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Multi-stage product development with exploration, value-enhancing, preemptive and innovation options

Nicos Koussis [a,*], Spiros H. Martzoukos [b], Lenos Trigeorgis [c]

[a] Department of Economics, Accounting and Finance, Frederick University, 18 Mariou Agathagelou Str., Agios Georgios Havouzas, 3080 Limassol, Cyprus
[b] Department of Public and Business Administration, University of Cyprus, P.O. Box 20537, CY 1678 Nicosia, Cyprus
[c] Bank of Cyprus Chair Professor of Finance, Department of Public and Business Administration, University of Cyprus, P.O. Box 20537, CY 1678 Nicosia, Cyprus

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ABSTRACT

We provide a real options framework for the analysis of product development that incorporates research and exploration actions, product attribute value-enhancing actions with uncertain outcome, as well as preemption and innovation options. We derive two-stage analytic formulas and propose a general multi-period solution using a numerical lattice approach. Our analysis reveals that exploration actions are more important when the project is out or at-the-money (near zero NPV) and less important for high project values. In a multi-stage setting, exploration actions are important even for in-the-money projects, when follow-on actions exist that can enhance the expected value of the project. With path-dependency, early actions are more valuable since they enhance the impact or reduce the cost of subsequent actions. Preemptive controls affecting rare event (jump) frequency and innovations that introduce positive jumps are more valuable for firms with higher frequency of competitive threats involving low volatility.

1. Introduction

We develop a real options model to study costly interacting managerial control actions. These actions involve pure research or exploration actions, investments that are expected to enhance value or reduce the cost of a project with an uncertain outcome, preemptive investments that reduce the damage of rare events (jumps) and innovation investments that introduce (or increase) the frequency of value improvements (positive jumps). In our model, the information revelation of exploration actions and the volatility of value-enhancing actions interact with exogenous demand-driven uncertainty (e.g., capturing changing consumer preferences). The latter is modeled using a Brownian motion or a jump-diffusion process. In the more general jump-diffusion model, the firm can also make preemptive investments that help control the frequency and size of negative jumps and innovations that increase the likelihood of positive jumps. Our model allows for optimal timing of staged product introductions (with earlier products providing information about future products) and for abandonment options resulting in partial recovery of invested capital.

Pure research or exploration actions include investments in early product versions (pilot projects), experimentation using new processes and marketing research. These actions help resolve uncertainty about the true project value or cost, enabling management to capitalize on new information before large or irreversible investment is undertaken. For example, Samsung conducted marketing research concerning what consumers considered most important attributes of a flat-screen TV that resulted in a more focused development that achieved a higher market penetration (Moon, 2006). Childs et al. (2001) and Bernardo and Chowdhry (2002) use a filtering approach to study information acquisition in a real options model with noisy assets. Pindyck (1993) examines sequential multi-stage investments involving technical uncertainty that decreases as the project approaches completion. Pindyck assumes continuous reduction of technical uncertainty while we allow for different levels of technical uncertainty resolution between stages. We also allow for interacting actions and derive analytic formulas for the two-stage problem. Childs and Triantis (1999) consider accelerated versus sequential strategies and learning spillovers between projects. They assume that actions affect the Brownian volatility while we allow for value

* Corresponding author. Tel.: +357 2573095; fax: +357 25735001.
E-mail addresses: bus.kn@fit.ac.cy (N. Koussis), baspiros@ucy.ac.cy (S.H. Martzoukos), lenos@ucy.ac.cy (L. Trigeorgis).

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enhancement maintaining a separate exogenous demand driven uncertainty; furthermore, we also consider path-dependency.

Direct value-enhancing actions include R&D efforts to improve the attributes or quality of a product, enhancement of customer perceptions through advertising, or efforts to reduce cost through adoption of new technologies in production. For example, Google invests in new technology in promoting online display advertising to enhance its revenues (Hof, 2009). As in Huchzermeier and Loch (2001), these actions aim at enhancing project value, but have an uncertain outcome. We assume that investment decisions are taken at discrete points in time and their outcome is realized immediately. Impulse-type actions with uncertain outcome were introduced in the real options literature by Martzoukos (2000). Childs and Triantis (1999) and Berk et al. (2004) consider projects that require completion of development stages before the commercialization of the product. In our setting, the firm may decide to develop the product immediately, delay development exploring further development opportunities or introduce early product versions. The expected impact, volatility and costs of investments and the cash flows of early product versions depend on the sequencing of decisions (path-dependency). For example, the firm may expect a higher impact of R&D, if prior marketing research has been implemented. New information following the results of an experimentation process may also reduce next-stage costs. Grenadier and Weiss (1997) provide a model for the adoption of technological innovations where firms adopting innovations early are better able to benefit from future innovations.

