where two technologies are developed in parallel (Scenario 4a), or slowly increases and then decreases in cases of parallel development of three technologies (Scenario 4b). Thus the parallel development of three technologies is also possible, but the marginal benefits of pursuing additional options will decline rapidly.

6 Empirical case study

6.1 Objective and setting

To support our simulation results, we collected additional, empirical case information from R&D projects at a Dutch multinational in the electronics industry. The company spends about 8% of its revenue on R&D. Our objectives were:

1. to demonstrate that R&D managers indeed pursue competing technologies in parallel projects to actively stimulate learning spillover during predevelopment
2. to verify the validity of the parameter settings we used in our simulations
3. to provide empirical evidence that this approach is more feasible in the predevelopment rather than in the research stage.

6.2 Method

Together with an insider, we identified two research and two predevelopment projects pursuing competing technologies in parallel. The project leaders were our key informants and on request, all agreed to participate. The data was collected using a survey instrument with semi-open questions in the presence of an interviewer.

The survey instrument (see Appendix B) was first drafted and then reviewed by a company R&D expert. Semi open questions enabled quick analysis of the data and gave the respondents the opportunity to comment and provide more details on each question. The instrument included qualification questions to verify that projects met the research requirements and the structure to validate our parameter settings and results. The qualification questions established that these were indeed research and predevelopment projects, involving the parallel development of substitute technologies. We also assessed the application readiness of the technologies by measuring to what extent the application had been defined at the beginning of the project. This helped us to calibrate the difference between research and predevelopment projects or stages.

To define our structure, we developed and applied simple measurements: for the relatedness between the technologies in each project, we used a single item five-point scale ranging from very low (= 1) to very high (= 5). Higher relatedness should enable more interproject learning. The management's objective to achieve learning spillover was measured using a single item five-point scale ranging from completely disagree (= 1) to completely agree (= 5). We measured the level of learning spillover with two factors, referring to the actual knowledge and learning transfer achieved, using a five-point scale for each, ranging from (almost) none (= 1) to high (= 5). We observed the time when one of the two technologies was abandoned on a single item four-point scale. If learning was not the objective, we could assume direct abandonment as soon as it was apparent that one technology proved superior (= 1). However, if learning was important, the process could be continued even beyond this point (= 2 or = 3), or till the budget was spent (= 4).

The data was analysed using simple descriptives, by computing average scores for the research and predevelopment projects, and by accounting for the respondents' additional comments.

6.3 *Empirical results*

Table 1 shows the results of the qualitative research. First, projects in predevelopment involve the parallel development of related $(\bar{x} = 4)$ rather than unrelated technologies as at the research stage $(\bar{x} = 1.5)$. Furthermore, at the predevelopment stage, the technology is developed with a specific application in mind $(\bar{x} = 5)$. In contrast, although the application focus for the research projects was fixed, a final decision still had to be made $(\bar{x} = 3)$. This illustrates the more applied nature of predevelopment compared to research projects.

Table 1 Results of the empirical case

Constructs	*R&D stage of parallel projects*	
	*Research**	*Predevelopment**
Application readiness:		
Definition of application	3	5
Technology relatedness:		
Relatedness of technologies	1.5	4
Learning spillover:		
Intention to create learning spillover (by sharing results)	2	3.5
Level of learning spillover between the two projects	1.5	4
Level of knowledge transfer between the projects	2	3.5
Abandonment:		
Time of abandonment of first project	4	2

Notes: *Number of cases: each 2; displayed values are averages.
For scales, see Appendix B.

Moving to interproject learning, the results confirm that the learning objective was low for the research projects $(\bar{x} = 2)$ and substantially higher $(\bar{x} = 3.5)$ for the predevelopment projects. In line with these objectives, the results also show that the actual learning effects are higher for predevelopment than for research projects, $\bar{x} = 3.5$ versus 2 for knowledge transfer; and $\bar{x} = 4$ versus 1.5 for learning spillover. Finally, while the competing predevelopment project was terminated sometime after one technology proved to be superior $(\bar{x} = 2)$, the research projects were typically continued till the end, that is to say, till the budget was exhausted $(\bar{x} = 4)$. The reason for continuing technology development in research, even of inferior technology, is the aim to explore. At the research stage, management simply follows the pathways it has selected and funds it has allocated; it does not recall or question these decisions given their exploratory nature. The continuation in the case of predevelopment is because learning can still take place even when one solution is performing less well. In addition, the superiority of one solution is rarely immediately clear.

The empirical results confirm our views; the simulation settings we used for the relatedness between technologies and opportunities for learning appear indeed to be highest during predevelopment. The results also confirm that predevelopment aims to create learning spillovers, whereas this is not (or less) the case at the research stage. Furthermore, the importance of continuing projects beyond the moment superiority has been established, also supports our viewpoint. In research, a less successful alternative project was only abandoned after the budget was all spent, or was even continued in a project focusing on another product application. In predevelopment, the alternative project was abandoned sometime after it became apparent that one technology was superior. This is because in research, parallel projects strive for exploration in general, while predevelopment aims to select the best option for applying a technology in product and interproject learning.