In the presence of severe competition causing negative jumps in value, the firm may engage in preemptive or innovation investments. Preemptive controls exercised at an optimal time allow management to reduce the frequency and size of competitive threats (negative jumps). Brown and Petersen (2010) discuss how new entrants use high levels of R&D, posing a danger on established firms regarding their profitability and market share. Theoretical arguments in Lambrecht and Perraudin (2003) demonstrate that, in a competitive environment with preemptive investments, equity returns will exhibit jump discontinuities and skewness. Empirical evidence on the presence of jumps in equity prices has been documented in the literature (e.g., Ball and Torous, 1985; Bates, 1991; Nimalendran, 1994). Our model extends the standard jump-diffusion models by incorporating heterogeneity in the frequency and size of jumps between periods, allowing these characteristics to be controlled by the firm through preemptive and innovation investments. Nimalendran (1994) provides empirical evidence of jump heterogeneity that is affected by corporate events and managerial actions. Camara (2009) models the stock price following a jump-diffusion process where upward and downward jumps can have different means and standard deviations, showing that it can better capture volatility smiles and skews in option markets. Pennings and Lint (1997), drawing on experiences from their involvement in Philips' R&D program, also propose discrete and instantaneous updating of information, based on the arrival of new information about competitors and the impact of R&D. Our framework extends theirs in several dimensions, including the incorporation of multiple classes of jumps, jump heterogeneity between decision points and controls that affect the frequency and impact of these jumps.[1] Our framework also allows for innovation investments, which increase value by increasing the frequency and size of positive jumps. They involve, for example, investments in human capital or technological infrastructure that intend to create future growth potential.

We derive analytic solutions for a two-stage problem that involves multiple value-enhancing actions. Our analytic solutions nest several known results as special cases, including those of Geske (1979) and Longstaff (1990) (see also Chung and Johnson (2011) for the multi-stage extendible option). We further incorporate path-dependency and optimal timing of managerial exploration and value-enhancing actions. We extend our model to a multi-stage framework using a numerical lattice approach and provide applications with multiple actions, path-dependency and controls on jump diffusion parameters.

Consistent with results in Bernardo and Chowdhry (2002) and Huchzermeier and Loch (2001), we show that managerial exploration actions may be more valuable for projects that are marginal or break-even. However, we show that in the case of interacting actions, exploration actions may be important even in deep in-the-money projects, when follow-on value-enhancing actions are involved. Furthermore, we show that multiple and interchanging decision regions (as a function of project value) between delay, early development, exploration and value-enhancing actions are possible. Path-dependency has a substantial impact on these regions.

In the jump-diffusion case, we use prior empirical study estimates of jump-diffusion parameters and analyze two classes of firms: firms with low frequency of jumps and high impact/volatility and firms with high frequency and low impact/volatility. We find that preemption actions are more important for at-the-money to in-the-money range options and for the high frequency group. Innovation investments that bring about positive size and preemption options that open-up future opportunities are the most valuable and may be exercised in the out-of-the-money range as well.

The rest of the paper is organized as follows: Section 2 describes the model and assumptions. Section 3 derives analytic formulas for the two-stage problems and discusses the decision regions and the impact of path-dependency. Section 4 provides numerical results for the general multi-stage applications involving path-dependencies in new product development, involving preemption and innovation options. The last section provides the conclusion. An Appendix A includes the numerical lattice-based model for the diffusion model. Appendix B includes the numerical lattice-based solution for the jump-diffusion. Appendix C presents analytic solutions for the jump-diffusion and Appendix D includes an investigation of the numerical accuracy of the lattice-based model.

2. The model and assumptions

We consider an investment decision problem where the management faces uncertainty about market demand, as well as competitive erosion causing jumps in value. Fig. 1 shows a broad categorization of the managerial control (*MC*) actions that can affect project value. These can be summarized into four types of actions: (1) Value-enhancing actions (*VE*) like product attribute-enhancement innovations, quality improvements, or advertisement actions that are used by the firm so as to increase value, albeit they have an uncertain outcome; (2) Exploration or learning actions (*L*) like pure research, marketing research or early product versions, that reduce uncertainty and provide a better estimate about the demand and value of the final product[2]; (3) Competitive preemption options (*P*) that intend to limit or eliminate competitive erosion and downward jumps in value, like entry barriers through acquisitions, advertising and product differentiation; (4) Innovations

[1] Other extensions we incorporate include abandonment options (relaxing the irreversibility assumption), optimal timing of R&D and product introduction, and path-dependency in the impact of R&D. We also allow for exogenous uncertainty to capture market conditions and consumer preferences which are interacting with the uncertainties in the R&D development program.

[2] *L* denotes learning (through information revelation); it should be distinguished from the context from the same symbol used later to denote the lower threshold.