7 Conclusions and discussion

Running parallel projects in research and development has drawn much research attention and is well understood. However, this research strand has not focused on predevelopment and its peculiarities. Lodged between research and development, parallel projects in predevelopment might be expected to be less valuable than in research and more than in the development stage. However, by accounting for the fact that parallel development in predevelopment involves projects with related technologies and thus high learning opportunities, we show that this conclusion is incorrect and should be revisited.

Based on practices in technology driven firms, we recognise and define predevelopment as an important R&D stage. Accordingly, we define predevelopment as the stage when projects have a 0.5 +/– 0.2 probability of success. Predevelopment aims to take the technology output from research and prepare it for development by selecting from remaining options the best competing technology for the job, i.e., the application and its production. Predevelopment projects typically have moderate success rates and high potential for improvement.

Thanks to the focus on selecting the best option from a set of two related technologies, the potential for learning spillover is high when running projects in parallel. Although only one variant of the technology will be selected and brought to market, our results show that the benefits of this learning spillover do exceed the additional costs involved, at least if the parallel project is terminated on time. This corroborates the observation that the method is practised in high-tech firms (see earlier mentioned examples and empirical case).

Using the real option model described by Huchzermeier and Loch (2001), but amended for interproject learning and additional costs, we find that when moving from research to development, the effectiveness of pursuing parallel projects in predevelopment first increases and then decreases, with a maximum positive result in predevelopment (see Scenario 1.2). This favourable result in predevelopment is down to two effects. First, there is much interproject learning because the parallel projects' underlying technologies are related. Second, the fact that the S-curve is steepest in predevelopment suggests great opportunities for performance improvements and thus optimal learning conditions. Managers in predevelopment should seriously consider the parallel project approach to increase the market value of their product applications.

The outcomes of our empirical case support the simulation results. These results confirm that the research projects involve unrelated technologies, while the predevelopment ones focus on the parallel development of related technologies. The research goal is to use parallel projects to explore diversity. In predevelopment, the goal is to narrow down the options for a particular product application. This is evidenced by the fact that the application is generally fixed. More importantly, the results also support higher learning spillovers in predevelopment than in research. Interproject learning is sought and generally achieved during predevelopment. This confirms our assumptions that in cases of related technologies, the learning advantages are useful and cost effective. Interesting is the fact that in predevelopment, the activities for a technology were not immediately stopped after it became apparent that the alternative technology was superior. The parallel project approach was continued for learning purposes and because managers wait for more certainty before deciding to discontinue the less viable alternative. It illustrates managers' belief that learning benefits outweigh the additional costs involved (e.g., Bartezzaghi et al., 1997; Ward et al., 1995).

Particularly remarkable is the fact that the approach renders more favourable results in predevelopment than in research. Prior studies (e.g., Loch et al. 2001b; Childs and Triantis, 1999; Liker et al., 1996) have shown over and over again, that the parallel project approach pays off most handsomely in the research stage. However, these studies focus on exploring projects with unrelated technologies[7], not on related technologies.

The strategy of pursuing competing technologies in predevelopment has proved to withstand several manipulations. Our findings reveal that the competing project could often be continued halfway through the anticipated project duration without incurring a loss in value (e.g., jeopardising cost, time-to-market and performance). Still, the strategy seems most appropriate for 'true' predevelopment projects, with a 0.5 probability of success. In our opinion, the findings confirm that the 0.5 point is best warranted a separate status and should be considered a stage. The traditional 'tipping point' approach suggests an absolute boundary, while the transition from research to development is clearly arbitrary and a sliding scale. Recognising it as a stage draws attention to the activities of final technology selection for the application concerned.

Finally, although the parallel development of three or more technologies is also possible, the marginal benefits of pursuing additional options will decline rapidly.

8 Limitations and implications

Our study has some limitations that provide opportunities for future research: first, our model and parameter settings are based on Huchzermeier and Loch (2001) and appeared robust, however, other more sophisticated models could be applied e.g., those of Childs and Triantis (1999), Lint and Pennings (2002), or Kauffman and Li (2005). Moreover, although we tested boundary conditions using several scenarios, more variations and thus robustness tests could be made.

Second, the learning spillover effects and major differences between the projects at the various stages were modelled in a simple way. For example, we assume that the probability of success at a specific period in a project depends on whether a competing project is developed simultaneously or not, and that the increase in probability is equal over the periods in a single project. Future research can extend our work by better modelling the complexity of interproject learning in R&D (Bartezzaghi et al., 1997). It could also account for the fact that learning spillovers might decrease over time [see Lint and Pennings, (2002), p.19]. Future research opening this black box could draw on the knowledge management literature and its constructs e.g., facilitators of knowledge transfer such as social connectedness, trust and technological capability (Santoro and Bierly, 2006).

Third, quantitative studies using empirical data would be beneficial. They could help validate our findings. The research could also explore conditions under which pursuing competing technologies in parallel projects makes most sense. Potential contingencies to consider include the presence of different learning contexts or 'landscapes' (Prencipe and Tell, 2001) and efforts to develop core or peripheral technologies in parallel.

Our work has several important managerial implications. Firstly, we offer a model for maximising R&D investments by analysing the trade-off between the higher costs and learning benefits of pursuing competing technologies for the same application. It could be beneficial to pursue competing technologies in parallel projects under predevelopment conditions. Project relatedness and learning opportunities should be assessed carefully. The selection of competing technologies could be based on the relatedness of these technologies.

Secondly, because the costs of R&D projects increase rapidly over time, managers should monitor cost accumulation and technical progress carefully, especially in the second half of a project. They need to take measures to ensure that interproject learning can occur and materialise.

Finally, a precondition of our model is that sufficient resources are available to carry out both options. A more constant resource-burning rate can be achieved by pursuing competing technologies in parallel projects. If the parallel option is abandoned halfway to two-thirds through the project, this could improve resource management.

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Notes

1 Predevelopment is also known as advanced development.

2 In large R&D firms, research, predevelopment and development projects are conducted in different departments.

3 The dependence of the value function on the parameter set θ_k is not shown for notational reasons.

4 A time-varying market requirement variability can be also used. See Scenario 3 in Section 5.

5 Note that the individual values of projects A and B in Scenario 2 are similar to those presented by Huchzermeier and Loch (2001).

6 We perform additional analyses, manipulating the probabilities of success and market requirement variabilities under research and development conditions, that is to say projects with a 0.3 and 0.7 probability of success. The results confirm our conclusions under these conditions.

7 If technologies are unrelated, the interproject learning is extremely low or even absent.

Appendix A

Table A1 Overview of data and parameter settings

	Probability		*Dsig (market requirement variability)*			*Premium profit margin*
	p^{min}_{B}	p^{max}_{B}	$Dsig^{min}_{B}$	$Dsig^{max}_{B}$	$\Delta Dsig^{step}_{B}$	M_B
Scenario 1.1a*	0.3	0.5	3	3	0	334.72
Scenario 1.1b	0.5	0.7	3	3	0	280
Scenario 1.1c*	0.7	0.9	3	3	0	233.02
Scenario 1.2a*	0.3	0.4	3	3	0	334.72
Scenario 1.2b	0.5	0.7	3	3	0	280
Scenario 1.2c*	0.7	0.8	3	3	0	233.02
Scenario 2a	0.5	0.5	3	3	0	280
Scenario 2b	0.5	0.6	3	3	0	280
Scenario 2c	0.5	0.7	3	3	0	280
Scenario 2d	0.5	0.8	3	3	0	280
Scenario 3a	0.5	0.5	3	3	0	280
Scenario 3b	0.5	0.5	3	2.5	0.5	280
Scenario 3c	0.5	0.5	3	2	1	280
Scenario 3d	0.5	0.5	3	1.5	1.5	280
Scenario 3e	0.5	0.5	3	1	2	280
Scenario 3f	0.5	0.5	3	0.5	2.5	280
Scenario 4a	0.5	0.7	3	3	0	280
Scenario 4b	0.5	0.7	3	3	0	280

Note: *Settings are 'reversely engineered' using Huchzermeier and Loch's original values.

Appendix B

Table B2 Constructs and measurements used in case study

Construct	*Scale*
Qualification items	
R&D stage	1 = research, 2 = predevelopment, 3 = development.
Technologies were developed simultaneously	1 = no, 2 = yes.
Technologies were substitutes	1 = no, 2 = yes.
Application readiness items	
Definition of application	1 = unknown, 2 = several potential applications in mind; 3 = defined but could change, 4 = defined unlikely to change, 5 = completely fixed.
Technology relatedness item	
Relatedness of technologies (sharing same physical principle/similar technology)	1 = very low, 2 = low, 3 = moderate, 4 = substantial/high, 5 = very high.
Learning spillover items	
Intention to create learning spillover (e.g., by sharing results)	1 = completely disagree, 2 = disagree, 3 = neutral, 4 = agree, 5 = completely agree.
Level of learning spillover between the projects	1 = (almost) none, 2 = low, 3 = moderate, 4 = substantial, 5 = high.
Level of knowledge transfer between the projects	1 = (almost) none, 2 = low, 3 = moderate, 4 = substantial, 5 = high.
Abandonment item	
Time of abandonment of first project	1 = apparent one technology superior, 2 = sometime after apparent one technology superior, 3 = alternative project continued quite some time even knowing technology was inferior, 4 = when budget was spent.